

Grid-friendly operation of a building cluster

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Abstract. Energy flexibility of buildings plays an important role on the way to the net zero emission target. Investigation of the energy flexibility of a building cluster requires detailed information on building load depending on load management signal, electricity generation, the local electrical grid and the transformer. The developed co-simulation environment allows detailed simulations with individual building load management signals and setpoints. Building load management uses day-ahead prices and CO₂ profiles with an hourly low, mid and high level for each day which can be overridden by transformer priority management when stress at the transformer occurs. Using a cluster of eight single-family buildings it is shown that both building load management signals lead to slightly lower costs for the cluster compared to a case without signal. But the price load management results in higher and the CO₂ load management in lower CO₂-emissions. Thermal comfort does not change significantly. The transformer priority management is seldomly active, as only grid draw is considered. The transformer is mainly stressed by PV feed-in. The considered building cluster can be operated in a grid-friendly manner in the scope of the building load management. Transformer priority management effects are limited due to cluster size and configuration.

1. Introduction

As part of the Swiss Energy Strategy 2050, it is becoming increasingly important to consider the energy flexibility of building clusters. The expected variable energy supply will make the management of power grids more complex. To relieve the burden on power grids, building clusters should be operated in a grid-friendly manner. For this purpose, appropriate detailed information about the buildings and the power grid must be available. The aim of this project is to analyze the impact of load management signals based on electricity day-ahead prices and greenhouse gas emissions of the electricity mix on energy costs and emissions of the buildings and the cluster. Also, the impact on thermal comfort is observed.

The building cluster is simulated in detail in conjunction with the power grid. The impact of various management signals on the building cluster and transformer is investigated using a bespoke system architecture. The influence of batteries and electromobility is not considered.

2. Methodology

2.1. System architecture for co-simulation of a multi agent system

The agent-based system architecture developed uses EnergyPlus (buildings incl. HVAC, [1]), Mosaik (multi-agent co-simulation, [2], [3]), Pandapower (electrical grid, [4]) and a transformer model based on IEC 60076-7 [5] and [6]. Each building agent knows the building, heating buffer tank and domestic



hot water tank temperatures and the grid agent knows the transformer load and temperature for each time step. Depending on the load management signal and building/transformer status, the agents initiate various actions in the building cluster. Priority management (grid agent, transformer) is superimposed on base load management (building agents). The buildings are operated in a grid-friendly manner by acting upon management signals for space heating while honoring thermal comfort requirements.

The simulation timestep is 10 min. The EnergyPlus weather file for the station Basel-Binningen in Switzerland based on the years 2007 – 2021 [7] is used.

2.2. Building cluster

The building cluster considered consists of eight single-family terraced houses. Each building has 36 kWh/(m² y) heat demand according to SIA 380/1:2016 and 137 m² heating reference area. Each building is equipped with a heat pump, a heating buffer tank, a hot water storage tank, a photovoltaic (PV) system and has an individual usage profile for household electricity, occupancy and window opening schedules (natural ventilation). During summer from May 1st until September 15th the heat pump space heating function is switched off in all buildings. The own photovoltaic yield is always used in each building first and any surplus is used within the cluster if possible.

To reduce simulation time, the building cluster size is restricted to eight buildings in this study. Since there are usually significantly more buildings connected to a local transformer than eight single-family buildings, the transformer is scaled down accordingly.

2.3. Load management signals

2.3.1. Day-ahead price and greenhouse gas (GHG) emissions. Hourly day-ahead prices (DAH) [8] and greenhouse gas emissions based on the electricity mix (CO₂) [9] are used as base load management. It is assumed that both parameters are known by the building agents in advance. The hourly DAH and CO₂ values of each day are divided into three levels as follows (see also figure 1 and figure 2).

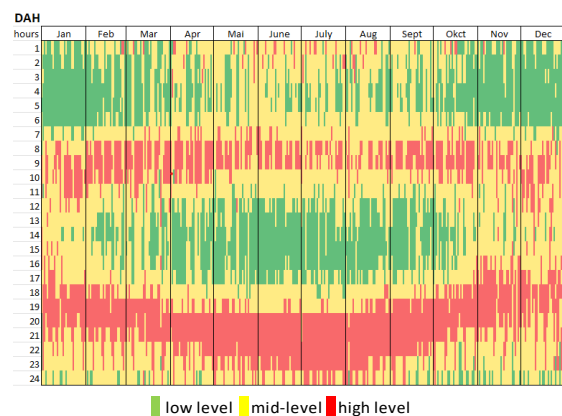


Figure 1. Hourly DAH level, year 2023.

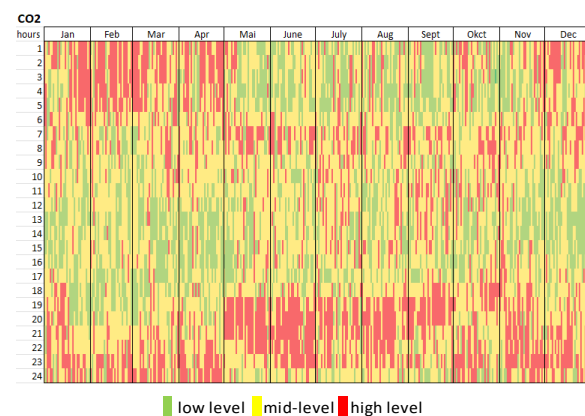


Figure 2. Hourly CO₂ level, year 2023.

- Low level (green): The lowest 25 % of the hourly DAH or CO₂ values (≤ 25 % daily quartile) are used to preheat the rooms so that less heating/electricity is required at times when DAH or CO₂ is higher. The room temperature setpoint is increased from 21 °C to 23 °C. This scenario is applied to six hours per day.
- High level (red): The rooms should be heated to a lower temperature during the highest 25 % of the hourly DAH or CO₂ values (> 75 % daily quartile) to save costs or CO₂ emissions. The room temperature setpoint is set to 18 °C. This scenario is also applied to six hours per day.

- Mid-level (yellow): The standard room temperature setpoint (21 °C) is maintained for the remaining 50 % of the hourly DAH or CO₂ values. This scenario is applied to the remaining 12 hours per day.

Once a day the domestic hot water is heated in a fixed two-hour block window. Three different block windows are used within the cluster. The water heating always occurs in the early morning when DAH or CO₂ are almost always at a low or mid-level.

The total costs for the cluster are calculated based on the day-ahead prices with the addition of grid costs and other levies. A price for self-consumption and grid feed-in is also considered. The total CO₂ emissions are calculated with the emissions of the grid electricity mix. They are zero for self-consumption and grid feed-in, because the GHG emissions of the PV systems themselves are accounted for in the embedded GHG emissions of the building.

2.3.2. Transformer limit and temperature. Transformer overload or overheating can reduce their expected lifetime and must be avoided. A corresponding transformer overload signal must override the base load management. In this project only overload due to grid draw is acted upon. Overload caused by grid feed-in due to PV surplus is not considered.

If the transformer limit value is exceeded, the individual building agents receive an adapted signal according to a priority list to switch off the heat pump (figure 3, list below).

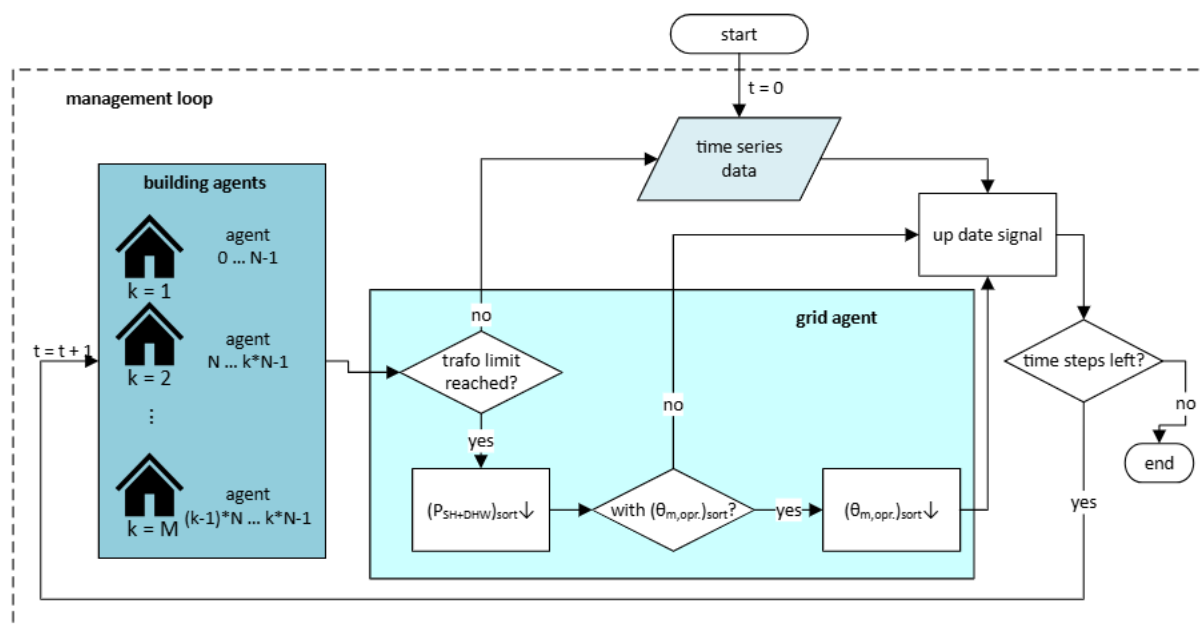


Figure 3. Example for management loop with building agents and grid agent for transformer limit with consideration of sorting I/II (k: building index, N: number of agents, M: number of buildings, t: timestep, P_{SH+DHW}: power for heat pump space heating/domestic hot water, θ_{m,opr}: mean operative room temperature).

The priority sorting ensures that only the required number of heat pumps are switched off. Two different sorting methods are examined:

- Sorting I (TL I): Descending, by electricity demand of the heat pumps until the transformer limit is met.
- Sorting II (TL II): Descending, by electricity demand of the heat pumps and the average operative room temperatures until the transformer limit value is met. Only buildings with an average operative room temperature of at least 18 °C are considered.

In case of transformer temperature based management (TT), all heat pumps are switched off in buildings with room temperatures greater than 18 °C when the transformer temperature exceeds 110 °C. After cooling down to 90 °C the heat pumps are allowed to switch on again if needed.

2.4. Cases

Considered cases and setpoint temperatures are shown in table 1. To be able to implement flexibility and to use load management, temperature ranges must be defined. The room temperature levels and spread are within the scope of SIA 382.711:2019 [10]. The standard room temperature of 21 °C is taken from SIA 2024:2021 [11] for the design of the heating system. The fall back to 18 °C is quite low, but this is to ensure that no or rarely room heat is needed at times of high level day-ahead prices or CO₂-emissions. However, this does not mean that the rooms cool down to 18 °C. The standard hot water tank temperature of 55 °C is taken from [12]. The low fall-back temperature of the hot water tanks is rarely used, as the water is usually heated at times with low or mid-level day-ahead prices or CO₂-emissions.

Table 1. Setpoint temperatures applied to base load management (low, mid and high level for DAH or CO₂) and transformer priority management (TL, TT) (room: average operative room temperature, TL: transformer power limit, TT: transformer temperature limit).

case	room	buffer tank	DHW tank
base (no signal)	21 °C	50 °C	55 °C
DAH/CO ₂	18, 21, 23 °C	40, 50, 55 °C	45, 55 °C
DAH/CO ₂ +TL I/II	18, 21, 23 °C, if TL < TL max, else 18 °C	40, 50, 55 °C, if TL < TL max, else 40 °C	55 °C, if TL < TL max, else 45 °C
DAH/CO ₂ +TT	18, 21, 23 °C, if TT < 110 °C, else 18 °C	40, 50, 55 °C, if TT < 110 °C, else 40 °C	55 °C, if TT < 110 °C, else 45 °C

3. Results

3.1. Base load management

DAH and CO₂ load management leads to a higher total electricity demand for space heating and slightly lower costs for the cluster compared to the base case (see figure 4). The CO₂-emissions of the cluster increase with the DAH and decrease with the CO₂ load management. The numbers vary for different years because the pattern auf the hourly DAH and CO₂ differs in each year.

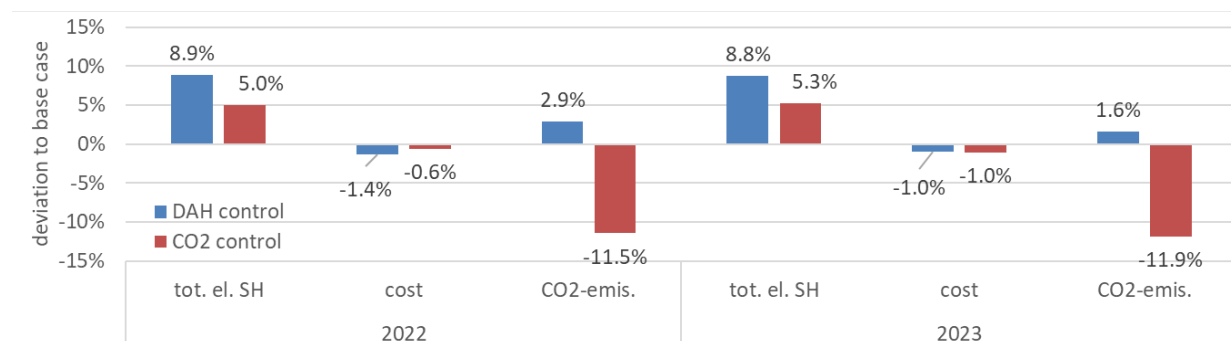


Figure 4. Relative deviation from the base case of consumption for space heating (tot. el. SH), costs and CO₂-emissions for the cluster based on DAH and CO₂ load management (blue/red) for the years 2022 and 2023.

3.2. Transformer priority management

In winter, the DAH+TL I and DAH+TL II priority management is seldomly activated as the maximum transformer load is seldomly exceeded. In spring, the maximum transformer load occurs when there is a high PV surplus (grid feed-in) despite heat pump operation at midday. In this case, the DAH+TL I or DAH+TL II priority management is not active, as the priority management only influences the grid draw. The maximum transformer utilization for the DAH and DAH+TL I/DAH TL II cases is around 132 % in each case. The observed cluster shows the same results for DAH+TL I and DAH+TL II because the room temperatures never drop below 18 °C in the heating season and therefore the temperature sorting option of DAH TL II is never activated.

The DAH+TT case has a maximum transformer utilization just shy of 137 %. This higher value is caused by the switching-off of heat pumps at times when the transformer temperatures are already high. The high transformer temperatures occur around midday, when there is also a high PV yield. If heat pumps are switched off during such times, an even greater PV surplus is fed into the grid, which in turn increases the transformer utilization and temperature. The DAH+TT case is seldomly activated because the overlap time between the heating season and available PV surplus is short.

In general, no significant differences between all cases of DAH can be observed. This is also valid for the CO₂ cases. The distribution grid itself is not overloaded at any time.

3.3. Thermal comfort

Thermal comfort evaluation is based on the comfort region of SIA 180:2014 [13]. As an example, the comfort evaluation of building 5 is given for the base case in figure 5 and for DAH+TL I case in figure 6. In the DAH+TL I case (year 2023), the shortfall in the heating season (grey area) is slightly larger than in the base case because the room temperature setpoint is lowered to 18 °C at times with high level day-ahead prices. However, 18 °C is never reached during the heating season, where room temperatures in the range [20.5, 21.0] °C are found for 106 hours, which is only 29 hours more than for the base case. The room temperature falls below 20.0 °C for 22 hours, compared to 10 h for the base case. The yearly average shortfall is found to be 0.6 K for both cases.

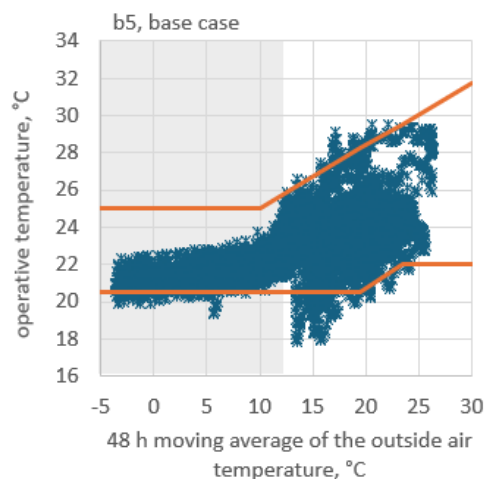


Figure 5. Building 5, base case, SIA 180 comfort plot (grey area; heating season).

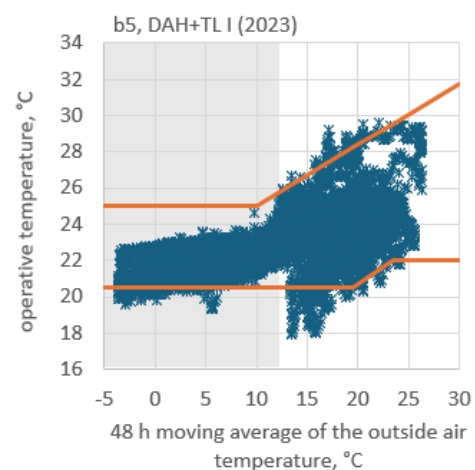


Figure 6. Building 5, DAH+TL I case, SIA 180 comfort plot (grey area; heating season).

For low level day-ahead prices, the target room temperature is increased to 23 °C, which results in higher room temperatures in the heating season for the DAH+TL I case than for the base case. With load management applied, there are greater fluctuations in the room temperatures during the heating season. In summer, when the heat pump is switched off for space heating all cases show the same temperatures.

Table 2 summarizes results for all buildings. The difference of total hours between DAH+TL I case and base case below 20.5 °C e.g. 20.0 °C varies for each building. The DAH+TL I case can have more

and less hours than the base case. The average shortfall to 20.5 °C is between 0.3-0.6 K. The heating demand increases with load management by 6 – 22 % compared to the base case.

Table 2. For each building: differences of total hours between DAH+TL I case and base case below 20.5 °C e.g. 20.0 °C, average shortfall to 20.5 °C for DAH+TL I case and additional space heating demand due to load management DAH+TL I case compared to the base case.

	b1	b2	b3	b4	b5	b6	b7	b8
diff. hours below 20.5 °C, h	-11	-39	-85	49	22	-44	-39	31
diff. hours below 20.0 °C, h	7	-2	-16	10	10	3	5	84
average shortfall to 20.5 °C, K	0.5	0.3	0.3	0.5	0.6	0.3	0.3	0.5
additional heating demand, %	19	8	6	22	12	9	13	7

4. Discussion and conclusion

The load management signals studied do not result in higher electricity costs for the building users although the space heating demand increases. For the grid operator, load management results in advantages in grid-friendly operation. They can switch off the heat pumps as required at times with high day-ahead prices and thus avoid or reduce expensive additional purchases at the electricity stock exchange. In addition, the grid operator can reduce transformer overload by switching off heat pumps when required, which benefits the service life of the transformer. The grid operator can react to greenhouse gas emissions in the same way if this should be a management target in the future.

The results also show that load management should be applied carefully. Depending on the situation, not all load management signals can be acted upon. For transformer management, it is important to differentiate whether grid draw or grid feed-in leads to an overload. Different activities regarding the activation or deactivation of consumers or reducing PV production are needed.

Based on the simulations, it can be shown that the selected load management is suitable for the grid-friendly operation of the investigated building cluster without significantly restricting the thermal comfort of the residents. However, it is also clear that grid feed-in plays a major role compared to grid draw. Without considering mechanical cooling or (short and/or long-term) storage, the building cluster has very limited flexibility, especially in summer, and can only respond to load management to a limited extent.

The results reflect the selected cluster and the chosen approach. Other assumptions may lead to different results. The system architecture developed can be used for any number and type of buildings and can be extended with e.g. cooling function, soil regeneration through geothermal probes, thermal collectors and batteries. The load management design is adaptable to other base load management signals e.g. a combined signal of DAH and CO₂ or a different transformer priority management in case of transformer overload due to grid draw or grid feed-in.

Credit-author statement

MH: conceptualisation, methodology, simulations & evaluation, writing – original draft, writing - review & editing, AG: simulation system extension, review & editing

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