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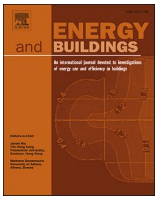

Assessment of the thermal energy flexibility of residential buildings with heat pumps under various electric tariff designs

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ABSTRACT

With the electrification of the heating sector in Europe, there is increased pressure to reduce stress to the electric grid from increased demand. Understanding the flexibility potential of the current building stock, including both efficient buildings as well as less efficient buildings, will be vital to assess the efficacy of demand-side strategies such as time-varying pricing in enabling shifts in consumer heat demand.

The aim of this study is to assess the thermal flexibility potential of residential buildings with electric heating under different tariffs, and the effect of these tariffs on heating expenditure and electricity consumption. To accomplish this, a resistance–capacitance heat demand model was integrated into a linear optimization model set to find the lowest cost heating schedule for a consumer under four different tariff designs.

The results indicate that time-varying tariffs can be effective in enabling shifts in the heat consumption, although the additional cost savings due to the flexibility provided by an efficient building envelope is limited (1% to 4.65% additional reduction in cost savings). The results suggest that potential flexibility is price sensitive and a function of the alignment of price and heating demand. Measures such as capacity tariffs should be considered to avoid preheating surges.

1. Introduction

The heating and cooling (H&C) sector is the most energy-intensive end-use sector in the European Union (EU), contributing to more than 50% of final energy consumption [1]. In the residential sector alone, space heating (SH) and domestic hot water (DHW) account for almost 80% of final energy use [2]. As a result, the EU is pushing for the electrification of heating to increase energy efficiency, take advantage of the contributions of grid-connected renewable energy, and allow for the use of automated control systems in shifting heating demand via demand response (DR) [3]. In the EU, this electrification is being made possible largely due to the increase in utilisation of electric heat pumps (HPs) [4]. As the electrification of heating increases, flexibility services will be vital in developing strategies for long-term planning and resiliency in the power sector, and there will be an increased need to assess the flexibility of thermal load in buildings [5].

Since energy demand for heating varies throughout the day due in part to consumer behaviours, the hours of peak energy demand can cause undue stress on the power grid and potentially cause bottlenecks on constrained energy supply. Flexibility services, which typically imply a combination of technological and organisational measures (e.g., demand side management and/or energy storage), can moderate this inequal temporal distribution of energy demand [5].

To maximize heating flexibility, technological and managerial approaches should be pursued. HPs offer new avenues for thermal energy flexibility, especially when paired with energy storage [6] and time-varying tariff structures [7]. HPs couple the thermal and power sectors, which makes SH susceptible to electricity pricing. Enabling

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Abbreviations: COP, coefficient of performance; CPP, critical-peak pricing; DHW, domestic hot water; DR, demand response; DSM, demand-side management; EDF, Électricité de France S.A.; EU, European Union; H&C, heating and cooling; HP, heat pump; LF, load factor; MPC, model predictive control; RC, resistance-capacitance; SH, space heating; ToU, time-of-use.

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consumer interventions using time-variant electricity pricing schemes can result in behavioural changes (or, more effectively, lead to further adoption of automated heating controls [8]) and push consumers to modify their energy use activities [9]. Under the concept of DR, dynamic pricing strategies that are adapted to heating schedules can facilitate efficient HP use on the demand side [6]. This is important because by coupling the thermal and power sectors, SH contributes to power peaks, and so efforts to reduce thermal power peaks are increasingly significant, as well.

DR can be split into two distinct categories: implicit DR and explicit DR [10]. Explicit DR describes schemes that have participating consumers shift their load in return for incentive payments whereas, in the case of implicit DR, time-variant pricing is used to encourage consumers to shift their load. While explicit DR is often characterized by a predetermined nomination of controllable load that can, therefore, be assessed based on the potential curtailable or shiftable load of each consumer, implicit DR potential is more difficult to evaluate. This is especially true in the residential sector, where load is largely determined by time-varying climatic conditions and user behaviour. As such, an individual's willingness to change her or his heating habits is dependent on each individual's thermal comfort zone. There are technical solutions to shift electricity generation for heating, including thermal energy storage options such as hot water tanks, however these are often expensive options that are dependent on consumer adoption. Rather, a potentially more effective way of enabling DR is by offering time-of-use (ToU) electric tariffs.

The effectiveness of various energy efficiency demand-side management (DSM) measures for thermal energy services is largely dependent on the building itself, as the thermal performance of its construction materials determines the extent to which the building envelope can act as a thermal "battery" and enhance other flexibility options, including storage solutions and control devices that enable DR [6].

Literature on the assessment of flexibility in buildings was reviewed to determine the current state of knowledge in this area, both in terms of the understanding of topic as well as the methodologies used. The work by Pena-Bello et al. 2021 [11] considers HP storage modelling under time-variant pricing, however, this work does not optimise the internal temperature or include set point temperatures as constraints. Instead, it assumed identical hourly heat supply by HPs as by fossil fuel boilers. Other studies, explore the flexibility of the building envelope in combination with other flexibility-enabling solutions (e.g., [12,13]), but limit their case study to a single building type rather than assessing how building archetype might affect overall SH demand and overall flexibility.

Several studies that assess building flexibility do not consider typical or older residential buildings (for example, the studies by Bechtel et al. 2020 [14], Ren et al. 2021 [15], and Reynders et al. 2013 [16]). Instead, these studies solely observe an optimum situation, where the building envelope is already highly efficient. As such, assessing different building archetypes is not the focus of these studies. Since the improvement of the thermal performance of the building stock by new buildings (replacement and additions) as well as by energy retrofit takes decades, it is, however, highly relevant to consider different archetypes. Finally, studies assessing flexibility often do not investigate the role of tariff designs as a driver in enabling this flexibility (for example, flexibility studies that consider dynamic pricing often do so by assessing static ToU tariffs (e.g., the studies by Pallonetto et al. 2016 [17] and Torriti 2012 [9]). However, static ToU tariff structures may not be the most appropriate for SH purposes, and more dynamic pricing that more accurately captures the wholesale price of energy can result in more significant results. The studies by Ali et al. 2014 [12], Bechtel et al. 2020 [14], and Fitzpatrick et al. 2020 [18] consider dynamic pricing through the inclusion of the market spot price but investigate auxiliary storage technologies rather than purely the flexibility provided by the building envelope. Additional studies by Ramos et al. 2019 [19] and Kirkerud et al. 2016 [7] also found varying effects on customer energy bills from different tariff structures. Based on the varying results due to tariff structures, it is advantageous to consider multiple tariff designs when assessing flexibility in thermal energy use.

In terms of DSM, understanding the economic cost of an intervention or service on the building owner or manager is essential. Studies present economic savings either to the customer (i.e., monetary savings through bill minimization, e.g., Pena-Bello et al. 2021 [11], Ren et al. 2021 [15]) or to the electric grid/larger energy system (e.g., Arteconi et al. 2016 [20] and Rinaldi et al. 2020 [21]). There are advantages to framing the results to both perspectives, however, the latter is more closely related to actual decision making by actors and can therefore be considered more relevant for providing practical advice. For this reason, economic savings in this paper are also defined in terms of energy costs to the customer.

The focus of this paper is to assess the potential thermal energy flexibility of residential buildings through the combined utilization of a HP system and the thermal properties of the building. Building archetypes are characterized by the efficiency level of the building, thus determining not only the energy demand of the building but the thermal inertia of the building envelope. For this analysis, results have been generated for two building archetypes.

The purpose of this study is to answer the following question: How does the thermal flexibility of a residential building enable electrical flexibility in the SH schedule of an air-to-water HP under different tariff designs?

The goal of this work is to assess the extent of the building's inherent thermal flexibility capabilities along with the flexibility provided by HPs with and without the presence of a thermal storage tank to provide an indication of the "base" flexibility (that is, the flexibility enabled without additional technologies such as battery or added thermal storage) that can be offered by a residential building using electric-supplied SH. The flexibility of the building is observed under different tariff schemes to determine how the combination of these treatments affects overall flexibility and the cost for the consumer. This study produces optimal heating schedules that utilise the thermal mass of the building envelope based on its specific archetype in combination with an air to water HP under different pricing conditions. With the results based on different tariffs, the economic value of flexibility for a consumer of each building archetype is estimated.

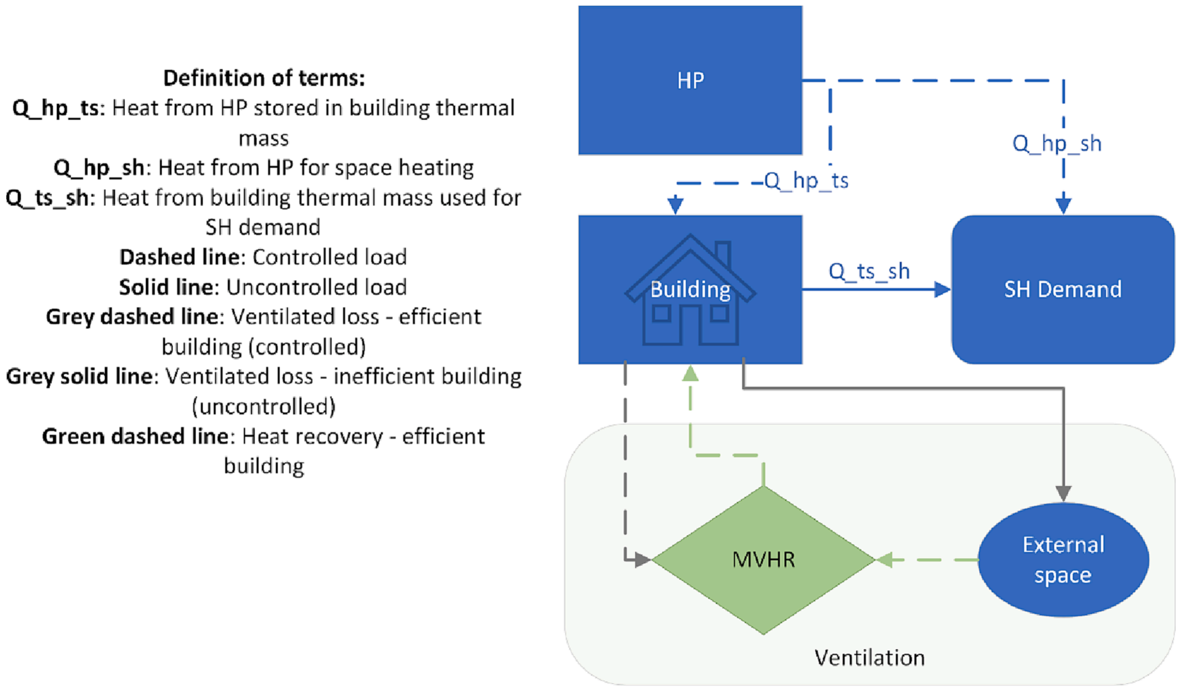
The scope of this study was developed by considering the lacks in knowledge identified previously in the literature review. This paper is distinct from current literature in that it investigates a combination of considerations not previously assessed together, including the consideration of both efficient and inefficient building archetypes representative of more typical or older residential buildings, the assessment of different tariff schemes and their effect in enabling flexibility in a residential building, and the framing of economic results in terms of energy savings to the customer.

2. Methods

The linear optimization model used to find the lowest cost heating schedule to consumers is described in the Section 2.1. Subsequently, the model used to generate the heat demand for the consumers under different building archetypes is explained in Section 2.2. Finally, the definition of the selected tariff designs is described in Section 2.3.

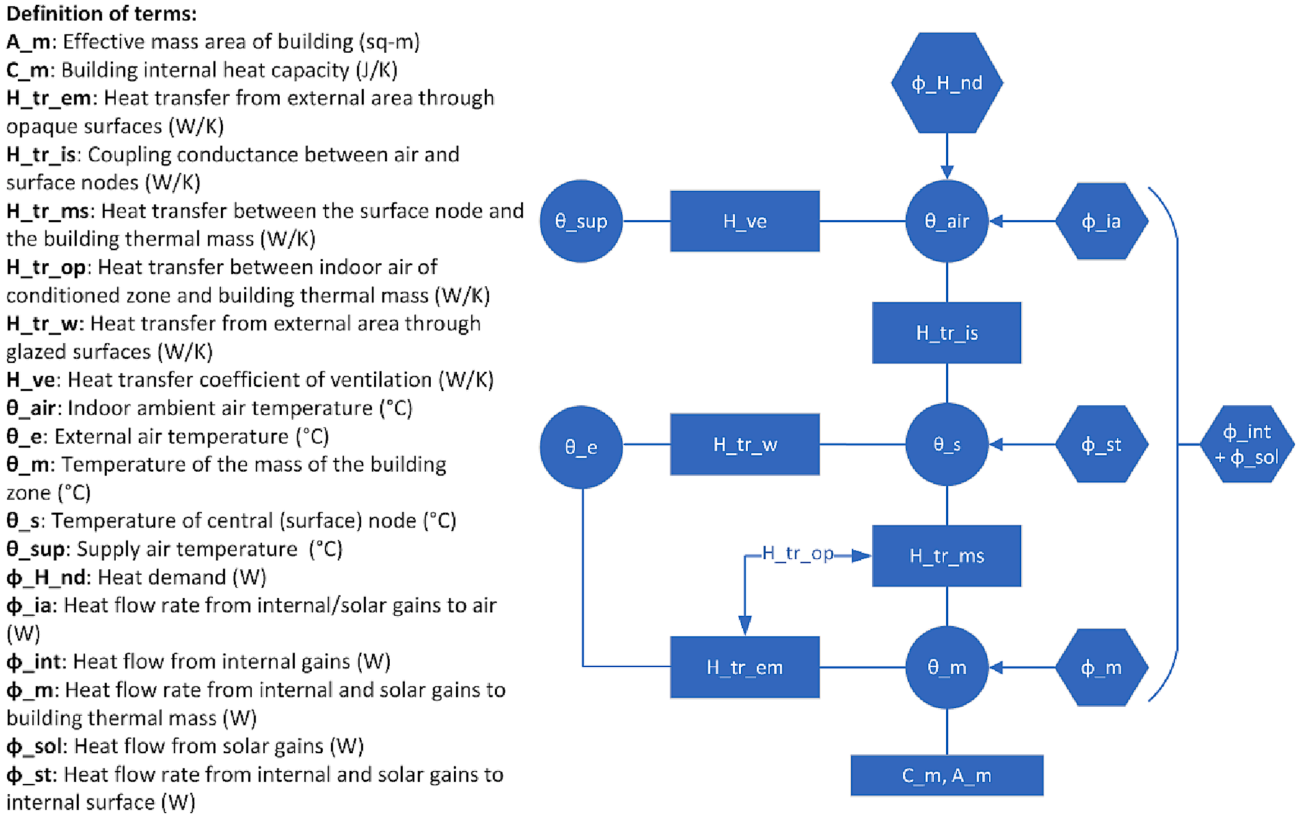
2.1. Building heat pump optimization model

This study considers the optimized control of the HP system paired with the thermal inertia of the building for different tariff structures and building archetypes. This was accomplished by including the indoor temperature as an optimized parameter with SH setpoints (representing the acceptable comfort zone) as constraints through the integration of the building heat demand model discussed in Section 2.2. The indoor comfort zone was defined as within the limits of 19 °C to 23 °C (in line



Definition of terms:
Q_hp_ts: Heat from HP stored in building thermal mass
Q_hp_sh: Heat from HP for space heating
Q_ts_sh: Heat from building thermal mass used for SH demand
Dashed line: Controlled load
Solid line: Uncontrolled load
Grey dashed line: Ventilated loss - efficient building (controlled)
Grey solid line: Ventilated loss - inefficient building (uncontrolled)
Green dashed line: Heat recovery - efficient building

Fig. 1. Energy flow of HVAC system.



Definition of terms:
A_m: Effective mass area of building (sq-m)
C_m: Building internal heat capacity (J/K)
H_tr_em: Heat transfer from external area through opaque surfaces (W/K)
H_tr_is: Coupling conductance between air and surface nodes (W/K)
H_tr_ms: Heat transfer between the surface node and the building thermal mass (W/K)
H_tr_op: Heat transfer between indoor air of conditioned zone and building thermal mass (W/K)
H_tr_w: Heat transfer from external area through glazed surfaces (W/K)
H_ve: Heat transfer coefficient of ventilation (W/K)
θ_air: Indoor ambient air temperature (°C)
θ_e: External air temperature (°C)
θ_m: Temperature of the mass of the building zone (°C)
θ_s: Temperature of central (surface) node (°C)
θ_sup: Supply air temperature (°C)
ϕ_H_nd: Heat demand (W)
ϕ_ia: Heat flow rate from internal/solar gains to air (W)
ϕ_int: Heat flow from internal gains (W)
ϕ_m: Heat flow rate from internal and solar gains to building thermal mass (W)
ϕ_sol: Heat flow from solar gains (W)
ϕ_st: Heat flow rate from internal and solar gains to internal surface (W)

Fig. 2. Five resistance, single capacitance (5R1C) model.

with ASHRAE human occupancy standards [22]).

The objective of the optimization problem is to determine the hourly SH schedule for the heating season (defined as January through April and September through December) that has the lowest thermal energy costs while maintaining an indoor ambient air temperature that falls within the accepted comfort zone based on the building archetype and various tariff designs. To assess the most economically viable option for consumers, the objective function is therefore set to minimize the energy cost, *C* (Equation (1). The values for the HP's rated coefficient of performance (COP) for different external air temperatures were obtained

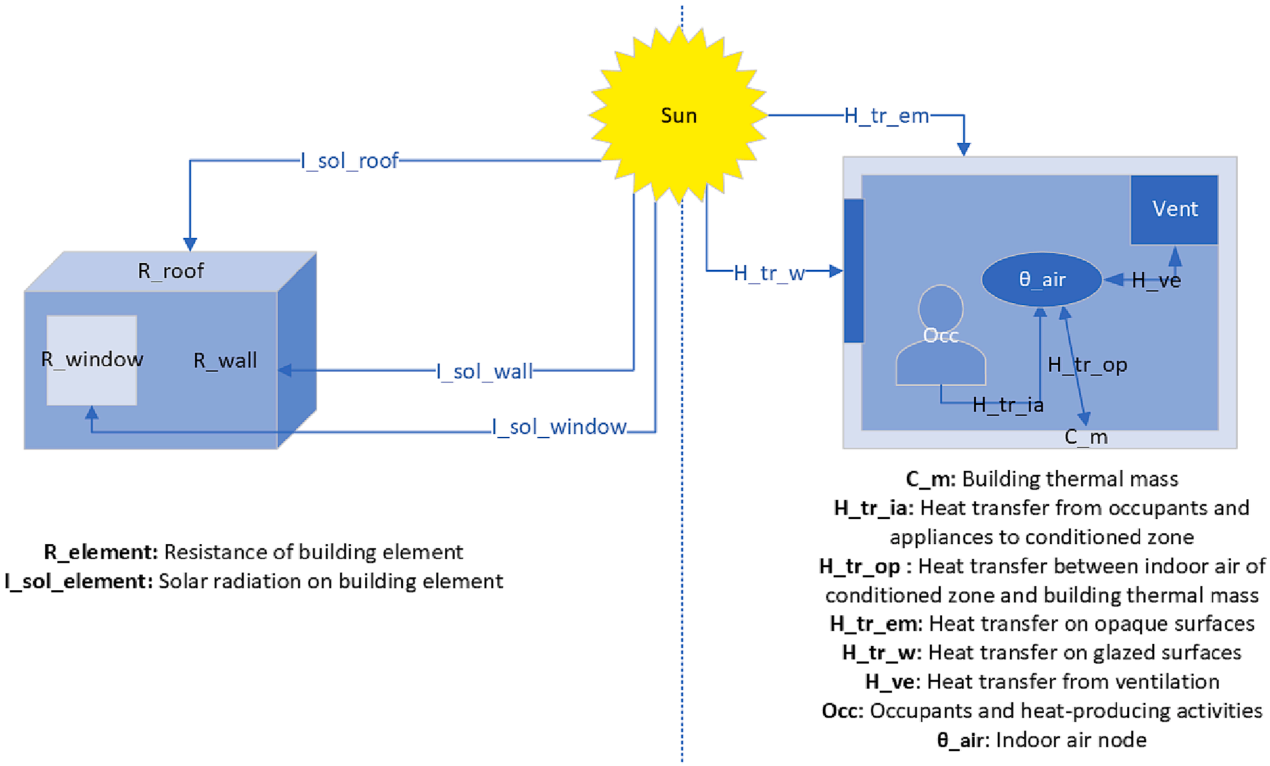


Fig. 3. Heat gains and losses of the energy system.

from the product specifications for a HP system [23]. The CPLEX Solver [24] was selected for optimization. Finally, system power was capped to ensure a reasonable output of the optimal solution. A schematic of the HVAC system and its respective energy flows is provided in Fig. 1.

$$min(C) = min\left(\sum\nolimits_{i=0}^{t} p_i \times \frac{\phi_{H,nd,i}}{COP_i}\right) \quad (1)$$

Where:

p is the price of electricity (CHF/kWh).

$\phi_{H,nd}$ is the heat flow of supplied heating to the indoor air node (i.e., heating demand) (kW).

θ_e is the external air temperature (°C).

COP values were obtained from [23].

2.2. Building heat demand model

The heat demand of each building archetype (described in Section 3.1) is determined using a resistance–capacitance (RC) model, where thermal mass (or thermal capacitance) is determined based on the mass and specific heat of the building material, and the inclusion of thermal resistance for each building element with relation to the heat transfer between the outdoor and indoor temperatures. The model was developed in accordance with the methods described in ISO 13790:2008 for a five-resistance, single capacitance (5R1C) model (see detailed model schematic and description in Fig. 2 and simplified flow of heat gains and losses in Fig. 3) [25].

The 5R1C model is characterized by a single "capacitance", in this case describing a single component representing the building thermal mass (function of the building's effective mass and heat capacity of the building materials used, represented by C_m in Figs. 2 and 3), and five heat transfer nodes describing the five "resistances" that define the thermal bridges between five temperature nodes (represented by components with a θ prefix). These heat transfer nodes represent the transfer of heat between the conditioned space and the external environment via ventilation (H_ve in Fig. 2 and Fig. 3), the conditioned space and the internal surface (H_tr_is), the building thermal mass and the internal surface (H_tr_ms), the external environment and the building surface via glazed external building components (H_tr_w), and the external environment and the building thermal mass via the opaque external building components (H_tr_em). Finally, components represented with a ϕ prefix indicate heat flows from internal (ϕ_int in Fig. 2, the source of which is the "Occ" component in Fig. 3) and solar (ϕ_sol, the source of which is the "Sun" component in Fig. 3) gains. Heat from internal and solar gains flow to the conditioned space (ϕ_ia), the internal surface (ϕ_st), and the building thermal mass (ϕ_m).

Ultimately, the indoor ambient air temperature in the conditioned space is calculated based on factors related to the temperature set points, the building fabric, the outdoor temperature, and the building elements (see Equation (2). The model components were calculated based on the ISO 13790:2008 methods, with parametric input values coming from ISO 13790:2008 itself [25], ISO 6946:2017 [26], TABULA [27], and the ASHRAE Fundamental Handbook [28]. It should be noted that this paper considers only SH and not DHW and that all reference to thermal demand in this paper is specifically referring to thermal demand of SH. A description of the data used in this study can be found in Section 3.

$$\theta_{air} = \frac{H_{tr,is}\theta_s + H_{ve}\theta_{sup} + \phi_{ia} + \phi_{H,nd}}{H_{tr,is} + H_{ve}} \quad (2)$$

Where:

θ_{air} is the indoor ambient air temperature (°C).

$H_{tr,is}$ is the coupling conductance between air and surface nodes (W/K).

θ_s is a mix of air and mean radiant temperature (°C).

H_{ve} is the ventilation heat transfer coefficient (W/K).

θ_{sup} is the supply of ventilated air temperature (fresh, unheated air from outside).

ϕ_{ia} is the heat flow rate from internal and solar gains to the indoor air node (W).

$\phi_{H,nd}$ is the heat flow of supplied heating to the indoor air node (i.e., heating demand) (W).

Table 1
Internal gains schedule.

Days	Hours	Internal gains (W/h)
Monday to Friday	07:00 to 17:00	9
Monday to Friday	17:00 to 23:00	21
Monday to Friday	23:00 to 07:00	8
Saturday/Sunday	07:00 to 17:00	10
Saturday/Sunday	17:00 to 23:00	24
Saturday/Sunday	23:00 to 07:00	8

Table 2
Flat rate and static time-of-use values.

Tariff/tariff component	**Rate (CHF/kWh)**
Flat rate tariff	0.29
Static ToU tariff	Off-peak: 0.130034; On-peak: 0.204452
Electrical network usage charge*	0.09
Community services charge*	0.02
Renewable energy incentive charge*	0.01

*Components used in both Spot and HP dynamic tariffs.

2.2.1. *Ventilation rate*

Since an archetypical approach was utilized to categorize the archetypes as inefficient or efficient so that the analysis would involve a comparison of two archetypes that are prevalent in the building stock, ventilation strategies that are typical for each archetype were selected. In addition to being characterized by less efficient building materials, the inefficient building was assumed to use natural ventilation (i.e., window ventilation) to exchange the building's stale air with fresh air. As the efficient building represents a newer building, a system heat recovery efficiency factor was computed based on the assumption that a mechanical ventilation with heat recovery (MVHR) system was utilized in the building. A system heat recovery efficiency factor of 87% was utilized based on a typical value for MVHR systems [29].

Natural ventilation is utilized sparingly in the winter—the current paper assumes a time operation per day equivalent to one hour for natural ventilation based on an existing winter ventilation strategy [30]. While MVHR systems can operate continuously at a low level, a time operation equivalent to two hours per day was utilized to represent the culmination of time when the system is operating at a high level of ventilation.

2.2.2. *Building geometry and solar gains*

The geometric design of both the efficient and inefficient buildings were identical. Both buildings had a single story, a flat roof (i.e., horizontal roof orientation) with no overhang, and a north-facing façade. The length and width of the building were both equal. The proportion of the wall space dedicated for windows equalled 25% for all walls except the façade-side, which equalled 10% (not including a 2 m^2 door that was attributed the same thermal resistance and transmittance values as the windows). The gross indoor floor area was approximately 100 m^2 for both buildings. The Perez diffuse irradiance model [31] was used to calculate the solar gains for the buildings using the pvlib Python library [32].

2.2.3. *Internal gains*

Identical representative internal gains values were added to the heat demand models for both the efficient and inefficient buildings based on the following schedule offered by the ISO 13790:2008 standard [25]:

It should be noted that despite the use of additional heat contributions from internal gains (from occupants and occupant use of appliances), occupancy was not considered for the operation of the HP. In other words, the heat pump schedule that was calculated was not influenced by the occupancy schedule used to determine internal gains found in Table 1. Instead, the operation of the HP to maintain the comfort zone is utilized continuously to observe the full dynamics of the heating schedule.

2.3. *Electricity tariffs*

Four electric tariffs were assessed: a flat rate tariff, a static time-of-use (ToU) tariff, and two dynamic tariffs: Spot dynamic and HP dynamic. The flat rate tariff is a typical constant price for energy, and acts as the basis for comparison for the static ToU and dynamic tariffs. The static ToU tariff is characterized by an on-peak/off-peak tariff based on an unchanging daytime on-peak and evening/weekend off-peak (specifically, the on-peak is on weekdays from 07:00 to 22:00 and weekends from 17:00 to 22:00).

The Spot dynamic tariff was created using the same logic and structure described in [33], which utilizes hourly wholesale prices combined with three fixed charges: an electrical network usage charge, a community services charge, and a renewable energy incentive charge (data described in Section 3). Since heat demand is not perfectly aligned with system demand, a dynamic tariff based on the demand trends of the wholesale market may not be suitable for affecting electric heating consumption. For this reason, an alternative dynamic tariff—the HP dynamic tariff—was considered as it is more closely aligned with typical heating profiles. The HP dynamic tariff is characterized by shadow wholesale market pricing data based on a scenario that assumes full HP penetration for SH needs [21]. The same fixed charges applied to the Spot dynamic tariff are added into the HP dynamic tariff, as well. Fig. 4 shows the mean hourly profile of the four tariffs considered in this study (*Flat*: Flat rate tariff; *ToU*: Static ToU tariff; *SPOT*: Spot dynamic tariff; *HP*: HP dynamic tariff) and Table 2 shows the values for the flat rate and static ToU tariffs and the additional charges for the two dynamic tariffs.

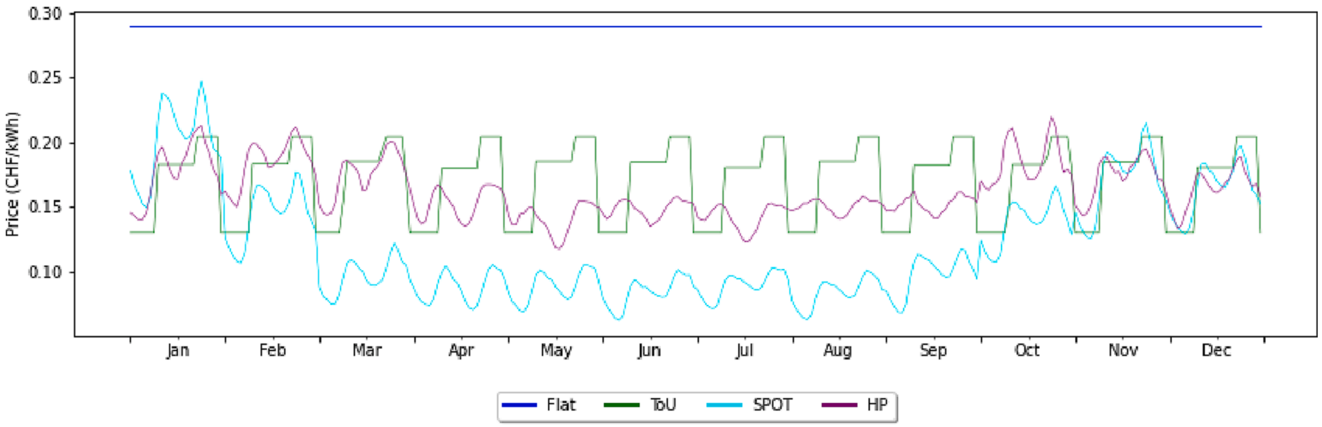


Fig. 4. Mean hourly profile of the four assessed tariffs per month.

Table 3
Building typology data.

Archetype	Wall U-value (W/m^{2}K)	Roof U-value (W/m^{2}K)	Window U-value (W/m^{2}K)
1946–1960	0.92	0.55	1.8
2011–2020	0.2	0.195	1.3

Table 4
Climate data.

Variable	Reference
2-meter temperature	[36]
Dew point temperature	[36]
Surface pressure	[37]
Surface Solar Radiation Downwards (SSRD)	[36]
Total sky direct solar radiation at surface (FDIR)	[36]
Relative humidity	[36]

Finally, an additional charge based on capacity was considered, as well, to observe the effects of imposing a charge on power consumption. The charge was implemented by taking the maximum power per month for each building archetype under the flat tariff and setting this as a threshold in the optimization model. Any power consumption past the peak power threshold for the flat rate tariff would include an additional charge of 0.13 CHF/kW.

2.4. Flexibility

There is no standard indicator for measuring and describing flexibility. The metric used in this paper was developed to correct for differences in tariff design. As described in Equation (3), added flexibility is defined as the percent additional cost reduction due to price signalling demand response behaviour observed in the total expenditure for efficient building archetype under each time-varying tariff versus the total expenditure for the inefficient building archetype under each time-varying tariff, all normalized relative to the flat rate tariff.

$$F_i = \left[\frac{(E_{eff,i}/E_{eff,Flat}) - (E_{ineff,i}/E_{ineff,Flat})}{(E_{eff,i}/E_{eff,Flat})}\right] \times 100 \tag{3}$$

Where:

F_i is the percent additional cost reduction attributed to flexibility under tariff *i*.

$E_{eff,i}$ is the expenditure on heating for the efficient building under tariff *i*.

$E_{eff,Flat}$ is the expenditure on heating for the efficient building under the flat rate tariff.

$E_{ineff,i}$ is the expenditure on heating for the inefficient building under tariff *i*.

$E_{ineff,Flat}$ is the expenditure on heating for the inefficient building under the flat rate tariff.

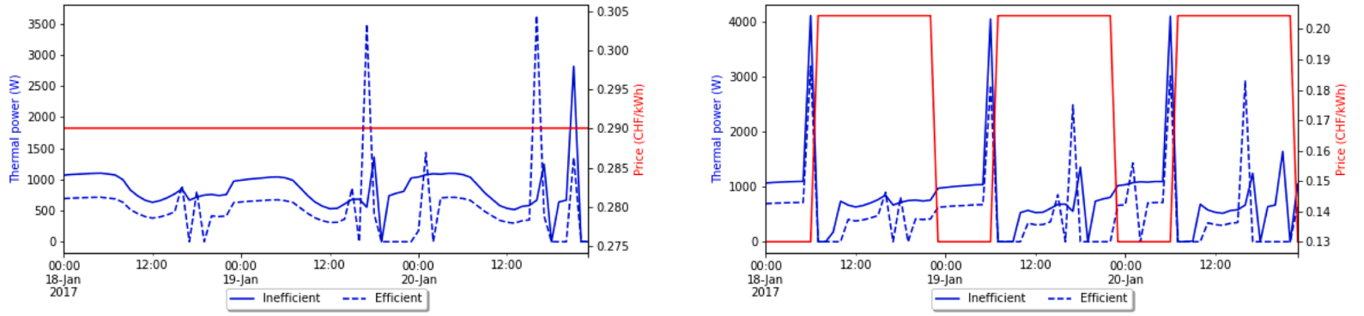
3. Data

3.1. Building typology data

Specific data was collected for a case study in Geneva, Switzerland. Geneva building typology and archetype data (specifically, U-values used in the building heat demand model based on the construction period and building type of each archetype in Geneva) were obtained from Streicher et al. 2018 [34]. Values for urban single-family homes were selected for two archetypes: a building archetype from 1946 to 1960 and a building archetype from 2011 to 2020 (see values in Table 3).

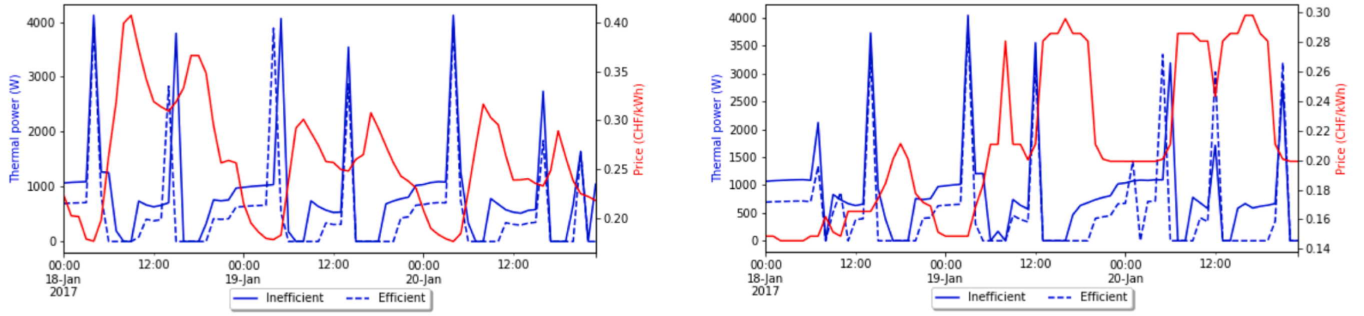
3.2. Climate data

Climate data to assess solar heat gains in the building heat demand model were obtained from the Copernicus Climate Change Service (see Table 4 for a summary of each dataset and reference). It should be noted that surface solar radiation downwards (SSRD) data was used as a proxy for global horizontal irradiance (GHI), and direct solar radiation at the surface (FDIR) was used as a proxy for direct normal irradiance (DNI).



5a. Flat rate tariff

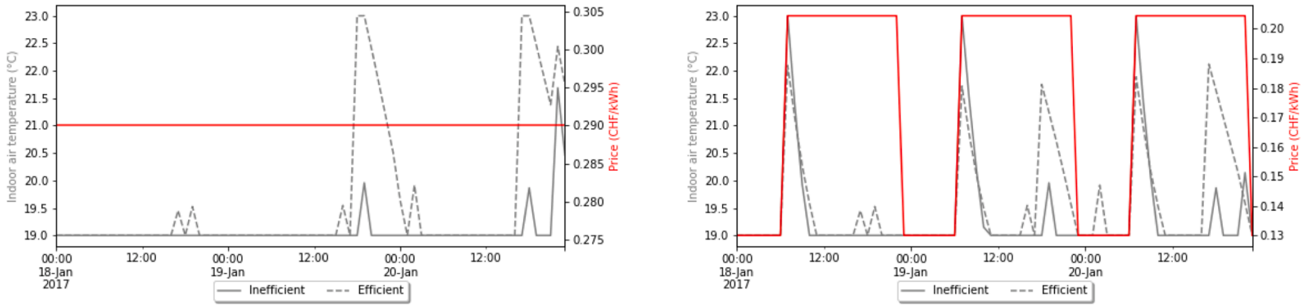
5b. Static ToU tariff



5c. Spot dynamic tariff

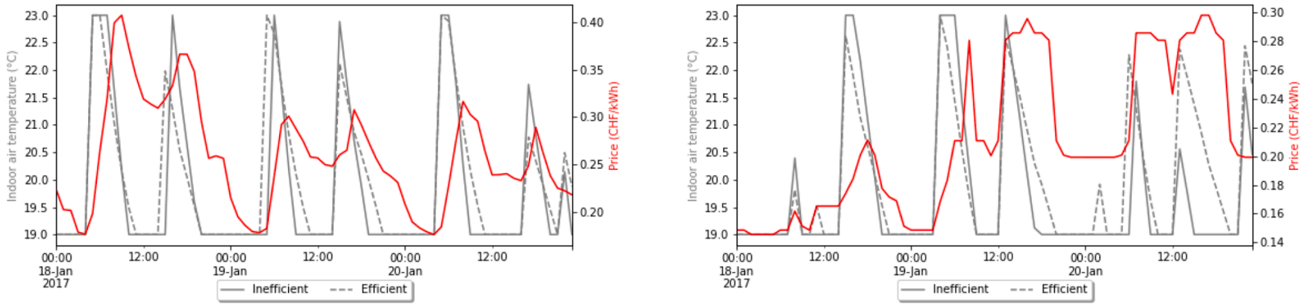
5d. HP dynamic tariff

Fig. 5. Electricity price and thermal power by building archetype.



6a. Flat rate tariff

6b. Static ToU tariff



6c. Spot dynamic tariff

6d. HP dynamic tariff

Fig. 6. Electricity price and indoor temperature by building archetype.

Diffuse horizontal irradiance (DHI) was computed by subtracting FDIR from SSRD [35]. Data for the year 2017 was collected and used for all parameters.

3.3. *Price data*

Electric rate data for Geneva was obtained from the Swiss Federal Electricity Commission (ElCom) [38]. The hourly wholesale market spot price data for Switzerland that was used for the Spot dynamic tariff was obtained from EPEX SPOT for 2017 [39]. The hourly wholesale market spot price data that was used for the HP dynamic tariff was obtained from the results of [21].

4. Results and discussion

The results are split into two sections: a description of the results in a 3-day window to describe the model behaviour in Section 4.1 and an assessment of the quantitative results aggregated at the annual level described in Section 4.2. The monthly trends for thermal energy consumption and expenditure are described in the Appendix.

4.1. *Model behaviour*

The results comparing the variables of interest are separated into four indicator comparisons and graphed for a mid-week, 3-day window in the middle of January. The flat tariff is considered the baseline as there is no dynamic pricing. In the results, the building archetype with characteristic efficiency values from 1946 to 1960 is labelled as the "inefficient" building, while the archetype from 2011 to 2020 is labelled as "efficient."

4.2. *Thermal power and electricity price comparison*

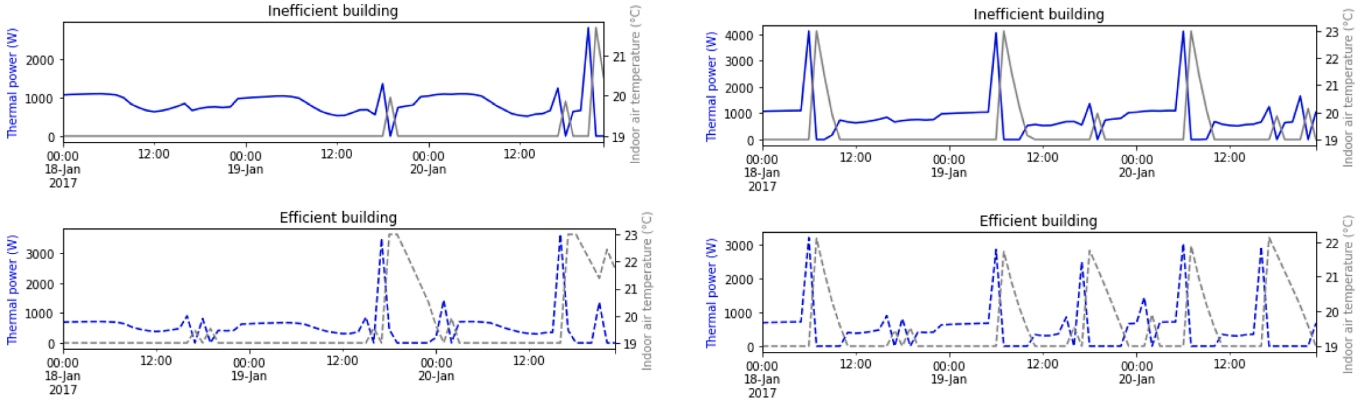
When observing thermal power and electricity price, the prevailing trend is that the thermal power is surged immediately before an increase in price. This behaviour is most evident in the static ToU tariff Fig. 5b, where there are thermal power spikes for both building archetypes before the on-peak pricing begins. It should be noted that, generally, the power spikes observed for the efficient archetype in the time-varying tariffs are lower than the power spikes for the inefficient archetypes. For the dynamic tariffs, the model takes advantage of temporary price "valleys" to initiate another heating surge before the price increases again (an example of this is in the early afternoon on January 18 for Fig. 5c). The thermal power behaviour for both the efficient and inefficient building archetypes are similar under the dynamic tariffs (5c and 5d). Under the flat rate tariff (5a), there is some unexpected spiking of thermal power—especially for the efficient archetype. For example, at around 17:00 on January 19, the model surged the thermal power to approximately 3.5 kW (which would result in around 1 CHF of expenditure for that hour). The hours immediately following this power surge required no power—suggesting a scenario where no power surge was utilized would result in higher total expenditure. It is likely that other variables (e.g., external air temperature, solar gains, etc.) created conditions that allowed the efficient archetype to utilize the building envelope to maximize the heat generated for a single hour.

4.3. *Indoor air temperature and electricity price comparison*

The following figures (Fig. 6) illustrate the relationship between the electricity price and indoor air temperature. These results demonstrate the outcome of the thermal power behaviour observed in Fig. 5. The overheating caused by the power surge that took place before the price increase results in a surge in the indoor air temperature at the time of the price increase. The temperature of the inefficient archetype is generally heated to the upper limit of the comfort zone (23 °C) while the efficient archetype is often only heated to around 22 °C. As expected, there is a noticeably slower rate of decay in the indoor air temperature for the efficient archetype than for the inefficient archetype. The lower power injection/overheating observed from Fig. 5 shows that the optimised behaviour for both building archetypes is to only supply enough power so that by the end of the higher price tier, the indoor air temperature has returned to the lower comfort threshold level.

7a. Flat rate tariff

7b. Static ToU tariff



7c. Spot dynamic tariff

7d. HP dynamic tariff

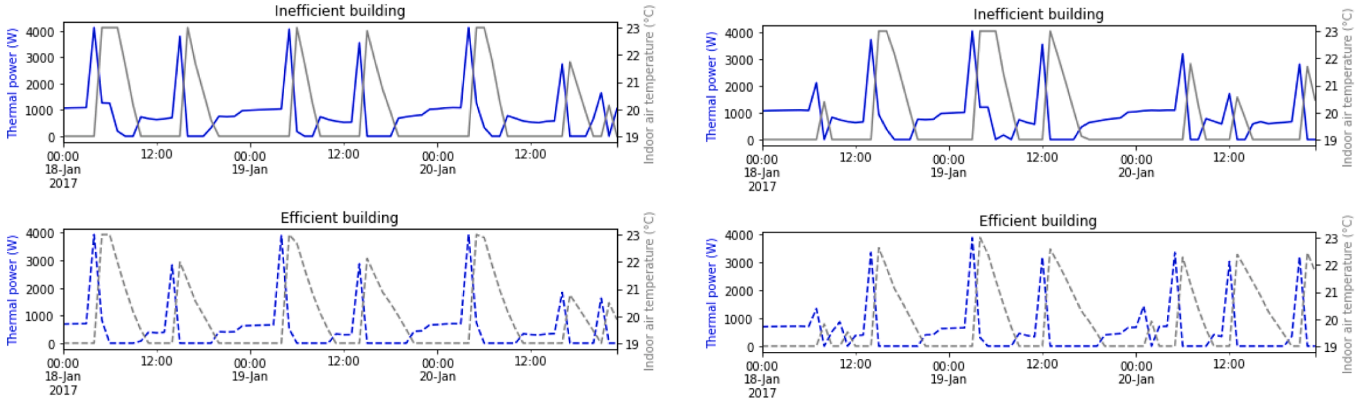


Fig. 7. Thermal power and indoor air temperature by building archetype.

4.4. *Thermal power and indoor air temperature comparison*

As observed in Fig. 6, the indoor ambient air temperatures of both the inefficient and efficient buildings mostly remain at the minimum allowable comfort threshold, however power and indoor temperature spikes are present for both archetypes. When viewed along with thermal power, the indoor air temperature of the efficient building archetype can be observed as having a significantly longer rate of indoor temperature decay for the same or less thermal power demand. The figures for the dynamic tariffs (7c and 7d) clearly show that the inefficient building archetype requires additional thermal power, even after a surge, to utilize its flexibility potential (maximum thermal power in this case is constrained by the upper comfort zone) (Fig. 7).

4.5. *Indoor and outdoor air temperature comparison*

Visualizing the indoor and outdoor temperatures together demonstrates the resulting behaviour of the model's anticipatory reaction to ToU pricing, and how building flexibility can be used to shift thermal energy demand. With the flat rate tariff, flexibility is used—primarily by the efficient building archetype—to pre-heat for an hour to provide heat for the following hours. For the time-varying tariffs, the heating operation is performed prior to a drop in temperature as the model utilizes the building envelope to similarly extend the period where heating can be minimized (Fig. 8).

4.6. *Annual results*

The results for each model run were aggregated at the annual level, which considered the eight months that define the heating season. In addition to total expenditure and energy demand, the energy intensity, maximum power, mean thermal power and indoor temperature differences, and load factor (computed by dividing the average load by the peak load for the observed period—in this case, for the heating season), the total cost reductions (which includes both the energy cost savings attributed to both the increased efficiency of the building archetype and also the energy cost savings attributed to the building flexibility), as well as just the additional cost reduction attributed to building flexibility are also reported (see Table 5).

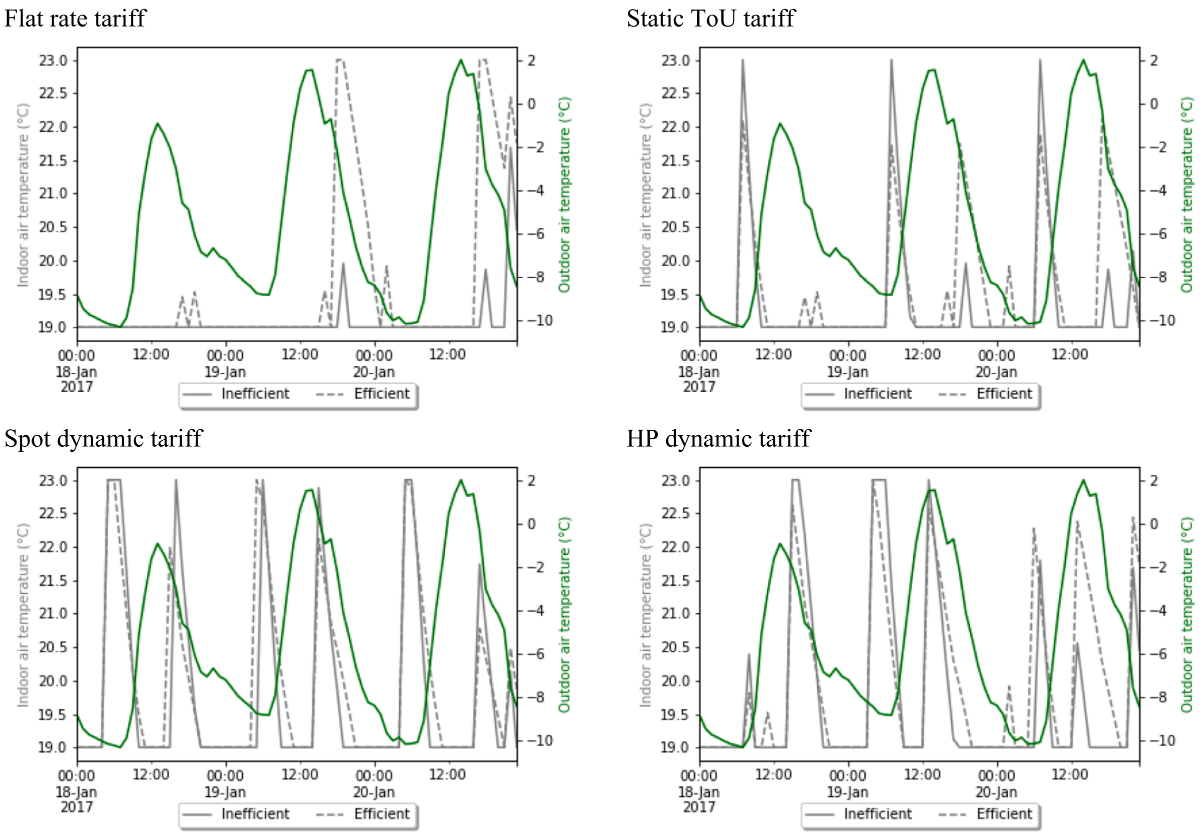
The additional cost reduction attributed to flexibility was calculated for each of the time-varying tariff designs. The static ToU tariff resulted in the highest additional reduction in expenditure (4.65%). The HP dynamic tariff resulted in 3.65% additional reduction in costs and the Spot dynamic tariff resulted in a 1% additional reduction in costs.

4.6.1. *Sensitivity analysis*

A sensitivity analysis was performed to investigate the effect of price differences on bill maximisation (Fig. 9). The ToU tariff was adjusted to four different upper-tier ("daytime") prices. Electric heating expenditure was calculated for a single week in January for each ToU tariff alternative to calculate and compare the resulting added flexibility (versus a flat rate tariff). The sensitivity analysis found a positive, logarithmic trend between the extent of the tiered price gradient and the additional flexibility due to the tariff, where larger differences (i.e., larger upper-tier prices) led to a greater amount of additional flexibility.

At an annual level (and fixing for the building archetype), the flat rate tariff is by far the most expensive option, followed by the Spot dynamic price, HP dynamic price, and, finally, the static ToU tariff. The expenditure for the inefficient building is nearly double that of the efficient building for each tariff design.

Under each tariff design, the efficient building consumed approximately 47% less than the inefficient building. Across tariff designs,


Flat rate tariff

Static ToU tariff

Spot dynamic tariff

HP dynamic tariff

Fig. 8. Indoor and outdoor air temperatures.

Table 5
Quantitative results—annual*.

	Flat		ToU		Spot dynamic		HP dynamic	
Archetype	Inefficient	Efficient	Inefficient	Efficient	Inefficient	Efficient	Inefficient	Efficient
Total expenditure (CHF)	601.64 (nc)	318.65 (nc)	316.20 (319.39)	160.03 (160.85)	309.45 (311.42)	162.27 (162.88)	342.63 (345.11)	175.08 (175.84)
Total thermal energy (kWh)	2074.6 (nc)	1098.8 (nc)	2136.9 (2142.6)	1136.8 (1134.2)	2187.3 (2176.7)	1164.5 (1161.8)	2162.0 (2150.0)	1148.3 (1144.9)
Energy intensity (kWh/CHF)	3.45 (nc)	3.45 (nc)	6.76 (6.71)	7.10 (7.05)	7.07 (6.99)	7.18 (7.13)	6.31 (6.23)	6.56 (6.51)
Max power (kW)	3.03 (nc)	3.66 (nc)	4.27 (3.07)	3.85 (3.64)	4.26 (3.07)	4.02 (3.64)	4.26 (3.07)	4.02 (3.64)
Mean thermal power difference (kW)	1.46 (nc)	1.61 (nc)	3.44 (1.45)	3.18 (1.57)	3.72 (1.45)	3.13 (1.57)	3.52 (1.45)	2.87 (1.57)
Mean indoor temperature difference (°C)	2.38 (nc)	2.87 (nc)	3.91 (3.76)	3.94 (3.84)	4.00 (3.96)	3.90 (3.85)	3.92 (3.54)	3.75 (3.64)
Load factor	0.08 (nc)	0.03 (nc)	0.06 (0.08)	0.03 (0.04)	0.06 (0.08)	0.03 (0.04)	0.06 (0.08)	0.03 (0.04)
Total cost reduction attributed to building efficiency and flexibility (%)				−73.40 (-73.26)		−73.03 (-72.93)		−70.90 (-70.77)
Additional cost reduction attributed to flexibility (%)				−4.65 (-5.16)		−1.00 (-1.25)		−3.65 (-3.94)

*Results with capacity charge in parentheses; nc: no change.

energy demand was lower for the flat rate tariff but did not change significantly among the time-varying tariffs (2.36% to 2.44% change).

4.6.2. Energy intensity, thermal power, and change in indoor temperature

Energy intensity (energy consumed per CHF spent) was lowest for the flat rate tariff and highest for the Spot dynamic tariff. It should be noted that the while the energy intensity was equal for the efficient and inefficient archetypes under the flat rate tariff, intensity was slightly higher for the efficient building under the other tariff designs.

As expected, the maximum annual power (representing the peak power for the heating season) was lowest under the flat rate tariff. For each building archetype, the peak power was identical for the Spot and HP dynamic tariffs. The largest different between the efficient and inefficient archetypes was from the static ToU tariff.

Finally, the mean thermal power difference (the mean of the differences between the maximum and minimum thermal power for each month) and the mean indoor temperature difference (the mean of the differences between the maximum and minimum indoor temperatures for each month) were both markedly lower for the flat rate tariff. This offers further evidence that the thermal power spikes were less evident for the flat rate tariff than for the ToU tariffs.

4.6.3. Load factor

For each building archetype, the load factor (LF) was the same with one exception. The LF for the inefficient archetype under the flat rate tariff design was 25% higher than the same archetype under the other

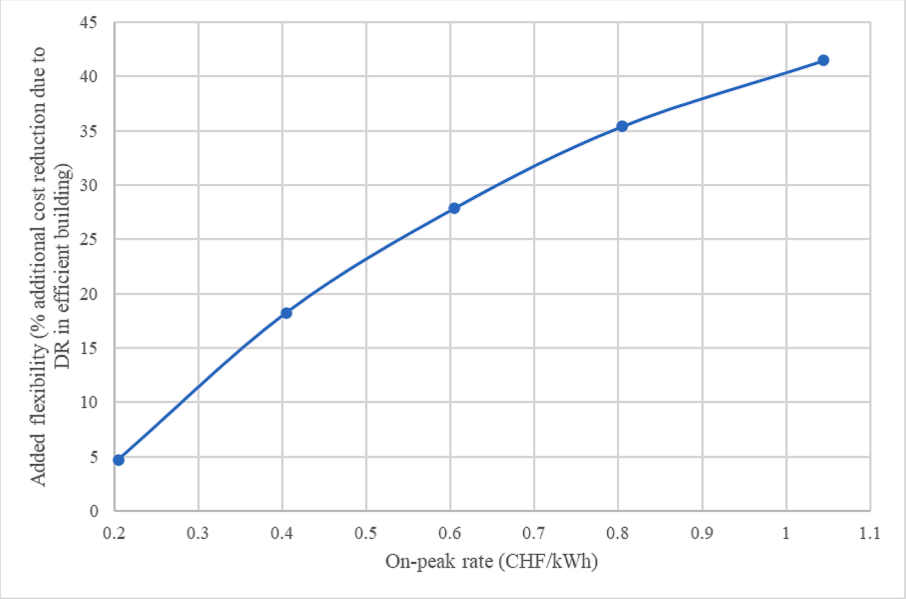


Fig. 9. Sensitivity analysis of on-peak price of ToU tariff on additional flexibility of efficient vs. inefficient building versus flat rate tariff.

tariff designs. For the time-varying tariff designs the LF was 50% higher for the inefficient archetype versus the efficient archetype. In conclusion, the load pattern is spikier for the inefficient building because it loses heat more easily than the efficient building.

4.6.4. *Capacity charge*

The inclusion of a capacity charge resulted in a much more efficient operation of the HP system without significant increases in cost or energy usage (see results in parentheses in Table 5). The max power for each of the time-varying tariffs is nearly equal to the set threshold which, when surpassed, would include the capacity charge component. In this case, the model behaviour treats this threshold as a constraint.

4.7. *Cost and energy savings*

In terms of cost savings to the customer, the results indicate a reduction in expenditure resulting from both the efficiency of the building envelope and the tariff design when compared with the base case. While the base scenario was, expectedly, the most expensive option to consumers of each archetype, the results for the time-varying tariff schemes indicated that the most dynamic schemes are not necessarily the cheapest option. This tracks with the notion that dynamic pricing would make heating more expensive during times when heat demand is closely aligned with high system electricity demand (which is evident for both the Spot and HP dynamic tariffs).

Energy consumption did not change drastically across tariff types due to the temperature setpoints that dictated a minimum level of energy required to maintain an indoor air temperature. The variation among tariffs is a function of the overheating behaviour that was evident when the model would preheat the building. This is evidenced by the fact that the flat rate tariff used marginally less energy than the other tariffs and had a lower max power and lower mean thermal power and indoor temperature differences (as less power surges were performed as preheating was not necessary). Based on the overheating behaviour observed in the ToU tariffs, it is expected that consumption would be lower for the flat rate tariff since overheating implies larger losses.

An additional consideration of these results is in terms of utility revenue. In this analysis, the dynamic tariffs represent low-revenue scenarios for the utilities, as the included charges only include the cost of electricity itself (wholesale electricity price), distribution (network charge), and community service and renewable energy incentive charges. The power generation component of a typical regulated electric tariff may also include the cost to generate and offer existing and new supply of electricity, including covering the costs of investment of new generation. With that in mind, it should also be noted that the purpose of dynamic pricing is to shift peak power usage and offset the need for additional electricity supply generation infrastructure. However, the current model does not constrain for total expenditure, and while the absolute values for expenditure may change, the resulting load curve would follow the same shape as the current results with the goal of minimizing expenditure for each tariff scenario.

4.8. *Flexibility*

The results demonstrated that flexibility has limited payback at the current levels of on-/off-peak and dynamic price differences. However, the results for the dynamic tariffs are more promising when aligning the electric tariff rate with heat demand. The HP dynamic tariff resulted in further savings due to flexibility versus the Spot dynamic tariff. Total expenditure was higher under the HP dynamic tariff since the times when heating is necessitated are also more expensive under this tariff, which functioned as a driver to increase the utilization of the flexibility provided by the building.

The sensitivity analysis of the static ToU tariff revealed that increasing the cost of on-peak times would lead to additional cost savings due to building flexibility, demonstrating that the additional gains in cost savings could be gained through flexibility by using critical-peak pricing (CPP) schemes. Many utilities utilize ToU CPP to shift demand, which introduces critical on- and off-peak tariffs for periods of the year when system load is precariously high. French energy company Électricité de France S.A. (EDF) “tempo” ToU tariff peak pricing ratio is as high as 2.79 for high system peak days [40]. California’s statewide pricing pilot that utilized an opt-in ToU tariff where CPP tariffs were as much as ten times greater than off-peak prices [41].

Therefore, the peak pricing ratios (that is, the ratio of the on-peak tariff/off-peak tariff) of the lower three tariffs introduced in the sensitivity analysis (upper-tier tariffs of 0.204, 0.404, and 0.604 CHF/kWh) are not implausible in the real-world. A ToU tariff scheme utilizing peak pricing ratios similar to those used by EDF or California, additional cost reductions attributable to flexibility could surpass 20% (in other words, 20% cost reduction in addition to the approximately 47% decrease in costs that the efficient building experiences over the inefficient building). Based on the general effectiveness of ToU tariffs demonstrated in this study, it would be interesting to extend the analysis to include a CPP ToU tariff where a narrower set of on-peak hours are considerably more expensive than the off-peak hours to further promote load shifting.

4.9. Model behaviour

The simulated maximum power (or peak) of the heating system has two major implications. First, as one of the purposes of the study was to assess flexibility of two building archetypes under different tariff schemes, the temporal shift of the power peak allows to assess the tariff's effectiveness in enabling demand response. Second, quantifying the optimized maximum power allows to establish the thermal demand peak that results from each tariff scheme. It should be noted that this discussion is based on load shifts in thermal energy demand whereas electric demand would be the prevailing metric for assessing peak load and its implications on the electric grid.

For the time-variant tariff schemes (static ToU and the two dynamic tariffs), the model behaves by surging the heating system power to the extent that the indoor air temperature comfort zone constraint allows, thus taking advantage of the low-price period and maximizing the use of the thermal inertia of the building envelope during a high-price period. This is not the most effective way of operating a heat pump, which loses efficiency and shortens the system's lifespan when turned on at full power and off completely instead of staggering the power over a longer period. However, the thermal inertia of the building only permits short-term storage potential, even in the efficient building. Therefore, to maximize the flexibility provided by the building envelope, a high amount of power is required to maximize heat output and to "charge" the building heat capacity quickly and as late as possible to maximize the storage properties of the building thermal mass.

The uncontrollable release of heat from the building mass is perhaps the biggest drawback of relying on the building envelope for flexibility. Traditional storage options, e.g., heat stored in a hot water tank or electricity stored in a battery, provide easier avenues for a consumer to take advantage of lower electricity tariffs. In terms of economics, it is possible for building retrofit efforts to be justified independent of flexibility gains [42]. However, in the presence of volatile prices and absence of suitable financial aid, deep building retrofits may not be economically feasible [43,44]. This paper demonstrates that the benefits for the grid are probably more important than the benefits for the building owner in terms of cost savings, which reflects that there is a misalignment in the incentives.

While the current study does not suggest strong energy or cost savings due to added flexibility from a more efficient building, the additional savings resulting from the efficient building's added flexibility should be considered as an added benefit of retrofit measures and measured as an incremental cost saving rather than in terms of absolute cost savings. In addition, as demonstrated in this study, a carefully considered tariff design could make substantial improvements to the cost savings resulting from a building's flexibility potential. Aligning dynamic pricing in the winter months with heating schedules could be an effective strategy to motivate consumers with electric heating systems to shift when they heat their homes and, in the case of consumers living in efficient homes, the inherent flexibility provided by the building envelope could be more beneficial in terms of both energy and cost savings.

4.10. Capacity charge

The reported load factors in Table 5 suggest that there is a high potential for improving the smoothing of the model. Since the current utilization rates are exceptionally low (load factor < 0.1), the model is using electric energy inefficiently. This is expected since none of the tariffs include a capacity component. When the capacity charge is considered, the load factors are increased (meaning the utilization rate of electricity is being consumed more efficiently), and the peak thermal power and the mean difference in thermal power are both significantly reduced. While costs increased slightly for each tariff, an increased share of the cost reduction in the time-variant tariffs was attributable to the building's flexibility with the capacity charge.

5. Conclusions

While it is expected that the level of a building's thermal efficiency will result in heating-related energy and cost savings, the extent to which a building might utilize the efficiency of its building components and the thermal storage potential of the building thermal mass is less apparent. The results from this study indicate that:

1. Multiple benefits can be achieved from an efficient building stock via a cost-effective switch to an electric heating system.
2. Albeit small, the efficiency of the building does play a role in that building's flexibility potential, and that even small single-family houses with new construction materials are at an advantage in terms of how much additional cost savings can be acquired via flexibility versus their older counterparts.
3. Depending on the tariff scheme, additional cost savings due to flexibility can increase significantly relative to a flat rate tariff.
4. On the demand side, the results of this work further justify building renovation investments to create a more energy efficient building stock since, despite the cost savings resulting from flexibility being relatively small, retrofit investments should account for this flexibility when assessing their economic feasibility.
5. On the supply side, time-varying tariff designs can be a valuable tool in promoting shifts in heat demand for consumers with electric heating. However, as the model in this study suggests, different tariff designs may lead to new (and higher) thermal power peaks. Therefore, capacity-based pricing is strongly considered for peak shaving based on the potential for shifted but insufficiently reduced peaks.

A critical drawback in the design of each of the studied tariffs is that each is based solely on the cost of energy. In absence of a capacity-based cost component in each tariff, there is no disincentive to not surge the operation of the HP to generate as much heat as possible. This demonstrates that dynamic tariffs without any capacity component could simply shift heating-related power peaks.

Though outside of the scope for the present paper, investigating cost reductions due to building archetypes while considering the investment costs to reach the efficiency level of an efficient archetype in older buildings would provide a better context for the savings in terms of economic feasibility. The work undertaken in this study can be further developed to extend to other facets of the energy system, including electric and thermal energy storage technologies, to observe the interactions among flexibility services at both the building- and grid-levels. Future research could also further investigate the effects of ventilation strategies on building archetypes or include ventilation as an optimized parameter if using a similar method (e.g., where an optimal ventilation schedule is identified assuming a minimum ventilation time requirement), and consider additional inputs, such as air quality and air tightness. Finally, considering human behaviour would be a valuable component to consider, as well. While typical occupancy times are used to consider internal gains, the current study does not differentiate times when occupants may not be home and may decrease their temperature setpoint for heating.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

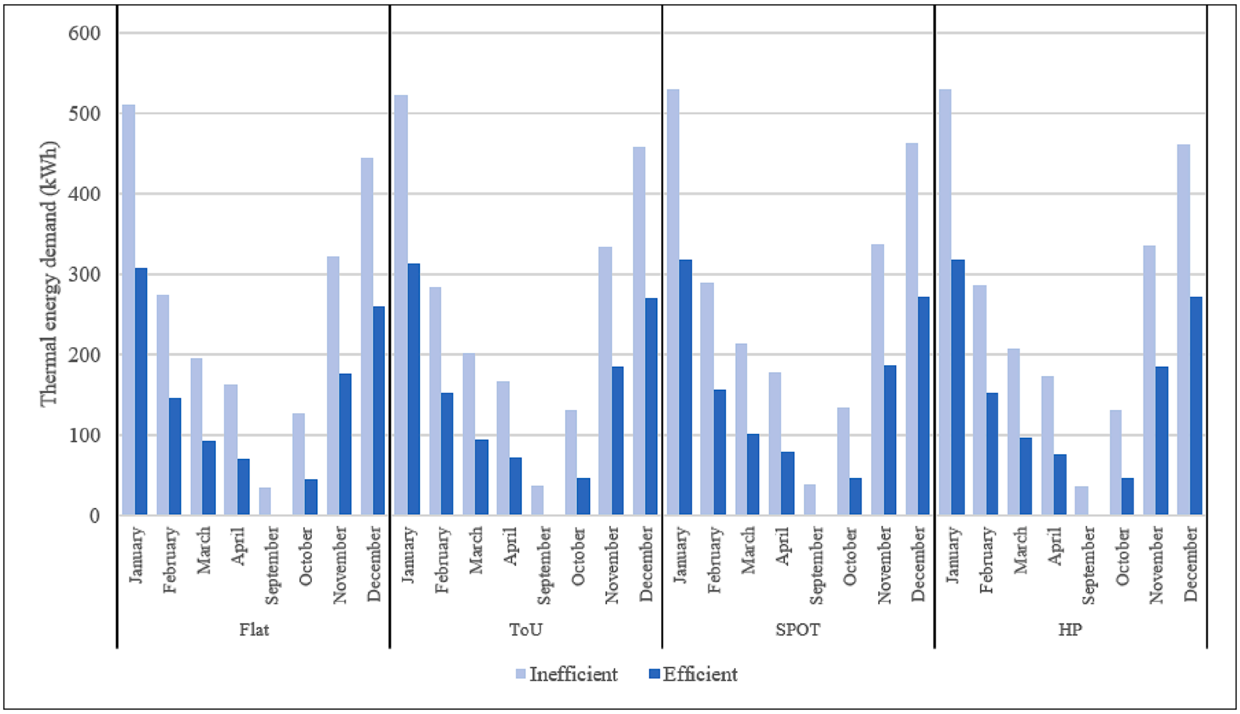


Fig. A1. Total thermal energy demand for SH per month by tariff type (kWh): light blue represents inefficient building.

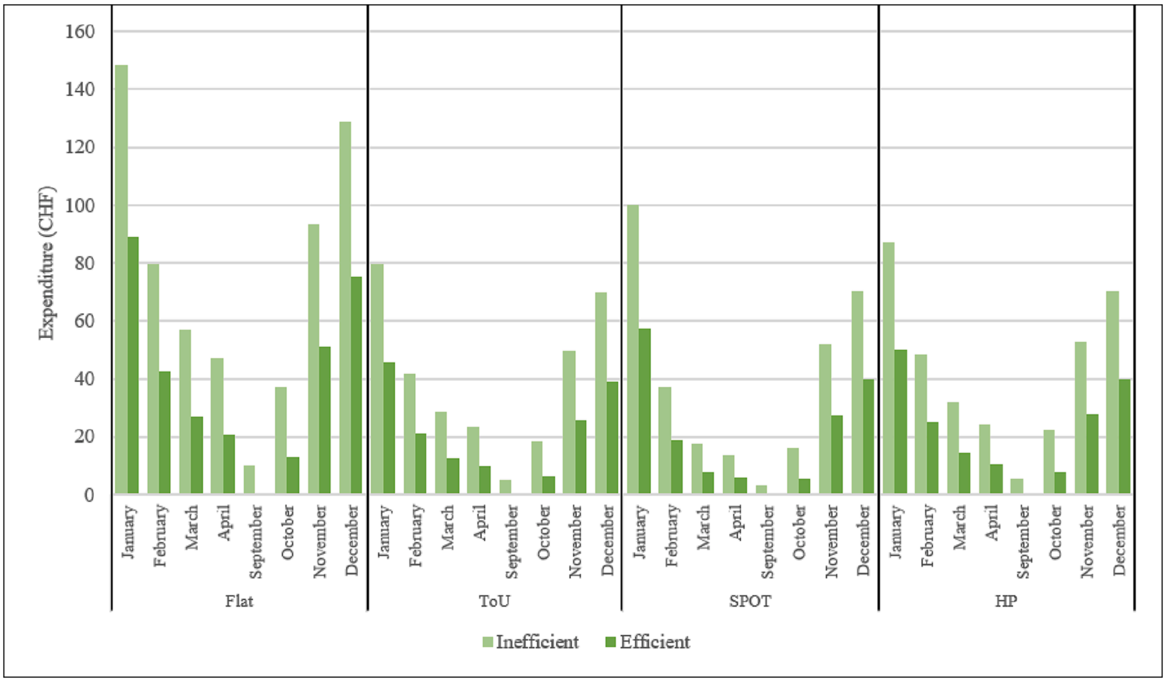


Fig. A2. Total expenditure on SH per month by tariff type (CHF); light green represents inefficient building.

Data availability

Data will be made available on request.

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Appendix:. Monthly results

The following figures visualize the monthly totals for energy demand and expenditure, respectively, for the eight months of the heating season

(January to April and September to December). As is evident from Fig. A.1, energy demand does not change drastically across tariff designs. The only noticeable anecdote to be made is that the flat rate tariff resulted in less energy demand for both building archetypes across all months. The results for monthly expenditure, shown in Fig. A.2 shows larger differences. Expenditure is highest for the flat tariff across all months and is lowest for the static ToU tariff for January, when energy demand is highest. While expenditure for the HP dynamic tariff is lower than that of the Spot dynamic tariff in January, it is generally higher in the following months and nearly the same for December.

References

[1] S. Pezzutto, S. Zambotti, S. Croce, P. Zambelli, G. Garegnani, C. Scaramuzzino, R. Pascuas, A. Zubaryeva, F. Haas, D. Exner, A. Müller, M. Hartner, T. Fleiter, A. Klingler, M. Kühnbach, P. Manz, S. Marwitz, M. Rehfeldt, J. Steinbach and E. Popovski, "Building Stock EU28," 2018. [Online]. Available: https://gitlab.com/hotmaps/building-stock/-/blob/master/README.md.

[2] European Commission, Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables), 2016. [Online]. Available: https://ec.europa.eu/energy/sites/default/files/documents/mapping-hc-excecutivesummary.pdf.

[3] European Commission, Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions, 2022.

[4] N. Calcea, Heat pumps are on the rise in Europe, 2020. [Online]. Available: https://energymonitor.ai/heating-cooling/heat-pumps-are-on-the-rise-in-europe.

[5] European Commission, Communication on an EU Strategy on Heating and Cooling, 2016. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016DC0051&from=EN.

[6] R. L. Jan Rosenow, Heating without the hot air: Principles for smart heat electrification, 2020. [Online]. Available: https://www.raponline.org/knowledge-center/heating-without-hot-air-principles-smart-heat-electrification/.

[7] J.G. Kirkerud, E. Trømborg, T.F. Bolkesjø, Impacts of electricity grid tariffs on flexible use of electricity to heat generation, Energy 115 (3) (2016) 1679–1687, https://doi.org/10.1016/j.energy.2016.06.147.

[8] S. Yilmaz, S. Weber, M.K. Patel, Who is sensitive to DSM? Understanding the determinants of the shape of electricity load curves and demand shifting: Socio-demographic characteristics, appliance use and attitudes, Energy Policy 133 (2019) 110909.

[9] J. Torriti, Price-based demand side management: Assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy, Energy 44 (1) (2012) 576–583, https://doi.org/10.1016/j.energy.2012.05.043.

[10] O. Valentini, N. Andreadou, P. Bertoldi, A. Lucas, I. Saviuc, E. Kotsakis, Demand response impact evaluation: a review of methods, Energies 15 (14) (2022) pp, https://doi.org/10.3390/en15145259.

[11] A. Pena-Bello, P. Schuetz, M. Berger, J. Worlitschek, M.K. Patel, D. Parra, Decarbonizing heat with PV-coupled heat pumps supported by electricity and heat storage: impacts and trade-offs for prosumers and the grid, Energ. Conver. Manage. 240 (2021) 114220.

[12] M. Ali, J. Jokisalo, K. Siren, M. Lehtonen, Combining the Demand Response of direct electric space heating and partial thermal storage using LP optimization, Electr. Pow. Syst. Res. 106 (2014) 160–167, https://doi.org/10.1016/j.epsr.2013.08.017.

[13] A. Toradmal, T. Kemmler, B. Thomas, Boosting the share of onsite PV-electricity utilization by optimized scheduling of a heat pump using buildings thermal inertia, Appl. Therm. Eng. 137 (2018) 248–258, https://doi.org/10.1016/j.applthermaleng.2018.03.052.

[14] S. Bechtel, S. Rafii-Tabrizi, F. Scholzen, J.-R. Hadji-Minaglou, S. Maas, Influence of thermal energy storage and heat pump parametrization for demand-side-management in a nearly-zero-energy-building using model predictive control, Energ. Build. 226 (2020) 110364.

[15] H. Ren, Y. Sun, A.K. Albdoor, V.V. Tyagi, A.K. Pandey, Z. Ma, Improving energy flexibility of a net-zero energy house using a solar-assisted air conditioning system with thermal energy storage and demand-side management, Appl. Energy 285 (2021) 116433.

[16] G. Reynders, T. Nuytten, D. Saelens, Potential of structural thermal mass for demand-side management in dwellings, Build. Environ. 64 (2013) 187–199, https://doi.org/10.1016/j.buildenv.2013.03.010.

[17] F. Pallonetto, S. Oxizidis, F. Milano, D. Finn, The effect of time-of-use tariffs on the demand response flexibility of an all-electric smart-grid-ready dwelling, Energ. Buildings 128 (2016) 56–67, https://doi.org/10.1016/j.enbuild.2016.06.041.

[18] P. Fitzpatrick, F. D'Ettorre, M. De Rosa, M. Yadack, U. Eicker, D.P. Finn, Influence of electricity prices on energy flexibility of integrated hybrid heat pump and thermal storage systems in a residential building, Energ. Build. 223 (2020) 110142.

[19] J. Sánchez Ramos, M. Pavón Moreno, M. Guerrero Delgado, S. Álvarez Domínguez, L.F. Cabeza, Potential of energy flexible buildings: Evaluation of DSM strategies using building thermal mass, Energ. Build. 203 (2019) 109442.

[20] A. Arteconi, D. Patteeuw, K. Bruninx, E. Delarue, W. D'haeseleer, L. Helsen, Active demand response with electric heating systems: Impact of market penetration, Appl. Energy 177 (2016) 636–648.

[21] A. Rinaldi, M.C. Soini, K. Streicher, M.K. Patel, D. Parra, Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation, Appl. Energy 282 (2021) 116110.

[22] ASHRAE, "Standard 55-2017 – Thermal Environmental Conditions for Human Occupancy," 2017.

[23] Hoval, *Hoval Belaria® SRM (4-16),* 2014, p. 13.

[24] IBM, IBM ILOG CPLEX 12.6 User Manual, IBM Corp, 2013.

[25] International Organization for Standardization, EN ISO 13790:2008 thermal performance of buildings - calculation of energy use for space heating and cooling, 2008.

[26] International Organization for Standardization, EN ISO 6946:2017 Building components and building elements — Thermal resistance and thermal transmittance — Calculation methods, 2017.

[27] TABULA, TABULA WebTool, [Online]. Available: https://episcope.eu/building-typology/webtool/. [Accessed 2022].

[28] ASHRAE, ASHRAE Fundamental Handbook, 2009, p. 880.

[29] PassiveHouse Institute, Component Database: Small ventilation systems, 2022. [Online]. Available: https://database.passivehouse.com/en/components/list/ventilation_small. [Accessed September 2022].

[30] R. Galvin, Impediments to energy-efficient ventilation of German dwellings: A case study in Aachen, Energ. Build. 56 (2013) 32–40.

[31] R. Perez, R. Seals, P. Ineichen, R. Stewart, D. Menicucci, A new simplified version of the Perez diffuse irradiance model for tilted surfaces, Sol. Energy 39 (3) (1987) 221–232, https://doi.org/10.1016/S0038-092X(87)80031-2.

[32] W.F. Holmgren, C.W. Hansen, M.A. Mikofski, pvlib python: a python package for modeling solar energy systems, J. Open Source Software 3 (29) (2018) 884, https://doi.org/10.21105/joss.00884.

[33] D. Parra and M. K. Patel, Effect of tariffs on the performance and economic benefits of PV-coupled battery systems, vol. 164, pp. 175-187, 2016. doi:10.1016/j.apenergy.2015.11.037.

[34] K.N. Streicher, P. Padey, D. Parra, M.C. Buerer, M. Patel, Assessment of the current thermal performance level of the swiss residential building stock: statistical analysis of energy performance certificates, Energ. Build. 178 (2018) 360–378, https://doi.org/10.1016/j.enbuild.2018.08.032.

[35] R. Hogan, Radiation Quantities in the ECMWF model and MARS, 2015. [Online]. Available: https://www.ecmwf.int/node/18490.

[36] H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee and J.-N. Thépaut, *ERA5 hourly data on single levels from 1979 to present,* Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2018. doi:10.24381/cds.adbb2d47.

[37] H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee and J.-N. Thépaut, *ERA5 hourly data on pressure levels from 1979 to present,* Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2018. doi: 10.24381/cds.bd0915c6.

[38] Swiss Federal Electricity Commission (ElCom), Electricity prices in Switzerland, 2021. [Online]. Available: https://www.strompreis.elcom.admin.ch/.

[39] European Power Exchange (EPEX), EPEX SPOT, 2022. [Online]. [Accessed 2022].

[40] Électricité de France S.A., Qu'est-ce que l'option TEMPO?, 2022. [Online]. Available: https://particulier.edf.fr/fr/accueil/gestion-contrat/options/tempo.html.

[41] K. Herter, Residential implementation of critical-peak pricing of electricity, Energy Policy 35 (4) (2007) 2121–2130, https://doi.org/10.1016/j.enpol.2006.06.019.

[42] G.N. Gugul, M.A. Koksal, V.I. Ugursal, Techno-economical analysis of building envelope and renewable energy technology retrofits to single family homes, Energy Sustain. Dev. 45 (2018) 159–170, https://doi.org/10.1016/j.esd.2018.06.006.

[43] K.N. Streicher, S. Mennel, J. Chambers, D. Parra, M.K. Patel, Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches, Energy Build. 215 (2020) 109870.

[44] G. Kumbaroğlu, R. Madlener, Evaluation of economically optimal retrofit investment options for energy savings in buildings, Energy Build. 49 (2012) 327–334, https://doi.org/10.1016/j.enbuild.2012.02.022.