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Multi-agent based simulation of smart building cluster for electric grid stabilization

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Abstract. With the increasing number of photovoltaic systems and heat pumps in buildings existing substations of the electric grid could be overloaded. A multi-agent based simulation of a building cluster studies the impact of building flexibility in regard to the residual substation load. Each building announces its available flexibility, e.g. “heat pump can be switched off/on”. A master coordinator evaluates all incoming offers and decides which offers are accepted. This reduces the residual load at the substation. This paper presents results from a study of the impact at the substation of a smart urban building cluster with different penetration scenarios of heat pumps, photovoltaic systems, batteries and electric vehicles. It is shown that a high penetration of heat pumps and photovoltaic systems violates the substation’s limits for the studied building cluster. Batteries cannot reduce the peak utilization. The master coordinator’s load shifting options are limited.

1. Introduction

The increasing amount of fluctuating renewable energy is a challenge for grid stability and dimensioning. To support stability and avoid extensive reinforcement of the grid, new energy control strategies are necessary. Single buildings and building clusters can support the grid if they are able to control their loads and production/storage units in a grid friendly way. This is possible with an appropriate demand side management e.g. demand respond. To fulfill both the needs of the building or buildings and the grid a complex management system is necessary.

Multi-agent systems (MAS) are a promising solution not only for single building’s energy management but also for building clusters (smart grids). A wide range of literature is available on the topic. For example, [1] focuses on the algorithms of MAS which are tested in simulation at a chilled-water cooling system and a direct-expansion air conditioning system in a multi-zone building. In [2], a MAS is developed and installed in an existing residential building to control different consumers and production/storage units to support virtual grid voltage or frequency drops. A review of MAS shows their usefulness for smart grids [3].

In the study described in this paper the MAS operates a building cluster. It controls the flexible building loads in order to support the local power substation. The impact on the substation of different heat pump, photovoltaic (PV) and battery penetrations is investigate without/with MAS.



2. Methodology of SmartStability

The program used, SmartStability, is an own development by three different departments of the University of Applied Sciences and Arts Northwestern Switzerland based on Java [5]. For this project, the first version described in [4] was extended and enhanced.

SmartStability simulates load shifting within a building cluster to satisfy the substation limits based on MAS. The MAS consists of two main parts: the market coordinator and the agents representing individual buildings (figure 1). Every building agent decides individually about the sharing of its flexibilities. The flexibility is provided by tradable goods: on/off switching of heat pumps for space heat/domestic hot water (DHW) and de-/charging of batteries. Non-tradable goods are: plug loads/lighting and charging the e-vehicles. If PV yield is available, each building first satisfies its own energy demand, then charges its own available battery and lastly distributes any remaining power within the cluster. The building's PV surplus is always used within the cluster before adding to the substation's residual load.

In SmartStability, the flexibilities are traded in order to achieve an optimization function. SmartStability allows for optimization based on different strategies including the following of a predefined power schedule or – as used in this work – keeping the substation in its limits.

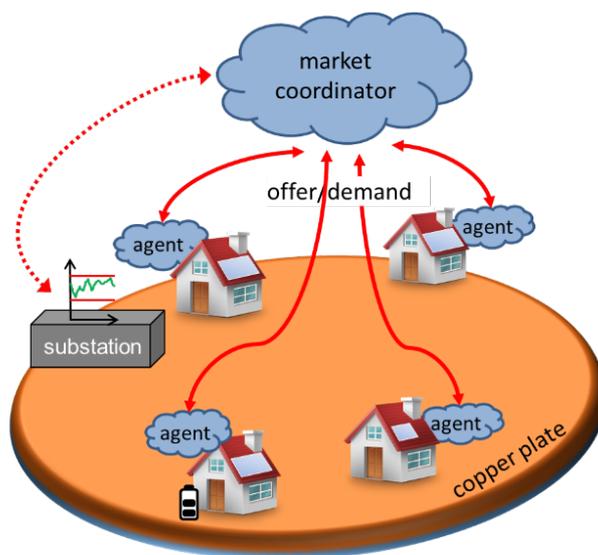


Figure 1. Basic methodology of SmartStability. Each building acts as an agent, the market coordinator strives to minimise the residual load at the substation. The grid within the building cluster acts like a copper plate.

Each building's characteristics, behaviour and flexibility, i.e. supported appliances, can be configured individually. As an example, it can be defined that a building has a PV system and a heat pump, another might have an electrical DHW boiler, a third may have a PV system and a battery. Furthermore, the electricity consumption profile for plug loads/lighting can be selected from a wide range and the participation in flexibility trading can be set. During the simulation, the building continuously calculates the state of its appliances, i.e. the demand for the heat pump, the temperature of the building (taking solar gains, heat pump action and thermal mass into account), the DHW storage temperature, the state of the battery and the amount of PV yield.

In order to trade flexibilities each building agent repeatedly sends flexibility offers to the market coordinator. The amount of flexibility which a building agent may offer is calculated based on the appliance's characteristics and current state as well as the building's needs, such as comfort aspects. For example, if the building is warm and the heat pump is on, the agent may offer to turn off the heat pump. Vice versa, if the building is getting cold (but not too cold) then the agent might offer to turn the heat

pump on. But if the building gets too cold and the comfort limits of the inhabitants are threatened, then the heat pump will be turned on and no flexibility in regard to the heat pump can be offered.

The market coordinator knows about the substations utilization and the state of the connected buildings. Based on the chosen optimization strategy and collected information, the market coordinator selects and accepts flexibility offers by the building agents if needed. The coordinator accepts as many offers as necessary so that no deviation is reported by the optimization function. Of course, if an offer is accepted, the building agent will control the specific appliance immediately. The market coordinator accepts flexibility offers available in a specific order:

- firstly, all PV production offers are accepted because direct use of locally produced electricity has highest priority.
- if the optimization function continues to signal a deviation (e.g. the substation's utilization is outside its limits) the remaining offers from the buildings are ranked.
- Fixed amounts like heat pumps or el. DHW heaters come first, battery offers are last.

The ranking is performed based a number provided by the building with each offer. This number indicates how easy it would be for the building to fulfill the submitted offer and is calculated by the building agent based on a time estimation of how long the appliance can stay in the offered, new status. The longer a building can maintain the new status, the lower the ranking number is and vice versa. E.g. turning off the heat pump if the building is warm implies a low ranking number if it takes a long time for the building to cool down. If the building is only slightly warm, it submits its "turn off heat pump" offer with a higher ranking number because less time is left until the heat pump needs to be turned on again.

The simulations are based on 15 min time steps, i.e. quarter-hour energy balances for DHW use, solar gains, space heat, battery usage etc. A complete simulation consists of an entire year in order to take seasonality into account (demand profiles vary between winter, transitional and summer). The system keeps track of different parameters like the overall demand profiles, DHW and building temperatures, the offers made and the substation's residual load for analysis and visualization purposes.

3. Building cluster and scenarios

In cooperation with an energy supplier a typical building cluster in Basel (Switzerland) is defined. The definition follows type C - one- and two family buildings with low density according to [6]. Table 1 shows the cluster's characteristics. A database of 348 sets of 15-min smart meter profiles from the energy supplier is used for domestic plug loads and lighting. Each unit is randomly assigned a profile from this database ($\bar{\Delta}$ 3'506 kWh/y and unit). 13 different hot water peg-profiles were generated with the tool from [7] and are also randomly distributed across the units.

Table 1. Characteristic of cluster type C

<i>building type</i>	<i>no flats</i>	<i>no units</i>	<i>no building</i>	<i>total heated area (m²)</i>
terraced houses	1	109	109	15'260
	2	18	9	2'250
single family building	1	24	24	6'000
	2	14	14	1'750
multi-family buildings	3	24	8	3'000
total		189	157	28'260



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Two base scenarios are considered. The scenario "today" is used as a reference scenario and a range of scenarios for the year 2035 with different penetrations of heat pumps, PV systems and batteries is defined. The goal is to analyze likely future residual load profiles at the substation and see if the existing substation of 400 kVA can deal with the new challenges or if an improvement of the substation may be necessary.

Today the penetration of heat pumps, PV systems and batteries is very low (table 2). For 2035, it is assumed that 50 % or 100 % of the buildings have a heat pump (40 % brine/water, 60 % air/water). In 2035, 80 % of the buildings have PV-systems and in one scenario a penetration of 50 % batteries is considered. In all, the penetration of electric vehicles increases [8]. When participation in flexibility trading is set, the trading starts when the residual load exceeds 95 % of the substation's limits.

Table 2. Basic data for different scenarios.

	<i>today</i>	<i>2035</i>
el. DHW heater	26% penetration	-
heat pump hp	6% penetration	50% / 100% penetration
PV peak	50 kWp, 6% penetration	694 kWp, 80% penetration
battery (use)	-	437 kWh, 50% penetration
el. vehicles	8 kWh/unit	243 kWh/unit
PV yield	53 MWh/y	731 MWh/y
total consumption	823 MWh/y	884 MWh/y / 1'000 MWh/y
PV yield/total consumption	6%	83% / 73%

Based on the available roof areas and orientations the PV systems are orientated SE, S or SW. The basic assumptions are: 6.5 m²/kWp, $\eta_{\text{Modul}} = 18\%$, $\eta_{\text{SYS}} = 85\%$ for 2035. The slop is 30°. The battery parameters are: max SOC: 98 %, min SOC: 20 %, start SOC 20 %, charge/discharge loss 98 %, self-discharge loss 1 %/month, de-/charge power: 100 % max. capacity. Only buildings with a PV system can have a battery. The heating demand of all buildings is 35 kWh/(m²y). It is assumed, that all buildings with a heat pump are retrofitted. Climate data of the year 2015 is used for both base scenarios.

4. Results

Figure 2 shows the incidences of the substation's utilization based on 15-min time steps. Values $\pm 100\%$ are within the substation's limits. Values above or below $\pm 100\%$ are outside the substation's limits and considered violations. The main findings are:

- Today only grid draw occurs. Feed-in doesn't exist, the low amount of PV yield is completely used within the cluster. The substation is underutilized.
- Upgrading of PV systems to 80 % penetration leads to feed-in overload of the substation.
- The penetration of 50 % or 100 % heat pumps increases the grid draw. The limit is slightly exceeded with 50 % heat pumps and strongly with 100 % heat pumps. In both cases the substation limits are violated in regard to the grid draw limit.
- Batteries can't reduce the peak utilizations. The substation remains overloaded at both feed-in and draw limits.
- The trading of flexibility reduces the utilization of grid draw. In case of 50 % heat pump penetration, the limit can be met due to trading. In case of 100 % heat pump penetration the achieved reduction is not enough to avoid violation of the draw limit.

Three annual substation residual load profiles illustrate the impact of batteries and trading for the scenario "2035: 50 % hp" (figure 3). The substation's overload for feed-in ($< -100\%$) due to PV surplus only occurs between April and September. Between November and March, the grid draw leads to the overload ($> 100\%$) due to no or low PV yield and high demand from the heat pumps. Batteries reduce the utilization of the substation for grid draw during spring, summer and autumn and for feed-in mainly in spring and autumn. They cannot reduce the peak utilization. In the summer they are full due to high PV yield and in the winter they are empty because of low PV yield. Thus, the studied battery sizes are not able to contribute to the trading.

In winter, the trading reduces the utilization of the substation due to the coordination of the heat pump run times for heating and DHW. In the summer, the heat pumps only prepare DHW. This means a smaller amount of available tradable energy; at the same time, a large amount of PV yield is available. Therefore, the trading's impact on the substation's utilization is very low.

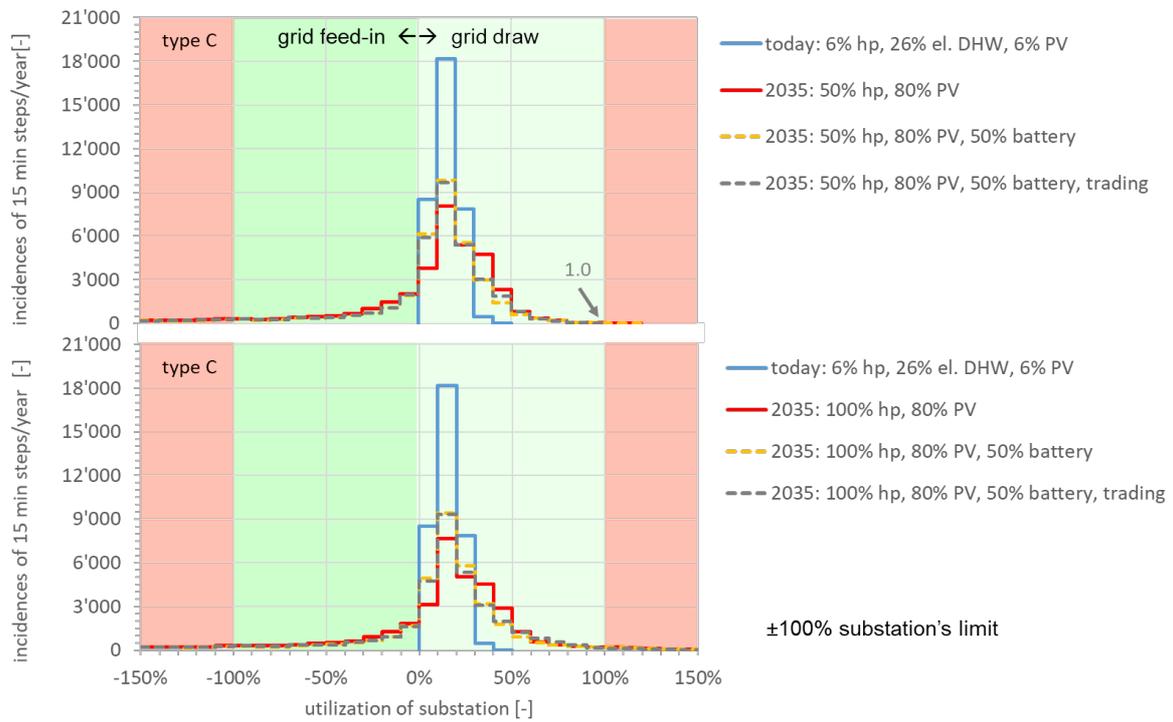


Figure 2. Substation’s utilization with different heat pump penetrations (top: 50 %, bottom: 100 %).

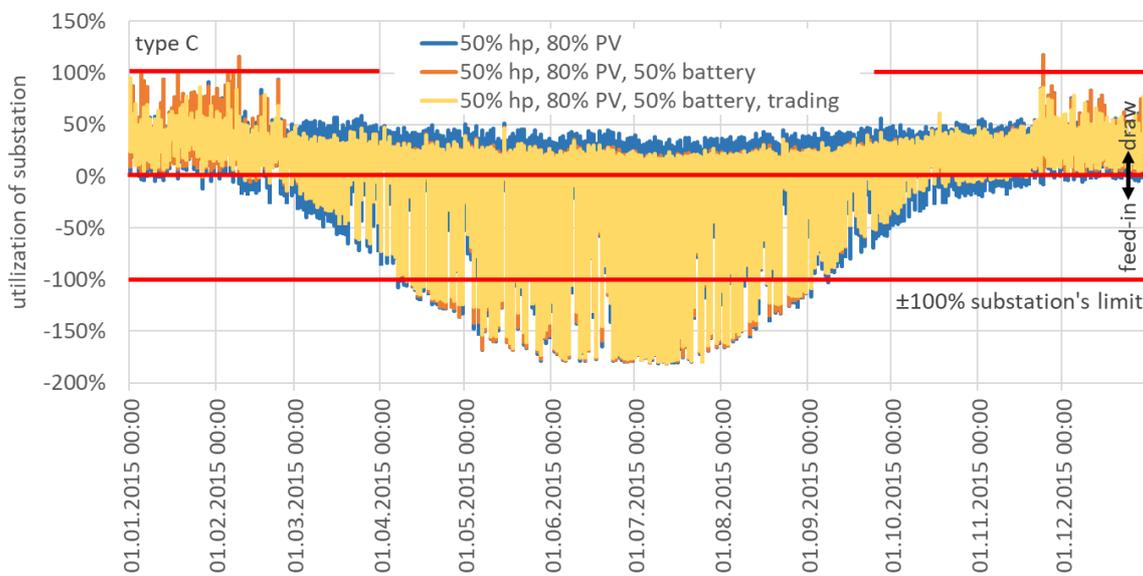


Figure 3. Different annual profiles of the substation utilization.

5. Conclusion

In the building cluster studied, the options for using flexibility are limited. In summer, the PV yield strongly exceeds consumption, in the winter the amount of shiftable energy is limited to the flexibility of the heat pumps.

The impact of the master coordinator's energy management only manifests itself in wintertime. The heat pumps can be switched off when the substation's draw limit is threatened and switched on when there is no risk. The coordinator is able to reduce the violations of the substation's draw limit, but only in case of small violations.

In general, batteries cannot alleviate the peak residual loads and can hardly be activated by the market coordinator. In summer, the batteries are fully charged most of the time, because of the high PV yield and it is not possible to fully discharge them overnight. On the other hand, only a low PV yield is available in wintertime, which is not sufficient to charge the batteries. Most of the time, the batteries are empty, therefore.

The results clearly show that the options of the master coordinator's management are limited. The existing substation needs reinforcement if the penetration with heat pumps and/or PV systems increases significantly.

The novel findings are that the flexibility of the studied building cluster is unexpectedly low because of the seasonal courses of the PV yield and heat pump demand. The results shown are only valid for the studied or a similar type of building cluster.

Acknowledgments

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