Building Energy Flexibility Provision via Optimal Thermal Energy Management

Ilaria Salerno[1], Miguel F. Anjos[1], Kenneth McKinnon[1], Juan A. Gómez-Herrera[2]
[1]School of Mathematics, University of Edinburgh, UK
[2]Expretio Technologies, Canada

July 2020

Abstract

Decarbonizing the energy sector requires the integration of renewable resources to the largest possible extent. However, renewable resources do not readily adapt to fluctuating energy needs. Instead, we can adapt the demand to the production, and this leads to demand-side management (DSM). Buildings have great potential for DSM. First, they represent 33% of the worlds total energy consumption. Second, their thermal mass can be used to store heat or coldness, and if these are procured electrically, then the building is in principle able to provide flexibility to the electric power grid. We study the ability of a mathematical-optimization-based thermal energy management system (TEMS) for residential/commercial/institutional units to improve the flexibility provided by such units to the grid. The TEMS provides benefits to both the unit users and the grid operator, since it manages heating while guaranteeing indoor thermal comfort and provides flexibility to the grid.

Introduction

Recent changes in power systems and the increasing integration of renewable resources have led to the need for a flexible energy demand. Imbalances between energy consumption and generation result in user discomfort and high operational costs for utility companies (Adika and Wang, 2014).

In this paper, we apply the thermal energy management system (TEMS) presented by Salerno et al. (2020) to real-world scenarios, and we discuss its potential to increase the flexibility of the heating demand of an independent unit and a heat network. We demonstrate that the TEMS also reduces the overall energy consumption.

We address three main challenges. First, we study how to make the heating demand flexible. Such demand has a significant potential for demand-response, but this is under-utilized because users have strong comfort preferences. A flexible heating demand can greatly improve the energy efficiency of buildings (Romanchenko et al., 2019), since heating often represents the largest component of the energy consumption.

Second, in existing studies the heating demand is often oversimplified: it is estimated from historical data or calculated by external software. We use a more detailed model.

Third, in existing studies flexibility is studied from the perspective of the grid operator in unit commitment problems. For example, Romanchenko et al. (2019) aim to improve the efficiency of the generators in the district heating (DH) system of Gothenburg, Sweden. We instead focus on the customer.

This study deals with the three challenges, and our contribution can be summarized as follows. First, we focus on the demand side and specifically on the customer. The TEMS improves the operations of the grid and reduces the heating demand. Second, it computes a detailed heating demand for each individual unit and exploits its thermal flows to maximize the flexibility. It adjusts the indoor temperature by controlling the shading, ventilation, and heating systems and considering the thermal mass of the representative elements of each unit. In contrast, other studies oversimplify the system. For instance, Romanchenko et al. (2019) consider only two zones, indoor and outdoor, and they estimate the heating demand by computing the heat flowing between the two. No existing studies consider the integrated control of shading, ventilation, and heating systems, and they often study only the thermal mass of the building as a whole.

Third, we introduce flexibility by allowing each unit to greatly reduce its consumption for a time. Other studies instead consider peak shaving, where energy is shifted from a peak to a valley. Our approach allows the user to be more independent of grid failure and reduces the electricity bill. The ability to reduce or turn off the heating system at times makes the unit resilient to grid uncertainties.

Our final innovation is in the way that the TEMS provides flexibility. When the TEMS is applied to a single unit, it takes advantage of the unit's thermal mass, using the unit's structure as thermal storage. When the TEMS is applied to a network of units, it can move the heat surplus from one unit to another, by ventilation. Heat that would have been wasted by one unit is thus used to warm the others.

The remainder of this paper is organised as follows. In the Literature section we discuss the state of the art and limitations of existing heat flexibility studies.

We focus on the impact of automation systems on energy demand, the optimization framework of the TEMS, and heat recovery processes. In the Methodology section, we present our approach. In the Applications and Results section, we apply the TEMS to a single residential unit and to a network of two connected units. We demonstrate the potential of the TEMS to introduce flexibility by analyzing three scenarios. Finally, in the Conclusions and Future Work section we provide concluding remarks.

Literature

Building automation systems

Various external factors, such as weather conditions, increase energy consumption, but building automation systems (BAS) can mitigate this phenomenon Lomas and Ji (2009). The automation of certain activities, such as the heating system control and the indoor temperature setting, can improve energy efficiency. Shaikh et al. (2014) state that unwitting energy activities can add one-third to the building's energy consumption.

Osma et al. (2015) study the BAS of the Electrical Engineering building of the University of Santander (Bucaramanga, Colombia). This BAS controls lighting and air conditioning, and the authors explore the impact of: a heat island, energy outages, new construction, and different user habits. They also consider a scenario with no BAS. They find that the BAS significantly reduces the energy consumption. It also reduces fuel consumption and CO_2 emissions in power-outage scenarios.

Braun (2003) studies the energy-saving potential of thermal mass. Braun finds that controlling the building's inertia can significantly reduce the cooling demand of a commercial structure. The total savings depend on many factors, such as the occupancy schedule and the climate.

Heat recovery and ventilation

O'Connor et al. (2016) discuss reducing a buildings' energy demand via heat recovery, i.e., using the exhaust air as a heat source or sink. They find that recent changes in the users' behaviour and the increasing use of electrical devices produce enough heat gains to provide a reliable heat source. Recovering this energy reduces the reliance on heating systems. Furthermore, it significantly reduces the HVAC (heating, ventilation, and air conditioning) demand (Dodoo et al. (2011)). O'Connor et al. (2016) point out the advantages of using ventilation for energy efficiency: the low running cost, improved indoor comfort, and low environmental impact make this technology attractive for both governing bodies and users.

TEMS' optimization framework

We use a TEMS based on the optimization framework (OF) proposed in Salerno et al. (2020). They show how the OF adapts to different structures, locations, energy systems, and objectives: it simulates a single independent unit using an RC circuit analogy. They demonstrate that the OF both ensures comfort and reduces the overall heating/cooling consumption or cost.

The nodes (or buses) of the OF represent elements having thermal capacity, and they are associated with temperature values. The nodes are connected by lines on which power flows (shown as blue arrows in Fig. 1). On each line, power may be lost or conserved. The lines connecting the nodes can be balanced or unbalanced and controlled or uncontrolled. The line is balanced if the flow leaving one end is equal to the flow arriving at the other end. Heat exchange between two nodes is an example of a balanced line. The line is controlled if the OF decides the timing and quantity of the flow; ventilation is an example.

In this representation, temperature plays the role of voltage in a circuit: if the temperatures of the two nodes connected by a line are different, then power flows from one node to the other. This is a balanced and uncontrolled line (P_l^L in Fig. 1); an example is heat exchange between two materials. Each line has a resistance, which is a parameter of the optimization model; these resistances are indicated by rectangles in Fig. 1 and denoted as r_l.

Ventilation is a balanced and controlled line. Power flowing from one node to the other (P_l^V) varies according to the variable $X_{i,l}$ and the parameter y_l^{air}, representing the air exchange rate and the air thermal capacity respectively.

The flow is unbalanced (P_l^H) when the power leaving the node at one end of a line is different from the power reaching the other end; an example is the behaviour of a heat pump. The electricity input required by the heat pump is indicated by a yellow arrow in Fig. 1. Moreover, the heat-pump line is associated with a function that represents its energy efficiency (E_l): this is the difference between the power leaving one end and that arriving at the other end of the line.

Each node can store energy. This is analogous to a capacitor in a circuit, and storage is represented by two parallel lines in Fig. 1. The heat capacity (or thermal mass) of a node is denoted y_s, and it is a property of the material.

A node can receive power from one or more external sources, referred to as generators. Sun radiation and heat from people and electrical devices are external resources. The sun radiation is controlled by the variable $\Delta_{i,g}$ and scaled by the parameter ϵ_g. These represent the status of the smart shading system and the clearness index of the external environment.

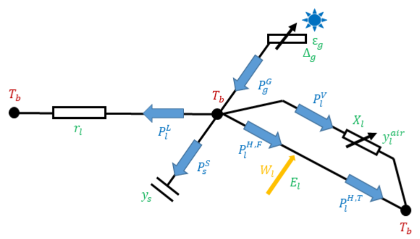

Figure 1: Visualization of OF operations.

Objective function

$$\min \quad \sum_{l\in\mathcal{L}}\sum_{i\in\mathcal{I}} c_i W_{i,l} \tag{1}$$

The objective of the OF minimizes the product of $c_i W_{i,l}$, where $\sum_{l\in\mathcal{L}}\sum_{i\in\mathcal{I}} W_{i,l}$ is the overall electricity input of the heating/cooling system during the total running period. The parameter c_i places a weight on the hours of the day: flexible hours have a higher weight.

Constraints
Balance, node b:

$$\sum_{l\in\mathcal{W}|b=T_l} P_{i,l}^{L} - \sum_{l\in\mathcal{W}|b=F_l} P_{i,l}^{L} +$$

$$+\sum_{l\in\mathcal{H}|b=T_l} P_{i,l}^{H,T} - \sum_{l\in\mathcal{H}|b=F_l} P_{i,l}^{H,F} +$$

$$+\sum_{l\in\mathcal{W}|b=T_l} P_{i,l}^{V} - \sum_{l\in\mathcal{W}|b=F_l} P_{i,l}^{V} +$$

$$+P_{i,b}^{G} - \sum_{s\in\mathcal{S}|b=B_s} P_{i,s}^{S} = 0 \quad \forall i\in\mathcal{I}, \forall b\in\mathcal{B} \tag{2}$$

Branch flows:

$$P_{i,l}^{L} = \frac{1}{r_l}(T_{i,F_l} - T_{i,T_l}) \quad \forall i\in\mathcal{I}, \forall l\in\mathcal{W} \tag{3}$$

$$P_{i,l}^{H,T} = E_l(T_{i,F_l}, T_{i,T_l}) W_{i,l} \quad \forall i\in\mathcal{I}, \forall l\in\mathcal{H} \tag{4}$$

$$P_{i,l}^{H,F} = P_{i,l}^{H,T} - W_{i,l} \quad \forall i\in\mathcal{I}, \forall l\in\mathcal{H} \tag{5}$$

$$P_{i,l}^{V} = X_{i,l}\ y_l^{air}\ (T_{i,F_l} - T_{i,T_l}) \quad \forall i\in\mathcal{I}, \forall l\in\mathcal{W} \tag{6}$$

Air change per hour in ventilation lines:

$$X_{i,l}^{min} \le X_{i,l} \le X_{i,l}^{max} \quad \forall i\in\mathcal{I}, \forall l\in\mathcal{W} \tag{7}$$

Constraint (2) ensures that the total power flowing into and out of each node is equal to zero. Power flows represent thermal fluxes, and we assume that the power flowing into a node has a positive sign.
There are five main types of flows. The first type is the power naturally flowing through a line, from a higher to a lower temperature node: this balanced and uncontrolled flow is represented by the first two terms of (2) and by (3).
The second type of flow is similar, but it is unbalanced. It is represented by the third and fourth terms in (2) and by (4) and (5). These unbalanced lines simulate the heating/cooling system of the unit, by one or more heat pumps. Power flows from the colder to the warmer node. This process requires a certain amount of work, which is represented by the variable $W_{i,l}$. Equation (5) describes the energy conservation of the heat pump system: the amount of heat allocated to the hot node ($P_{i,l}^{H,T}$) must equal the amount of heat taken from the cold node ($P_{i,l}^{H,F}$) plus the work ($W_{i,l}$). The efficiency of this process depends on the temperature of the two nodes at the ends of the heat-pump line. This dependence is described by (4). The output of the heat pump ($P_{i,l}^{H,T}$) is equal to its electricity input ($W_{i,l}$) times a function that represents the pump's energy efficiency (E_l). This efficiency (E_l) is a nonlinear function of the temperatures of the nodes to which it is connected (T_{i,F_l} and T_{i,T_l}).
The third category of flow is balanced and controlled ($P_{i,l}^{V}$ in Equations 2 and 6). It represents ventilation and simulates the air flowing from the warmer to the cooler node. The difference between this and the first type of flow is that ventilation is associated with a variable ($X_{i,l}$) that represents "air change per hour" (ACH). It ranges within bounds that guarantee comfort and hygiene inside the room (7). The ventilation flow depends on the amount of ventilated air ($X_{i,l}\ y_l^{air}$) and on the difference between the two nodes at the extremes of the line: ($T_{i,F_l} - T_{i,T_l}$). Moreover, y_l^{air} denotes the thermal mass of the air flowing in the ventilation line (6). The OF is nonlinear because of the ventilation constraint (6) and the heat-pump constraint (4).

Heat energy from generators:

$$P_{i,b}^{G} = \sum_{g\in\mathcal{G}|b=B_g} (q_{i,g}^{int} + Q_{i,g}^{sol}) \quad \forall i\in\mathcal{I}, \forall b\in\mathcal{B} \tag{8}$$

Solar gains:

$$Q_{i,g}^{sol} = \Delta_{i,g}\epsilon_g(q_{i,g}^{sol,B} + q_{i,g}^{sol,D}) \quad \forall i\in\mathcal{I}, \forall g\in\mathcal{G} \tag{9}$$

Smart shading system configuration:

$$\Delta_{i,g}^{min} \le \Delta_{i,g} \le \Delta_{i,g}^{max} \quad \forall i\in\mathcal{I}, \forall g\in\mathcal{G} \tag{10}$$

Energy storage:

$$L_{i,s} = y_s T_{i,B_s} \quad \forall i\in\mathcal{I}, \forall s\in\mathcal{S} \tag{11}$$

Storage level of charge:

$$L_{i,s} = L_{(i-1),s} + P_{i,s}^{S} h \quad \forall i\in\mathcal{I}, \forall s\in\mathcal{S} \tag{12}$$

The fourth type of flow comes from a generator. It is denoted by $P^G_{i,g}$ in (2) and defined in (8). The power generation in the unit derives from sun rays ($Q^{sol}_{i,g}$), people, electronic devices, and the lighting system ($q^{int}_{i,g}$). During the heating periods, these elements are free and sustainable energy resources, because they warm up the unit. During the cooling periods we may want to reduce them because they represent an additional load. Accordingly, the OF can simulate a smart shading system. The variable $\Delta_{i,g}$ controls the solar power entering the unit, and (10) gives bounds on its value. This guarantees visual comfort inside the room. Clouds may reduce the solar penetration, and the parameter ϵ is the clearness index of the location.
The fifth type of flow consists of power flowing into/out of a storage unit ($P^S_{i,s}$). Each node has an associated temperature and thermal mass. The thermal mass acts as thermal storage: it can be charged and discharged during different time frames (h in 12). This process is described by (11) and (12), where $L_{i,s}$ is the energy stored in the node. It depends on both the temperature ($T_{i,s}$) and heat capacity (y_s) of the node. Only changes in energy are relevant to the model, so the zero point can be chosen arbitrarily. We choose the zero point to correspond to a temperature of zero.

Temperature limit:

$$t^{min}_{i,b} \leq T_{i,b} \leq t^{max}_{i,b} \quad \forall i \in \mathcal{I}, \forall b \in \mathcal{B} \tag{13}$$

Ramping limit:

$$-l^D_b \leq T_{i,b} - T_{(i-1),b} \leq l^U_b \quad \forall i \in \mathcal{I}, \forall b \in \mathcal{B} \tag{14}$$

Power limit:

$$0 \leq W_{i,l} \leq p^W_{i,l} \quad \forall i \in \mathcal{I}, \forall l \in \mathcal{H} \tag{15}$$

Constraints (13), (14), and (15) control the operational limits of the unit. Equation (13) ensures that the node temperature stays within specified bounds. Equation (14) limits the rate at which the temperature varies. Accordingly, these two constraints may be applied to guarantee thermal limits. Constraint (15) ensures that the power flowing on the lines is within the operational capacity.
For further details about the OF, see Salerno et al. (2020)

Methodology

We adjust the OF to become the core of our TEMS for heating flexibility. We use the parameter c_i in the objective function (1) to maximize the heating flexibility of the unit. We apply the TEMS to a single unit and to a heat network, and we discuss its potential for providing flexibility. We demonstrate that it increases the flexibility provided during the selected hours and also reduces the overall heating demand. We measure flexibility via the user's ability to reduce the use of the heating system during the selected hours.

Applications and Results

In this section, we discuss the results of two case studies. We simulate two winter days with the weather conditions of Montreal (Canada). TEMS works to provide flexibility during two periods: from 7 to 10 a.m. and from 5 to 6 p.m. We refer to these periods as "flexible hours" (Fig. 2).

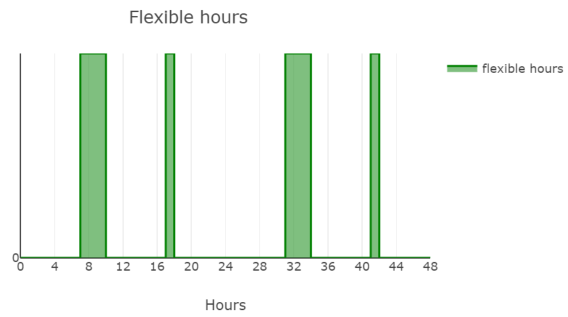

Figure 2: Flexible hours in a two-day period.

All the units have a double skin façade (DSF) and are designed as DYN units (Salerno et al., 2020).
In the two cases (single unit and network), we assume that the ventilation between the units satisfies the hygiene requirements. The two units exchange energy but not mass. If the unit does not have the TEMS, it does not maximize flexibility and simply calculates the demand that will keep the indoor temperature steady at 21°C. Accordingly, the cases without the TEMS have controlled ventilation and aim to stay within the temperature limits.
In the first scenario, we apply the TEMS to a single west-oriented residential unit. We compare the heating demand with and without the TEMS. In the second scenario, we model two units and simulate two cases. In case 1, we apply the TEMS to two residential units (one west-oriented and one south-oriented) from the same large building with a DSF. The air-cavity of the DSF may connect the two units. When the TEMS is present, it controls this connection and optimally moves warm air from one unit to the other via ventilation. When there is no TEMS, there is no connection and the two units are independent. In case 2, there are two institutional units. They are east- and west-oriented and they have different occupancy schedules. We assume that users are in the east unit from 9 a.m. to 12 noon and that they move to the west unit from 12 noon to 5 p.m. When the TEMS is present, the main room of the two units may be connected by a ventilation line; if there is no TEMS, the units are independent.

Scenario I: Single user

In this scenario we compare the heating demand of an independent west-oriented residential unit, with and without the TEMS. Table 1 shows the electricity input of the heat pump. The demand during the flexible hours is 83% lower for the unit with the TEMS. Furthermore, the overall demand is 40% smaller for the same unit. This is because the TEMS controls the ventilation and makes use of the unit's thermal mass.

demand [kWh]	without TEMS	with TEMS
during flex-hours	3.03	0.51
during two days	10.32	6.17

Table 1: Electricity demand of a west-oriented residential unit with and without TEMS

Figures 3 and 4 compare the two units. The first graph of each figure shows the electricity input of the heat pump (grey curve) and the heating output (pink curve). The TEMS pre-heats the unit before the flexible hours: it uses the building's structure as thermal storage, so that it can reduce its electricity requirement when needed. The second graph shows the temperature profiles of the elements in the unit with a thermal mass and the outside. During solar gain peaks, the air temperature in the air-cavity (green line) is warmer than that indoors. Thus, some heat spontaneously flows from the air-cavity to the room. The unit without the TEMS aims to keep a constant indoor temperature of 21°C and to stay within the air-cavity temperature bounds. It achieves this by ventilating the room and the air-cavity, pushing the surplus heat outside. In contrast, the unit with the TEMS uses the unit's elements as thermal storage: it stores the surplus heat in the walls, room, and DSF and uses it during the flexible hours.

The third graph shows this phenomenon. It represents the ventilation flows between the air-cavity and the outside (the red line labelled "pV DSF-ext"), the living zone and the DSF (the green line "pV LZ-DSF"), and the living zone and the outside (the blue line "pV LZ-ext"). When the curves are negative, ventilation cools the warmer zone; when they are positive, it warms. The unit without the TEMS uses only part of the energy from the sun (green curve in Fig. 3), and it wastes the surplus outside (blue and red curves). On the other hand, the unit with the TEMS ventilates the surplus from the air-cavity to the room (green curve in Fig. 4) and wastes less energy (red and blue curves).

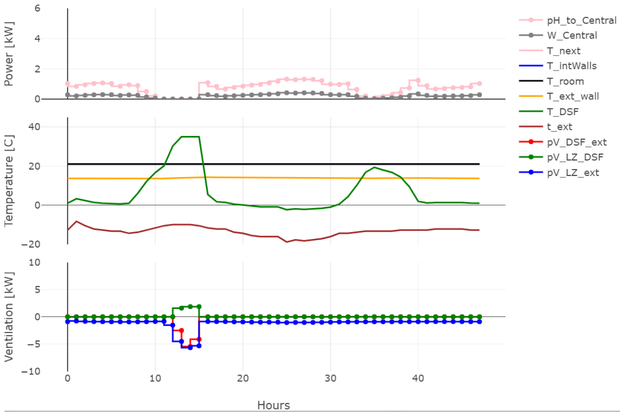

Figure 3: West-oriented unit without TEMS.

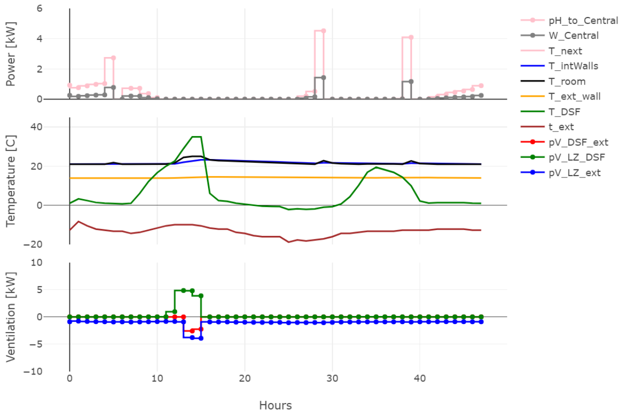

Figure 4: West-oriented unit with TEMS.

Scenario II: Heat network

In this scenario we compare the heating flexibility of two independent units without the TEMS and that of the heat network with the TEMS.

Case 1: Different orientation

The units' heating demand is significantly more flexible if the TEMS is present. In fact, it controls the ventilation between and within the units. The units have a different heating demand, since the south-oriented unit captures more solar gain and for a longer period than the east-oriented one, which receives solar radiation mainly during the morning. Table 2 shows that the TEMS reduces the units' heating demand by 80% during the flexible hours. Furthermore, the overall consumption is 37% lower.

demand [kWh]	without TEMS	with TEMS
during flex-hours	8.04	1.63
during two days	33.18	21.00

Table 2: Electricity demand of south and east units with and without TEMS

The connection between the two units allows heat recovery and sharing processes. When the units are independent (Fig. 3), the south-oriented unit (graphs on the left) wastes the surplus heat coming from the sun by ventilating with the outside. The heat wasted is represented by the blue and red curves, showing the energy ventilated from the room and the DSF towards the outside.

In contrast, when the units are connected (4), the TEMS recovers this surplus and moves it towards the east-oriented unit, where it is used instead of the heating system. This is shown by the third graphs of Figs. 3 and 4, where the units' connection is represented by the yellow curve. The energy wasted by the independent south-oriented unit (blue and red curves in Fig. 3) is now moved towards the east-oriented unit (yellow curve in Fig. 4). The advantage of the TEMS is visible in the first graphs of Figs. 3 and 4: the heating system of the connected units runs less than it does for the independent units.

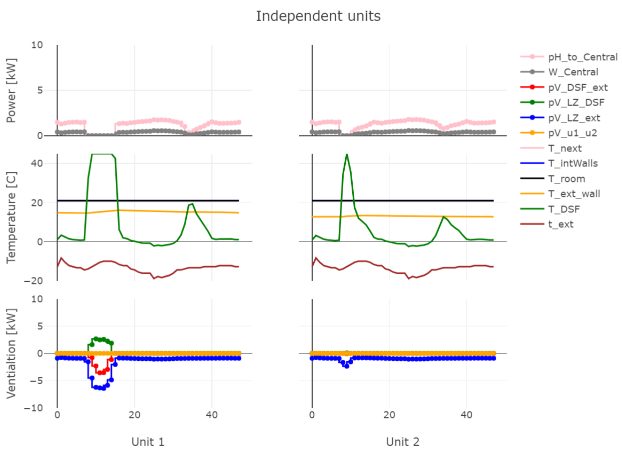

Figure 5: South- and east-oriented units without TEMS.

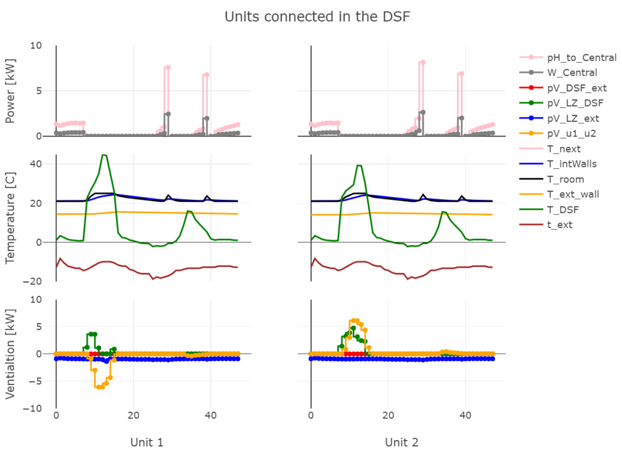

Figure 6: South- and east-oriented units with TEMS.

Case 2: Different occupancy

Occupants produce significant heat that can be used to reduce the unit's heating demand. Table 3 shows the impact of the TEMS when the occupancy varies. The heating demand with the TEMS is 99% lower during the flexible hours, and the overall consumption is 22% lower.

The east-oriented unit has solar gains during the morning; furthermore, occupants generate heat from 9 a.m. to 12 noon. On the other hand, the west-oriented unit captures solar gain during the afternoon, and occupants are present from 12 noon to 5 p.m. The TEMS controls the connection between the two units and uses the heat surplus of the east-oriented unit to warm the west-oriented one. When the units are independent, the heat surplus is wasted by ventilating the room to the outside (blue curve in the third graph of Fig. 7). In contrast, with the TEMS, the heat surplus is moved where it is needed (yellow curve in the third graph of Fig. 8).

demand [kWh]	**without TEMS**	**with TEMS**
during flex-hours	8.45	0.09
during two days	35.83	27.89

Table 3: Electricity demand of east and west units with and without TEMS

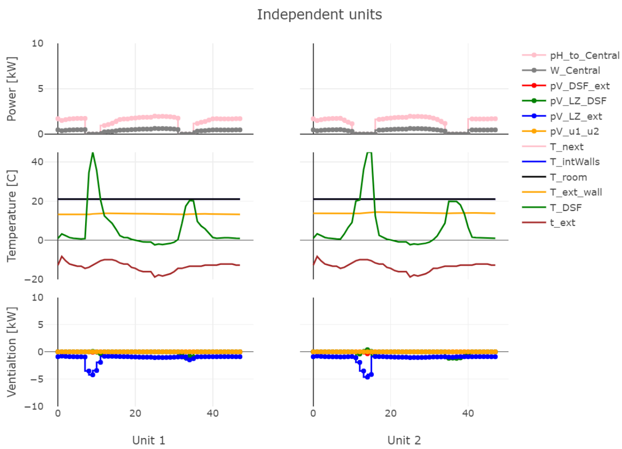

Figure 7: East- and west-oriented units without TEMS.

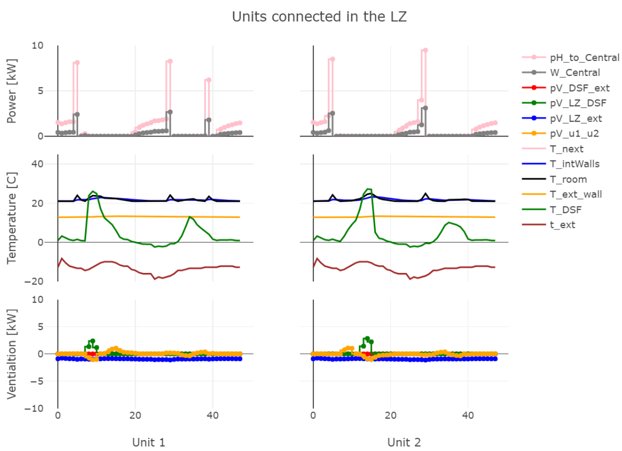

Figure 8: East- and west-oriented units with TEMS.

Conclusions and Future Work

We have demonstrated that using a TEMS introduces flexibility to the heating demand of a single unit and a heat network. The TEMS can reduce the heating consumption during specified hours by 83% for a single unit and up to 99% for a network of two units. The TEMS reduces the overall heating demand too: the consumption decreases by 40% for a single unit and up to 37% for the network.

The TEMS is affordable: it primarily benefits from the structure of the building, heat gains, and natural ventilation, limiting the use of additional tools. Accordingly, the initial investment cost and the operational cost are significantly lower compared to those of other technologies, such as batteries.

The TEMS has advantages for both the users and the grid operator: it reduces the unit's overall heating demand and provides flexibility to the power grid. Furthermore, it boosts the use of renewable energy resources, since the heating demand becomes more adaptable to the production.

In future work, it would be interesting to apply the TEMS to a larger network and real city districts. Furthermore, it may be of interest to evaluate ventilation system options for the network TEMS. For instance, heat-recovery and energy-sharing processes could be done by a cross-flow heat exchanger or a system of filters, in such a way that the units exchange energy but not mass.

Nomenclature

We use uppercase characters for the variables and lowercase for the parameters.

Set

- $\mathcal{I}$ set of time frames, indexed by i
- $\mathcal{B}$ set of nodes, indexed by b
- $\mathcal{G}$ set of energy resources, indexed by g
- $\mathcal{S}$ set of thermal storage, indexed by s
- $\mathcal{L}$ set of lines, indexed by l
- $\mathcal{W}$ subset of lines, crossed by conserved flow, indexed by $l \in \mathcal{L}$
- $\mathcal{H}$ subset of lines, crossed by nonconserved flow, indexed by $l \in \mathcal{L}$

Parameters

- F_l : node $b \in \mathcal{B}$ where line l starts
- T_l : node $b \in \mathcal{B}$ where line l ends
- B_g : node $b \in \mathcal{B}$ where energy resource g is connected
- B_s : node $b \in \mathcal{B}$ where storage s is connected
- r_l : thermal resistance of line l [m^2 K/kW]
- $q_{i,g}^{int}$: power generated by people, electronic devices, and lighting during time frame i [kW]
- $q_{i,g}^{sol,B}$: power generated by the direct component of solar rays during time frame i [kW]
- $q_{i,g}^{sol,D}$: power generated by the diffuse component of solar rays during time frame i [kW]
- ϵ_g : clearness index of smart shading, acting on resource g, during time frame i [-]
- y_s : heat capacity of storage $s \in \mathcal{S}$ [kJ/(K s)]
- y_l^{air} : heat capacity of air mass flowing in line l [kJ/(K s)]
- $\Delta_{i,g}^{min}$: minimum value of $\Delta_{i,g}$ related to resource g during time frame i [-]
- $\Delta_{i,g}^{max}$: maximum value of $\Delta_{i,g}$ related to resource g during time frame i [-]
- $t_{i,b}^{min}$: minimum value of temperature $T_{i,b}$ in node b during time frame i [-]
- $t_{i,b}^{max}$: maximum value of temperature $T_{i,b}$ in node b during time frame i [-]
- $p_{i,l}^{W}$: maximum power input of line l during time frame i [kW]

Variables

- $T_{i,b}$: temperature of node b during time frame i [°C]
- $P_{i,l}^{L}$: power in line l, from node F_l to node T_l, during time frame i [kW]
- $P_{i,l}^{H,T}$: power reaching node T_l of line l during time frame i [kW]
- $P_{i,l}^{H,F}$: power leaving node F_l of line l during time frame i [kW]
- $P_{i,b}^{G}$: sum of power from generators connected to node b during time frame i [kW]
- $P_{i,s}^{S}$: power flowing to/from storage s during time frame i [kW]
- $P_{i,l}^{V}$: ventilation air flow in line l during time frame i [kW]
- $W_{i,l}$: electricity input to the heat pump represented by line l [kW]
- $Q_{i,g}^{sol}$: power generated by solar rays during time frame i [kW]
- $\Delta_{i,g}$: coefficient of smart shading related to power generated by resource g during time frame i [-]
- $L_{i,s}$: level of energy stored inside storage s during time frame i [kWh]
- $X_{i,l}$: air exchange rate of the ventilation represented by line l during time frame i [-]
- E_l : function of the efficiency of a heat pump, working between temperatures T_{i,F_l} and T_{i,T_l} and represented by line l during time frame i [-]

References

Adika, C. O. and L. Wang (2014). Demand-side bidding strategy for residential energy management in a smart grid environment. *IEEE Transactions on Smart Grid 5*(4), 1724–1733.

Braun, J. E. (2003). Load control using building thermal mass. *Journal of Solar Energy Engineering 125*(3), 292–301.

Dodoo, A., L. Gustavsson, and R. Sathre (2011). Primary energy implications of ventilation heat recovery in residential buildings. *Energy and Buildings 43*(7), 1566–1572.

Lomas, K. J. and Y. Ji (2009). Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. *Energy and Buildings 41*(6), 629–653.

O'Connor, D., J. K. S. Calautit, and B. R. Hughes (2016). A review of heat recovery technology for passive ventilation applications. *Renewable and Sustainable Energy Reviews 54*, 1481–1493.

Osma, G., L. Amado, R. Villamizar, and G. Ordoñez (2015). Building automation systems as tool to improve the resilience from energy behavior approach. *Procedia Engineering 118*, 861–868.

Romanchenko, D., E. Nyholm, M. Odenberger, and F. Johnsson (2019). Flexibility potential of space heating demand response in buildings for district heating systems. *Energies 12*, 2874.

Salerno, I., M. F. Anjos, K. McKinnon, and J. A. Gomez-Herrera (2020). Adaptable energy management system for smart buildings. Technical report, School of Mathematics, University of Edinburgh.

Shaikh, P. H., N. B. M. Nor, P. Nallagownden, I. Elamvazuthi, and T. Ibrahim (2014). A review on optimized control systems for building energy and comfort management of smart sustainable buildings. *Renewable and Sustainable Energy Reviews 34*, 409–429.