Impacts of Residential Energy Efficiency and Electrification of Heating on Energy Market Prices

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Abstract

The decarbonisation of the energy system is attracting the attention of policy makers worldwide, with many measures targeting the residential sector. It is expected that emission reduction targets will bring changes on the energy system, such as energy conservation measures and the electrification of heating (in a context where the electric sector is mainly decarbonised). However, the changes on electricity prices due to the electrification of heating have been scarcely addressed in the literature.

This paper presents an assessment of the impact on electricity prices produced by the decarbonisation of heating and energy efficiency in the residential sector. A linear programming problem is used to find the optimal planning and operation of electric heating and residential loads, following a price-maker approach. Then, the potential cost changes for residential consumers and the impacts on electricity prices in the wholesale day-ahead market are estimated considering different residential electric heating profiles and energy conservation scenarios.

Following an explanation of the method, a discussion of results is presented, considering how the electrification of heating change the energy price curves and the policy implications of these findings. In addition, it is discussed how the optimal operation of heating systems with energy conservation technologies and thermal storage could mitigate the cost increase of these changes on the energy system.

Keywords: Electrification of Heating; Energy Efficiency; Energy Markets; Energy System Models.

Nomenclature

Sets

h	hour = 1 – 24
m	month = 1 – 12
y	years = 1 –*pLifespan*
c	type of houses = 1 – *pNumHouses*
p	points of the piecewise linear function = 1 – 23
seg	linear segments of the piecewise linear function = 1 – 22

Parameters

pLifespan	Expected lifespan for PV and HP systems in the study (years)
pNumHouses	Number of different house types (4 in this study)
$pHouseMultiplier_c$	Number of equivalent clients per house type c

$pDemandElec_{c,m,h}$	Base electric demand curve(in hour h and month m) for 12 representative days in each house c (MWh)
$pDemandTherm_{c,m}$	Total thermal demand for 12 representative days, one per month m and house c (MWh)
$pCostE_y$	Electric energy annual price increments at year y, relative to a base price at the beginning of the study (€/MWh)
$pCostT_y$	Thermal energy annual price increments at year y, relative to a base price at the beginning of the study (€/MWh)
pEnergyEff	Energy savings due to energy efficiency measures (building retrofitting and similar energy conservation technologies) (%)
pFixEpow	Access tariff for electric power (€/MW)
pFixTpow	Access tariff for thermal power (€/client)
pGridTariffEE	Share of the variable electricity tariff that correspond to network costs (€/MWh)
pCOP	Coefficient of Performance for the HP
$pDaysInMonth_m$	Number of days in month m
$pThermProfile_h$	Normalised residential heating demand profile (%)
$pXparameter_{p,m,h}$	"X" value (energy) of the point p in the piecewise linear functions (MWh)
$pYparameter_{p,m,h}$	"Y" value (energy cost) of the point p in the piecewise linear functions (€/MWh)
Positive Variables	
$vElecHPinput_{c,m,h}$	Electricity for thermal production with HP (MWh)
$vGridEnTotalPos_{s,m,h}$	Total energy transaction to the grid (positive side) (MWh)
$vGridEnTotalNeg_{c,m,h}$	Total energy transaction to the grid (negative side) (MWh)
$vBoughtEnergyT_{c,m}$	Thermal energy bought (natural gas) from the grid to meet the daily demand (MWh)
$vDemandNew_{c,m,h}$	New consumption curve after changing the base profile of *pDemandElec* (MWh)
$vPowElect_c$	Contracted maximum annual electric power in house of type c (MW)
$vGridCostEE_{m,h}$	Cost of electric energy transaction with the market (€)
$\lambda_{p,m,h}$	Auxiliary continuous variable for the piecewise linear functions
Free Variables	
$vGridEnTrans_{c,m,h}$	Energy transaction to the grid in each node (MWh)
$vElectricCost_{m,h}$	Cost of electric energy transaction (€)
vCostEE	Total electric energy cost for the considered residential clients for the duration of the study (€)
vCostPowE	Total electric contracted power (access tariff) cost for the considered residential clients for the duration of the study (€)

vCostET	Total thermal energy cost for the considered residential clients for the duration of the study (€)
vCostPowT	Total thermal contracted power (access tariff) cost for the considered residential clients for the duration of the study (€)
vAvgPriceChange	Annual average change of electricity price due to aggregator's actions (%)
vAvgPriceOriginal	Annual original average market electricity price (€/MWh)
vMaxPriceChange	Maximum change of electricity prices (%)
Binary Variables	
$\chi_{seg,m,h}$	Auxiliary binary variable for the piecewise linear functions

1. Introduction

In recent years, many governments worldwide have shown their commitment to tackling climate change, with ambitious targets and policies to reduce greenhouse gas (GHG) emissions, and transform the energy system into a largely decarbonized one. For example, EU countries have agreed on a new climate and energy framework, including EU-wide targets and policy objectives for 2030. These targets are:

- "a 40% cut in GHG emissions compared to 1990 levels
- at least a 27% share of renewable energy consumption
- at least 27% energy savings compared with the business-as-usual scenario" [1].

Similarly, in January 2017 Scottish Government proposed a new energy strategy [2] presenting Scotland's long-term vision of energy supply and use, aligned with the GHG emissions reduction targets. Scotland, as with the rest of the UK and other EU countries, has recognised the importance of reducing energy demand, and decarbonising the heating supply to achieve the GHG emission reduction targets [3], [4].

Electrification of heating through heat pumps (HP) technologies, in combination with a significant shift to renewable power generation, has been recognised as a potentially important contributor to the decarbonisation of the heat supply [5]. Much research has been conducted into the decarbonisation of residential heating. For instance, references [5] and [4] propose optimal modelling options of domestic HP systems, analysing its decarbonisation potential and affordability for the final consumer. These studies conclude that, in the context of an electricity system with high renewable energy penetration, HP systems have important decarbonisation potential. However, thermal flexibility is important (with energy efficiency measures and thermal energy storage), to ensure that the HP systems are cost competitive with conventional gas systems so that affordability is not significantly adversely impacted.

Other studies, such as [6] and [7], take a power system adequacy perspective. The former proposes a planning methodology to explore, in a heating electrification scenario, how weather events can stress the power system due to the increasing weather-dependence on both supply and demand sides, and capacity expansion requirements due to the increased net load demand. The authors conclude that different weather patterns considerably influence investment and planning choices. However, the buildings' thermal inertia could be used to partially decouple electricity and heat demand (through flexible heater operation and building pre-heating), greatly decreasing the impacts on the electric system while maintaining users' thermal comfort. The latter study analyses supply reliability in six published 2050 UK energy scenarios, proposing a range of decarbonised supply side technologies combined with electrification of transportation and heating. The authors report that electrification of heating combined with decarbonisation of the electricity system cannot be done with simple substitutions of existing energy forms. The authors conclude that heating demand reduction and demand side management (for balancing purposes) are of paramount importance to deliver a secure and clean energy future, in a cost-effective manner.

Despite the amount of research available about electrification of heat, it can be seen that most efforts focus on technical adequacy and decarbonisation potential, but affordability issues are only addressed partially, analysing energy costs under current tariffs (as in [5]). In particular, past studies have not taken into account the potential impacts of heating electrification on energy markets. It has been widely researched that changes in the electricity system, such as large wind power penetration, have an important effect on the market, e.g. [8]. Therefore, it seems necessary to analyse the potential impacts of a large scale electrification of heating on the energy market. The work proposed in this paper intends to fill this gap in the literature by analysing the effects of electrification of heating and energy efficiency on electricity market prices.

The proposed analysis is developed using an optimal long-term planning problem of aggregated residential clients (using electric heating) with market participation, following a price-maker approach. The impact of the aggregated residential clients on the market has been simulated by clearing the aggregator's energy bids against a set of residual demand curves (RDC) [9] (see section 2 for a brief description of RDC). Air-source heat pumps (HP) have been selected as the representative heating alternative to conventional gas boilers. Furthermore, three case studies, representing different heating demand profiles, and two residential energy efficiency scenarios have been analysed. Due to data availability issues, the residential energy profiles and electricity market data used correspond to the Spanish system. Even though the results might not be fully transposable to other contexts, they provide insight on the expected electricity market price changes due to heating electrification.

Energy affordability has been recognised is an important social and political concern, due to fuel poverty problems existing in the UK [3] and other European countries [10]. Therefore, this study could serve policy makers in better understanding how energy efficiency measures and the electrification of heating affects not only the energy markets but the final users as well, while also proposing solutions to mitigate the potential cost increments.

It is important to remark that the proposed methodology does not imply any market modification but only provides a better way to compute the interaction of the aggregated residential clients with electric heating systems, providing a better estimation of the final market price, in comparison with the simpler but less realistic price-taker models, which assumes that significant changes on the energy system (such as the electrification of heating in a major part of the residential sector) will not affect the market price. An estimation of the error due to following a price-taker approach is also developed in this paper (see section 5.1)

2. Model description

The base scheme considered in this study is composed of an aggregator that manages a large number of residential clients (implementing HP systems). This aggregator also has a connection to the electricity market, making it possible to sell and buy energy in the day-ahead market session.

The optimization model used is a mixed-integer linear programming one, and its objective is to minimise the annual energy costs over the duration of the study of a group of residential clients with electric heating. The particular assumptions and considerations for this analysis are summarized below:

- The residential clients are managed by an aggregator that allows buying and selling energy directly from the market. This assumption has been taken to make it possible for the residential clients to overcome market entry barriers, such as minimum size, and be able to actively participate in the electricity market.
- Only the electricity market is considered in this analysis. Other markets such as the gas and oil market have not been considered.
- Air-source heat pump (HP) systems have been considered to substitute a conventional gas boiler in the considered households.
- The inputs of the model are: energy demand profiles, HP performance parameters, and market data in the form of residual demand curves.
- The outputs of the model are the hourly optimal operation schedule of the HP system, the total energy costs, and the electricity market price.
- The Spanish electricity market is composed of the day-ahead wholesale market, the intraday markets, the balancing market and the ancillary service markets. Due to the long-

term scope of this study, and considering that most energy is traded in the day-ahead session, the proposed model considers only the participation in the day-ahead market. In addition, and for the sake of simplicity, complex offers and other transversal conditions (linking the offers of different hours) have not been considered in this analysis.

- The electricity market has been modelled with a set of market residual demand curves, which has been selected as it is a well-known approach for representing competitors' behaviour and is commonly used by market participants to formulate effective oligopolistic strategies [11]. Moreover, it has been considered that other market players do not change their strategy based on our aggregator's actions. See [12] for further detail on the residual demand curve formulation used in this paper.
- Three case studies are proposed for this analysis, representing different heating demand profiles, and two scenarios, representing the existence or not of residential energy efficiency measures in the considered households. In this paper, the above mentioned energy efficiency measures refer to building retrofitting and similar energy conservation technologies. The objective of these case studies and scenarios is to assess the impact of the heating profile and the presence of energy efficiency technologies, on the overall energy costs and market prices.

3. Mathematical formulation

3.1. Objective function

The objective function of the optimisation problem minimises the energy costs of all the residential consumers. It is composed of the thermal and electrical energy costs but it does not include the capital costs of the HP system and energy efficiency measures. This is to analyse the effect of the HP electric load on electricity prices and the overall change on energy costs, without considering equipment. Note that the objective function has been formulated for a total project lifespan of 20 years (reflecting the lifespan of the HP system [13]) and the time step for all the considered data is 1 hour. For the sake of simplicity, a year has been modeled with one representative day per month, for a total of 288h. It is calculated as:

$$min\{vCostEE + vCostPowE + vCostET + vCostPowT\} \tag{1}$$

where:

$$vCostEE = \sum_{y}\left(pCostE_y * \sum_{m}\left(daysMonth_m * \sum_{h}\left(vElectricCost_{m,h} + vGridCostEE_{m,h}\right)\right)\right) \tag{2}$$

$$vCostPowE = \sum_{y}\left(pCostE_y * pFixEpow * \sum_{c}\left(vPowElect_c\right)\right) \tag{3}$$

$$vCostET = \sum_{y}\left(pCostT_y * \sum_{c}\sum_{m}\left(pDaysMonth_m * vBoughtEnergyT_{c,m}\right)\right) \tag{4}$$

$$vCostPowT = pLifespan * pFixTpow * \sum_{c} pHouseMultiplier_c \tag{5}$$

From the previous equations, it can be seen that (2) sum up the electricity costs, bought from the grid. Equation (3) is used to compute the contracted electricity power costs and (4), (5) relate to the thermal energy costs and access tariffs, respectively.

Note that the parameters used for all the equations in this section are described in section 4.

3.2. Energy production constraints and balance equations

Equation (6) presents the considered thermal generation equation for an air-source heat pump. The energy savings percentage due to energy efficiency measures considered for each scenario is taken into account with the *pEnergyEff* parameter (see section 4 for more details on this parameter). Furthermore, it is assumed that the HP systems replace conventional gas boilers with 80% efficiency. Therefore, the thermal energy demand is represented by historic gas boiler consumption, adjusted by the gas boiler conversion efficiency and then by a further, optional energy efficiency parameter

$$\begin{aligned} vBoughtEnergyT_{c,m} &= (1 - pEnergyEff) * pDemandTherm_{c,m} * 0.8 \\ &- \sum_{h} \left(vElecHPinput_{c,m,h} * pCOP * (1 - pLossesHP) \right) \end{aligned} \tag{6}$$

Equation (7) limits the electric consumption of the heat pump below the nominal installed power. Constraint (8) are used to represent the HP operation in the proposed case studies, where the HP thermal production needs to follow a predefined demand profile: *pThermProfile*. Note that each case study presents a different *pThermProfile* parameter. For the full description on the case studies see section 4.

$$vElecHPinput_{c,m,h} \leq vPowerHP_c \tag{7}$$

$$\begin{aligned} &\sum_{h} \left(vElecHPinput_{c,m,h} * pCOP \right) * (1 - pLossesHP) \\ &\geq (1 - pEnergyEff) * pDemandTherm_{c,m} * 0.8 * pThermProfile_h \end{aligned} \tag{8}$$

Electrical energy consumption is modelled with (9), including the residential demands (*vDemandNew*) and the required electric energy input for the HP system (*vElecHPinput*).

$$vGridEnTrans_{c,m,h} = vDemandNew_{c,m,h} + vElecHPinput_{c,m,h} \tag{9}$$

3.3. Electricity cost constraints

The constraints in this and the next subsection have been used to calculate the electrical energy costs, which is composed by two parts: the electric energy and the electric power costs. Equation (10) has been used to calculate the required contracted electric power given the household demand and HP usage.

$$vPowElect_{c} \geq vGridEnTrans_{c,m,h} \tag{10}$$

The electric energy costs can also be split in two: energy market costs and the network equivalent costs. The former refer to the costs of buying energy at a certain market price. The latter is intended to meet the network operation and maintenance costs and potential network development, but not the actual costs of energy (which is a result from the market).

Equation (11) is used to compute the equivalent share of network usage cost, which is a function of the energy bought from the grid multiplied by a fix tariff (see section 4 for further details on the share of this costs).

$$vGridCostEE_{m,h} = pGridTariffEE * \sum_{c} vGridEnTrans_{c,m,h} \tag{11}$$

3.4. Piecewise linear function constraints

The electric energy cost, as a function of the market price, is calculated with the following equations. The piecewise linear function approximation of the energy cost curves is characterized by the points connecting the linear segments (characterised by *pXparameter* and *pXparameter*). In this paper 23 points have been selected to model each energy cost curve. See [12] for more details on the energy cost curve approximation process.

Equation (12) is used to compute the electricity cost as a linear combination of energy cost values of the considered points defined with *pYparameter*. Similarly, equation (13) shows how the energy value of the piecewise linear function is translated to a linear combination of the *pXparameter* values.

$$vElectricCost_{m,h} = \sum_{p} \left(\lambda_{p,m,h} * pYparameter_{p,m,h}\right) \tag{12}$$

$$\sum_{c} vGridEnTrans_{c,m,h} = \sum_{p} \left(\lambda_{p,m,h} * pXparameter_{p,m,h}\right) \tag{13}$$

The positive auxiliary variable λ is used in both equations to define the linear combination of the parameter values. Note that the sum of all λ variables cannot be greater than 1, as shown in (14).

Also, the binary variable χ (the sum of which also cannot be greater than 1, see (15)), is used to avoid being in more than one segment of the piecewise function. Note that this binary variable creates a mixed integer programming problem. Lastly, equations (16) – (18) complete the piecewise linear function formulation. A more detailed explanation of this piecewise approximation can be found in [14].

$$\sum_{p} \lambda_{p,m,h} = 1 \tag{14}$$

$$\sum_{seg} \chi_{seg,m,h} = 1 \tag{15}$$

$$\lambda_{p=1,m,h} \leq \chi_{seg=1,m,h} \tag{16}$$

$$\lambda_{seg,m,h} \leq \chi_{seg-1,m,h} + \chi_{seg,m,h} \ \forall seg \in [2,21] \tag{17}$$

$$\lambda_{p=23,m,h} \leq \chi_{seg=22,m,h} \tag{18}$$

4. Scenarios and Case Studies

The number of residential clients that are considered to change their heating system is 8 million, which is approximately one third of the total number of households in Spain [15]. Note that a significant load increment in such a large number of clients is very likely to have a considerable impact on prices which should not be overlooked. Hence the importance of following a price-maker approach.

The residential clients are represented in terms of 4 groups (house types), according to the age of the head of the family (HF) and/or the presence of young children in the household. Figure 1 and Figure 2 show the typical electricity demand curves for these archetypes in summer and winter seasons, calculated as an average of historical data [16]. Note that these are normalised curves, so the sum of all points (one per hour) of each curve is equal to 1.

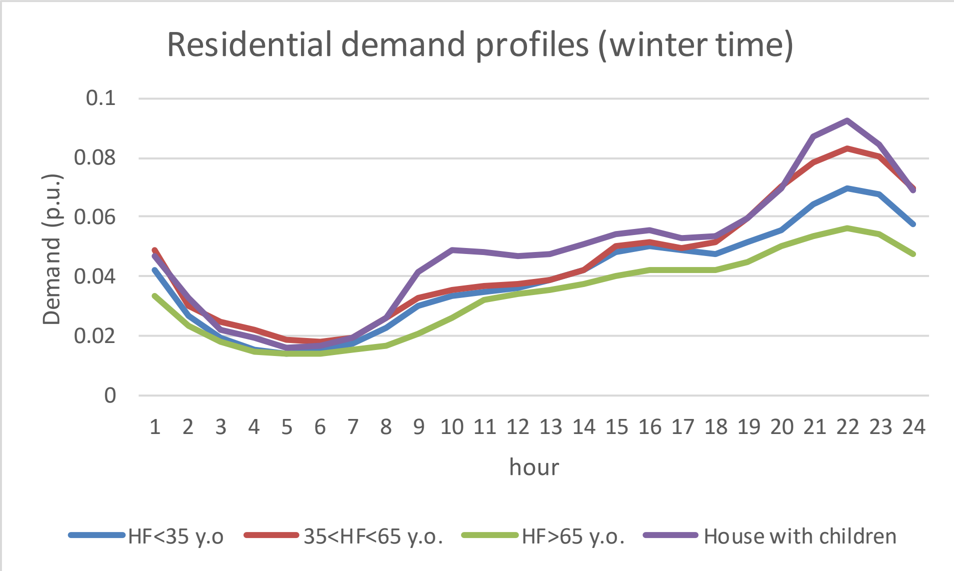

Figure 1. Normalized residential electric demand curves for winter time (4 types of users).

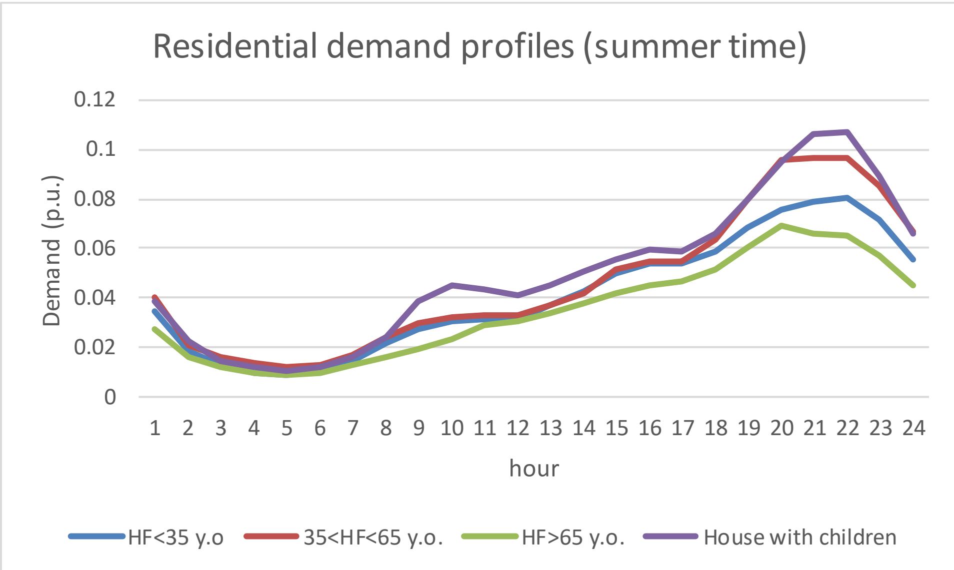

Figure 2. Normalized residential electric demand curves for summer time (4 types of users).

Moreover, the variation of monthly energy demand throughout a year is considered as represented in Figure 3. Table 1 summarizes the annual energy consumption per client type (for each of the four groups shown above) [16]**Error! Reference source not found.**. Note that the thermal demand refers only to heating and domestic hot water. Other thermal loads, such as cooking, are not considered here, as they are independent of the main focus of this study and they are relatively small (around 6% relative to the heating and hot water loads [17]).

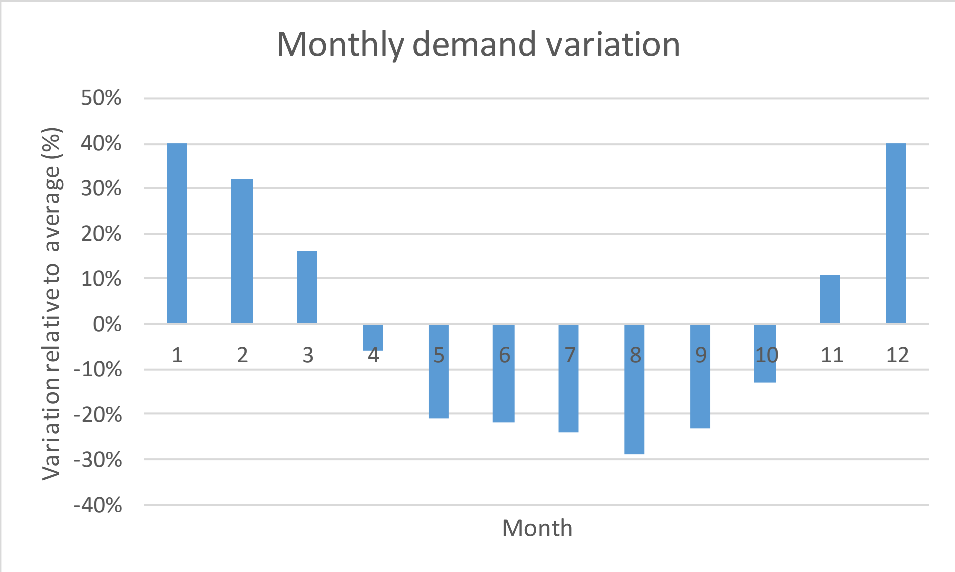

Figure 3. Monthly demand variation, relative to the monthly average electric demand consumption, for the residential electric sector in Spain.

Table 1. Total annual energy consumption per client type.

Type of client	Comparison with whole population average value	Annual Thermal (kWh)	Annual Electric (kWh)
HF<35 y.o.	-5%	6054.9747	3507.0613
35≤HF<65 y.o.	8%	6871.7046	3980.1140
HF≥65 y.o.	-19%	5174.3962	2997.0274
House with children	16%	7422.3987	4299.0778

For thermal energy, three case studies have been considered representing different heating demand profiles:

- Case study A: optimised heating demand profile (according to electricity price curves), with minimum requirement.
- Case study B: uniform, i.e. flat, heating demand profile.
- Case study C: typical heating demand profile.

Figure 4 shows the normalized heating demand profiles for the proposed case studies. Case study A allows the optimization problem to freely decide the best time to produce the thermal energy to meet the daily demand, but with a minimum production constraint (dotted line in Figure 4), so there is a minimum production throughout the day and at least 30% of the daily demand is produced between 14h – 21h (the peak time). This constraint has been implemented to avoid to produce all the heating during off-peak hours (normally from 1h – 7h) were is less likely to be needed by the households. Case study B follows a simple uniform profile, where the thermal demand is distributed uniformly throughout the day. Case study C uses a typical heating demand profile, taking from [18]. Note that, unlike the electricity demand profiles, all house types in this study follow the same heating demand profile (that changes according to the case study analysed), but adapted to the annual thermal demand values of Table 1. Also, the thermal demand follows the same monthly change pattern of Figure 3.

In addition, note that all the hourly points of the normalised total heating demand profiles of case studies B and C sum up 1, meaning that the same daily load is distributed according to the hourly values. However, case study A presents a minimum requirement profile (does not sum up 1) and not a normalised heating demand profile, so the actual profile will be decided by the optimisation model (that is the reason is not shown here), without violating the minimum production constraint (dotted line in Figure 4) and meeting the same daily demand as in the other case studies.

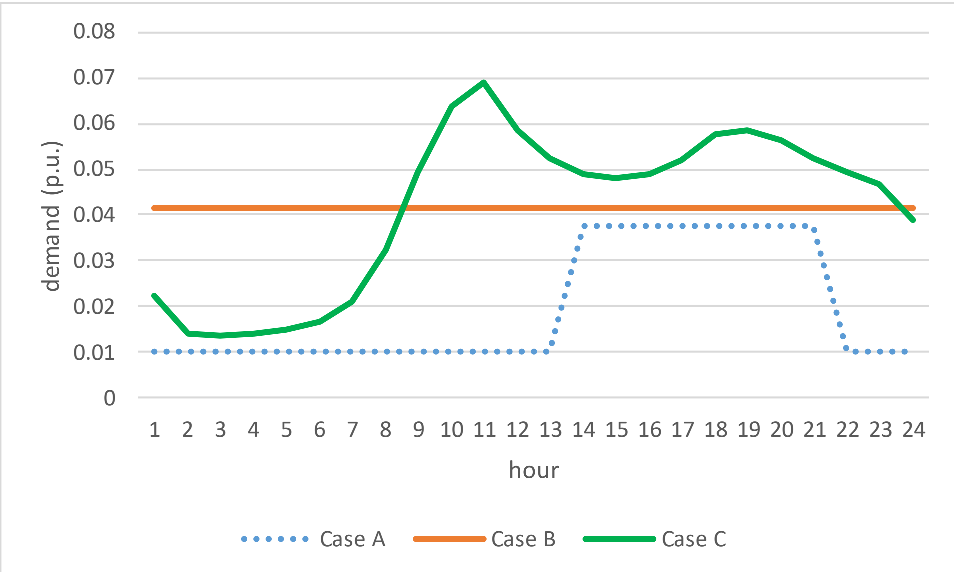

Figure 4. Normalized residential heating demand curves for case studies B and C, and minimum heating demand requirement for case study A.

Other required parameters have been summarized in Table 2 (with data taken from [19]), including the contracted power tariffs to be paid by each household (access tariffs), the thermal energy cost (in the form of natural gas) and the equivalent electric network cost (related to operation and maintenance, distribution and transmission costs, taxes, etc. [20]), to be paid in addition to the cost of the energy bought from the market (according to [21], the network cost and taxes represents about 60% of the tariff). Note that the electricity price will be the resulting price of the market (an output of the model), and it is not included here.

Table 2. Power tariffs and thermal energy pricing.

Access tariffs (Power)	Price
Electric (Annual)	38043 (€/MW)
Thermal (Annual)	106.08 (€/Client)
Natural gas tariff:	74.3 (€/MWh)
Electric network costs share:	44.02 (€/MWh)

The heat pump's coefficient of performance (COP) has been assumed in 2.5 units, which is considered the average COP throughout the year [22]. Indeed, the COP of an HP system varies constantly as a function of the difference between indoor-outdoor temperatures. Therefore, the COP is expected to be smaller in winter time, and larger in summer time [23]. However, given the long-term scope of this study, it is considered that the average value used deliver sensible results.

Lastly, to analyse the effect of energy efficiency, two heating demand scenarios have been analysed:

- Scenario 1: no energy conservation measures.
- Scenario 2: energy conservation measures implemented for a 20% heating demand reduction.

The first scenario represents the current state of the households, where no energy efficiency measures have been implemented, and the second scenario presents a 20% heating demand reduction (relative to the values shown in Table 1). This value have been selected as the average energy savings potential of retrofitting measures, such as double glazing and external wall insulation, in a typical household [24]. Note that the costs of the energy efficiency measures are not considered in this study. However, it is recognised the importance of such costs for a more detailed affordability analysis, which is expected to be developed in the future (see section 5.3).

5. Results and discussion

5.1. Discussion and case study comparison

The results of the case studies for both energy efficiency scenarios are presented in Table 3. As expected, all case studies increase the electric energy and power costs, relative to the base case, and the gas energy and access tariff cost disappear, as the HP system now provides all the heating demand. Note that the annual electric demand increase for all case studies due to HP operation is 64% relative to the base case, and approximately 9% of the total energy system demand (considering all sectors).

As would also be expected, these results show that case study A presents the smallest electricity costs increments and case study C presents the largest increments (e.g. 63% energy cost increment in Sc1 for case study A, whereas case study C presents 129% increment for the same scenario). This suggests that the less constrained HP operation in case study A allows the system to take advantage of cheaper off-peak prices, while in case study C the largest heating demands correspond with peak price periods. Case study B, with its flat energy profile, distributes the heating demand evenly to both off-peak and peak hours, and thus, the costs increments fall between those of case studies A and C (these effects are analysed in detail in section 5.2). Note that for the total energy costs case study A shows a reduction of almost 5% (in Sc1), unlike case studies B and C that exhibit increases of 17% and 33%, respectively. This shows that an optimal management of heating systems, sensitive to electricity prices, can significantly mitigate the additional costs of electricity. Nevertheless, it is important to remark that the HP operation in case study A, could be unrealistic in a real residential setting (see for example Figure 5) so this benefits on cost could be smaller than expected. To allow a HP operation such as this one, there will be need of a highly thermal efficient building with high thermal inertia, and thermal storage systems such as well insulated hot water storage tanks, to be able to preserve the heat inside the house and shift the heating loads in time, as shown in [5] and [25].

The energy costs for Sc2, presenting 20% heating demand reduction due to energy efficiency, are lower than those of Sc1. The biggest reduction appears in case study C, changing from 32.7% to 11% of extra cost (21.7 points of difference) relative to the base case. Case studies A and B also presents lower costs, but the difference between both scenarios is smaller: 8.5 and 14.5 points, respectively. These results show that energy efficiency measures alleviate the increment in costs due to the electrification of heating, especially in the case where the thermal demand behaviour does not change (case study C). Moreover, higher energy efficiency on buildings preserves the heat inside better, allowing shifting of the thermal load, at least partly (through preheating building thermal mass), to lower price hours [6]. In other words, HP operation profiles such as the one presented in case study A (see Figure 5) are more likely to be feasible with the presence of energy conservation measures, further mitigating the costs of electrification.

Table 3. Energy cost results and comparison with the base case.

	Base case	Sc1: No Energy Eff. Case A	Case B	Case C	Sc2: 20% Energy Eff. Case A	Case B	Case C
Elec energy costs	106920	174210	215130	244810	159210	187790	203460
Change %	*0%*	*63%*	*101%*	*129%*	*49%*	*76%*	*90%*
Elec. power costs	8115	9420	11015	11562	8115	10435	10873
Change %	*0%*	*16.1%*	*35.7%*	*42.5%*	*0.0%*	*28.6%*	*34.0%*
Gas energy costs	77275	0	0	0	0	0	0
Change %	*0%*	*-100%*	*-100%*	*-100%*	*-100%*	*-100%*	*-100%*
Gas access tariff costs	849	0	0	0	0	0	0
Change %	*0%*	*-100%*	*-100%*	*-100%*	*-100%*	*-100%*	*-100%*
Total	193159	183631	226145	256372	167326	198225	214333
Change %	*0%*	*-4.9%*	*17.1%*	*32.7%*	*-13.4%*	*2.6%*	*11.0%*

The average change in electricity prices and the maximum price change due to the electrification of heating have also been computed. The average price change has been computed with (19), whereas the average of the original prices has been computed with (20), and the maximum price change is calculated using (21).

$$vAvgPriceChange = \frac{\sum_m \sum_h \left(\frac{vPriceNew_{m,h} - vPriceOriginal_{m,h}}{vAvgPriceOriginal}\right)}{m * h} \tag{19}$$

$$vAvgPriceOriginal = \frac{\sum_m \sum_h \left(vPriceOriginal_{m,h}\right)}{m * h} \tag{20}$$

$$vMaxPriceChange = max\left(\frac{vPriceNew_{m,h} - vPriceOriginal_{m,h}}{vAvgPriceOriginal}\right) \tag{21}$$

Table 4 shows the average and maximum price changes for all case studies and scenarios. Looking first at the average values, the difference between case studies is relatively small. Also, it can be seen that for all cases and scenarios, there is an average increase of prices due to the extra electric load from the HP systems. Indeed, the increase in electricity market prices on Sc1 is around 14% and on Sc2 is around 11%. These increases impact not only on those households that directly benefit from the installation of the HP systems, affecting their own costs (see Table 3), but also for all the other residential customers and industry as well, which are indirectly affected by higher energy costs.

Analysing the maximum price changes, it can be seen that for both energy efficiency scenarios, case study A has the largest change, followed by case study C, and case study B exhibiting the smallest change. Certainly, case study A presented the largest hourly price change due to the "free" HP operation. Case study C also has an important peak in the thermal profile load (see Figure 4), producing a significant price increment, but not as large as those in case study C. Lastly, case study B does not present any peaks in its thermal profile, so the maximum price change is smaller than in other case studies, but is more constant throughout the day, having a slightly larger average price change. These price changes can be clearly seen in section 5.2.

Table 4. Electricity market price changes.

	Average price change			**Max. price change**		
	case A	**case B**	**case C**	**case A**	**case B**	**case C**
Sc1: No Energy Eff.	14%	15.2%	14.1%	67.2%	39.5%	50%
Sc2: 20% Energy Eff.	11.2%	12.3%	11.4%	59.9%	31.5%	40.9%

It is important to remark that all market participants affect the market price since they move the clearing point on the RDC by buying or selling energy. This is true even for relatively small agents, if the slopes of the RDC faced are large, they can have large impacts on the price (as shown in [26] and [27]). Hence it could be considered that a price-taker approach for an analysis such as the one considered in this paper would deliver inaccurate outcomes.

Nevertheless, to further analyse the usefulness of the price-maker model, the electric energy costs obtained with this model are compared with the equivalent costs that could be obtained with typical Spanish residential tariffs and with the final electricity market prices seen as a price-taker (considering that the energy transactions made by the residential clients do not affect the energy price). The residential tariffs considered are a flat tariff (same price all day) taken from [28] , and a time-of-use tariff (TOU) taken from [29], as shown in Table 5.

Table 5. Conventional residential tariffs for comparison purposes.

	Peak	**Mid-peak**	**Off-peak**
Flat tariff (€/MWh)		117.99	
Time schedule		0-24h	
TOU tariff (€/MWh)	163.2	84.3	56.4
Time schedule	13-22h	7-12, 23-24h	1-6h

The differences on electric energy costs of the case studies analysed with these residential tariffs and the market prices (as a price-taker) in comparison with the price-maker results is summarised in Table 6. The flat tariff presents around 24% higher costs than the price-maker ones. Note that the flat tariff does not discriminate the time of day so the electricity costs are the same for all case studies under this tariff, and consequently, case study A with the lower costs in the price-maker model has the higher difference with this tariff while case study C, with largest cost in the price-maker model, present the smaller difference here. Conversely, the time-of-use tariff with off-peak, mid-peak and peak prices, somehow replicates the market price curves, so the case study A with relatively larger consumption in the off-peak hours and less on the peak hours presents the lower costs and the lower difference with the equivalent price-maker results, whereas case study C has the largest difference due to its high energy consumption in peak time (see section 5.2 for further detail on the consumption behaviour). Lastly, the energy costs with the original market prices (as a price-taker) are around 14% lower than the those of the price-maker model. This is expected as the higher electric load due to the HP systems tend to increase the electricity prices (see Table 4), an effect that is not considered in the price-taker approach.

Table 6. Comparison of price-taker and price-maker results (Sc1)

	Energy cost change relative to price-maker model(%)		
	A	**B**	**C**
Flat tariff	26.7%	24.7%	22.7%
TOU tariff	24.0%	26.5%	29.7%
Price-taker market prices	-14.5%	-13.2%	-13.8%

This comparison in energy costs show that an error is expected if a price-taker approximation is used instead of a price-maker one (considering that a large number of residential clients are using HP systems, as in this study). This can be clearly seen when market prices are used, but the price changes due to increased electric load are not considered (price-taker), producing an estimation error of about 14%. Estimating energy costs with conventional residential tariffs also presented a significant difference regarding the price-maker approach, with around 25% higher energy costs. Thus, the importance of considering the impact on energy prices when a large-scale electrification of systems such as heating or transport is expected.

5.2. System behaviour examples at different seasons

This section shows examples of HP operation profiles of the different case studies and its impact on energy prices. For the sake of brevity, only two out of the twelve representative days have been illustrated (one for winter and one for summer). Figure 5 and Figure 6 show operation profile examples for winter and summer, respectively, for Sc1. In Figure 5, the off-peak time is in the early morning, where the original energy price (blue solid line) is lower, and the peak time is from 16h to 24h (higher prices).

As mentioned before and shown in Table 4, case study A present the largest hourly changes. Figure 5a shows that a large amount of HP production (dotted purple line) is done in the off-peak hours, increasing considerably the energy prices (red solid line). There is also HP operation during peak hours, but it is not as large as in the morning (the difference between the original load and the new load is smaller at peak hours, see the dotted lines in Figure 5a) so the price increment is not as significant. Note that this behaviour tends to flatten the energy price curve (red line in Figure 5a), so the difference between peak and off-peak prices is considerably smaller (around 38% difference, in comparison with the original 64%). Case study B, with its flat HP operation profile, creates an almost constant price increment throughout the day (see in Figure 5b). Lastly, case study C presented a heating profile very similar to the electrical energy profile (see Figure 1 and Figure 4). Hence, the energy price change is small in the early morning (off-peak time), but it increases in the middle of the day and in the evening (peak time). Note that this profile does the opposite of case study A: instead of flattening the price curve, it increases the difference between peak and off-peak loads, and consequently prices. Indeed, case study C presents a peak price change up to 35% at 20h and an off-peak price change around 8% at 2-5h (see Figure 5c), also the difference between the smallest and largest prices is 65%. This is an effect that should be taken into account as it might affect the power generation on the supply side, changing the requirements and merit order of some power plants.

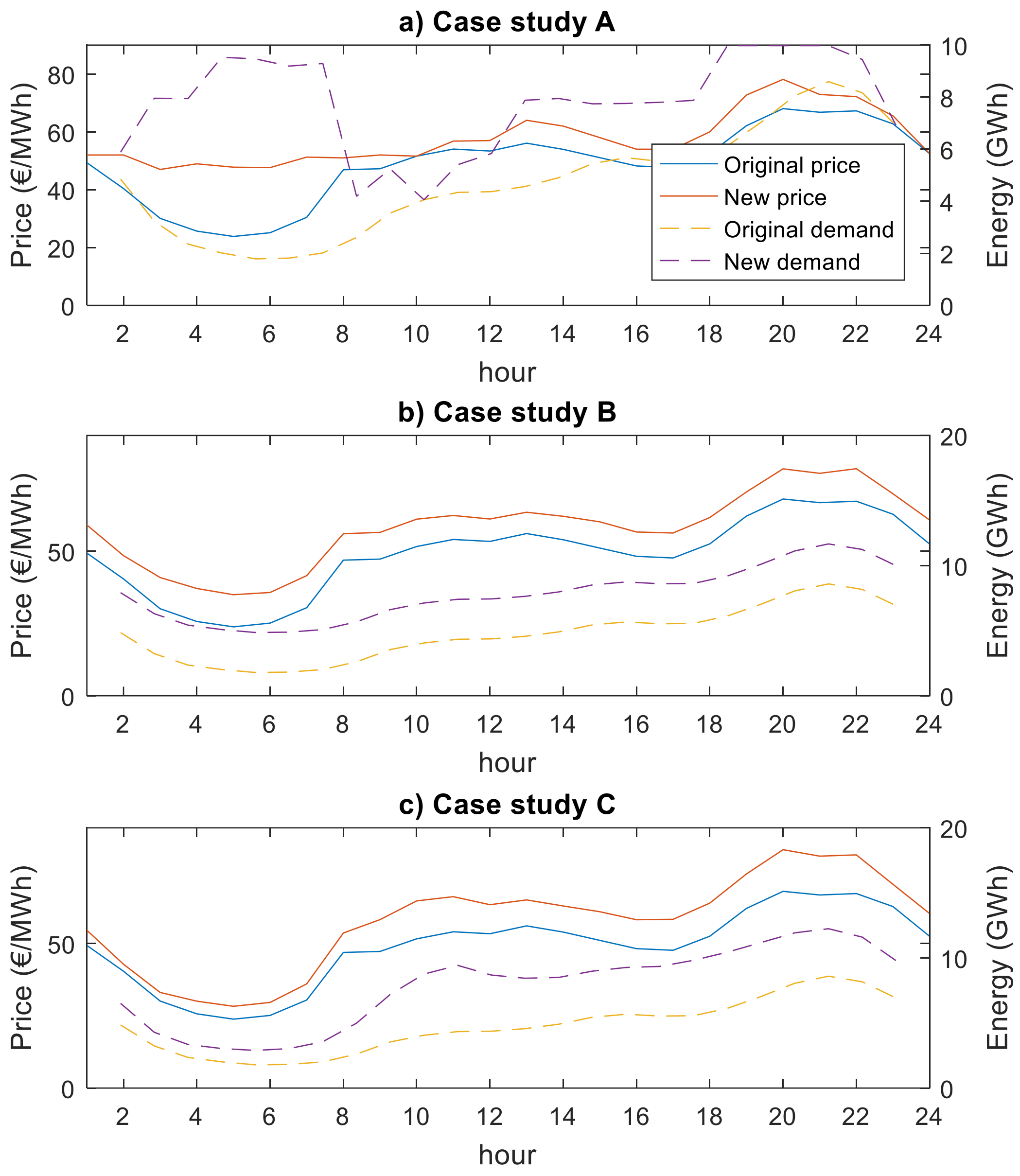

Figure 5. Energy transactions and effect on energy prices for the representative day of January (Sc1).

Figure 6 shows the representative summer day. For this day, the original price curve (blue line) is flatter than the one in winter. Nevertheless, the HP operation and the effect on prices is similar, especially in case studies B and C. Case study A presents once more larger thermal production in the early hours, flattening the price curve (red line Figure 6a).

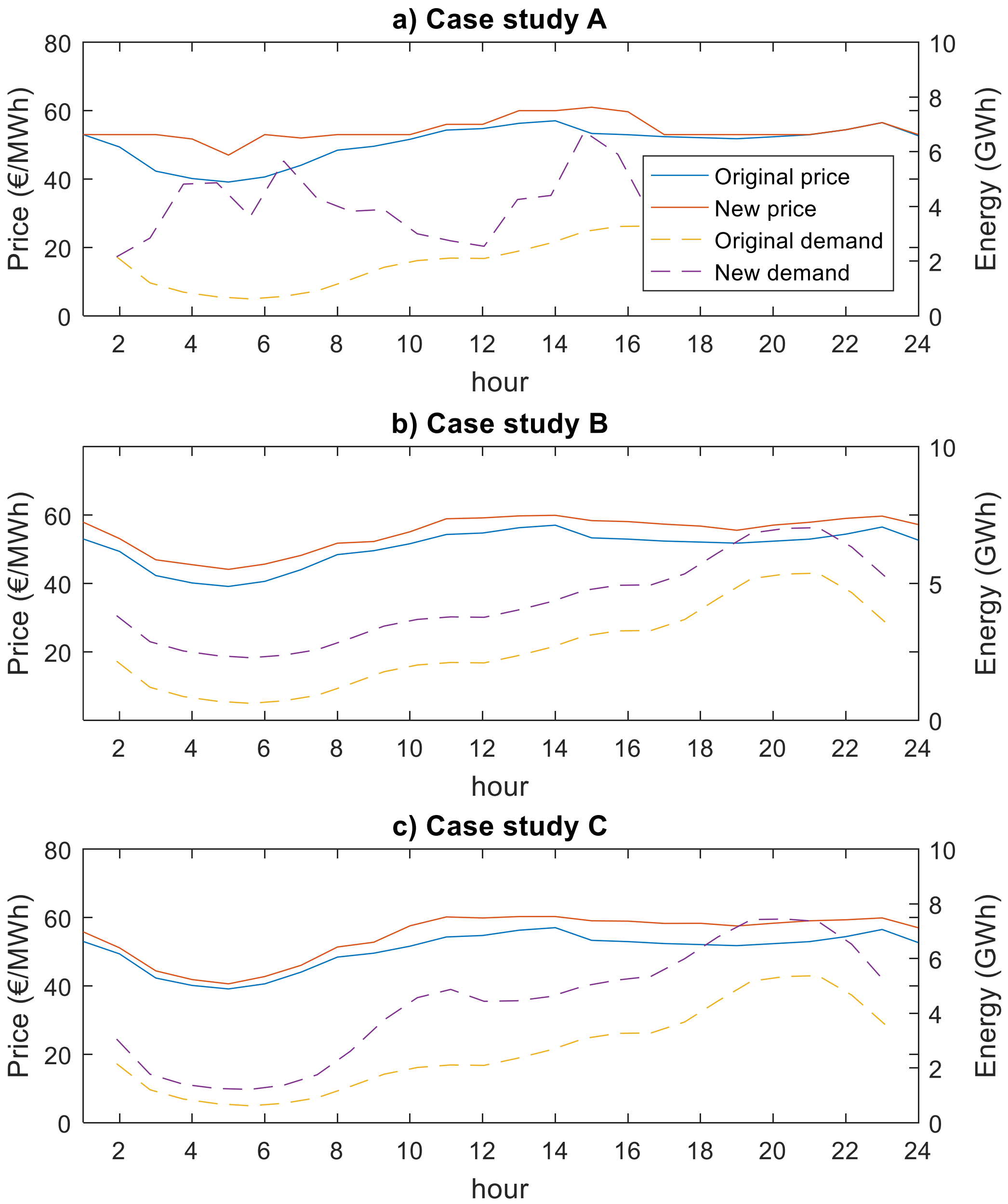

Figure 6. Energy transactions and effect on energy prices for the representative day of July (Sc1).

The behaviour of the residential clients for Sc2 is shown in Figure 7 and Figure 8, representing typical winter and summer days, respectively. In this scenario energy efficiency measures have been implemented, so the thermal energy requirements are 20% lower, so the effect on prices is slightly smaller (see also Table 4). However, note that the overall behaviour of all three case studies is consistent with that of Sc1, but with slightly smaller peak loads. For instance, in case study A, Sc1, the electric demand reached the 10GWh (Figure 5a), while in Sc2 goes up to 9GWh (Figure 7a) due to the energy demand reduction.

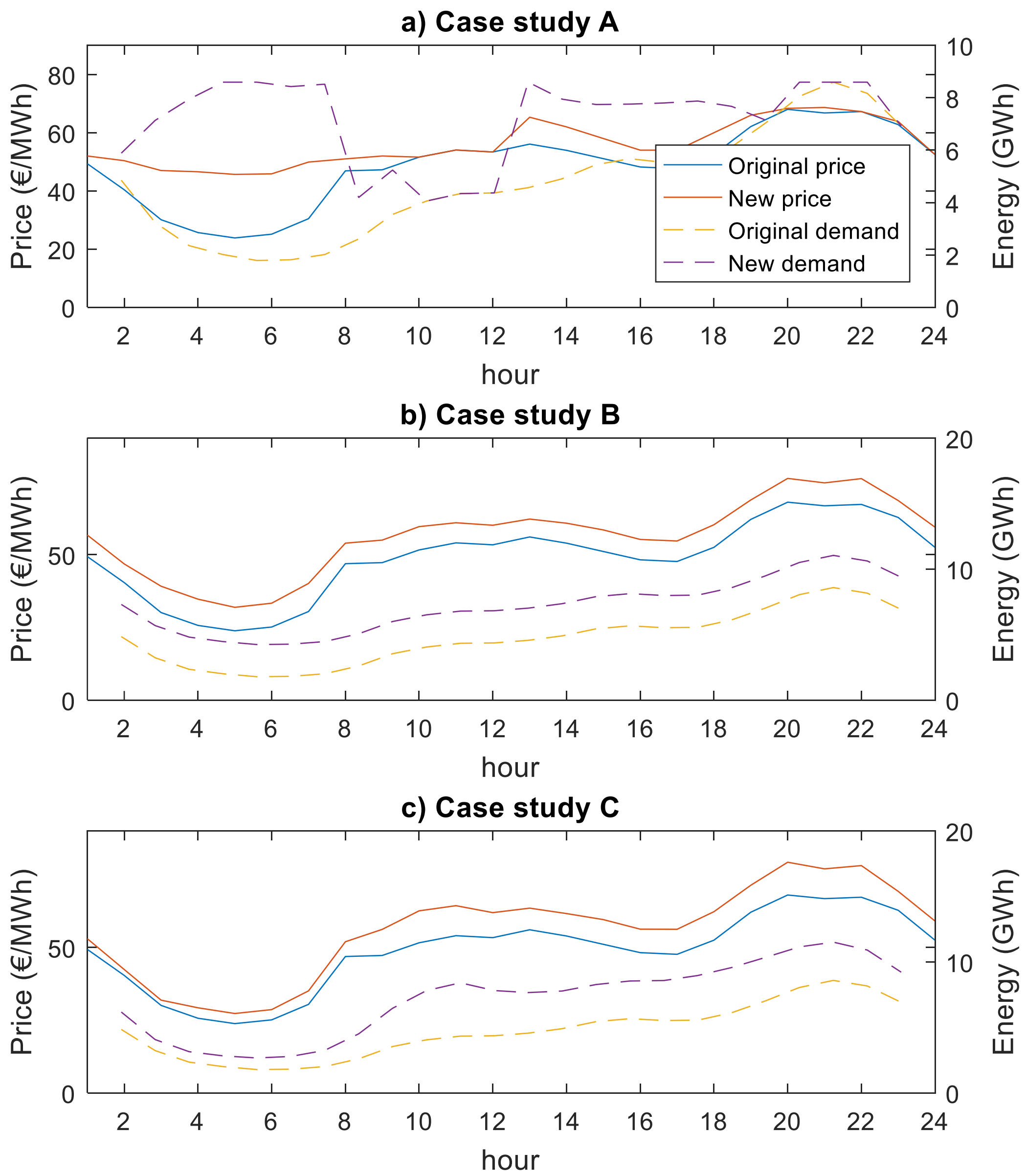

Figure 7. Energy transactions and effect on energy prices for the representative day of January (Sc2).

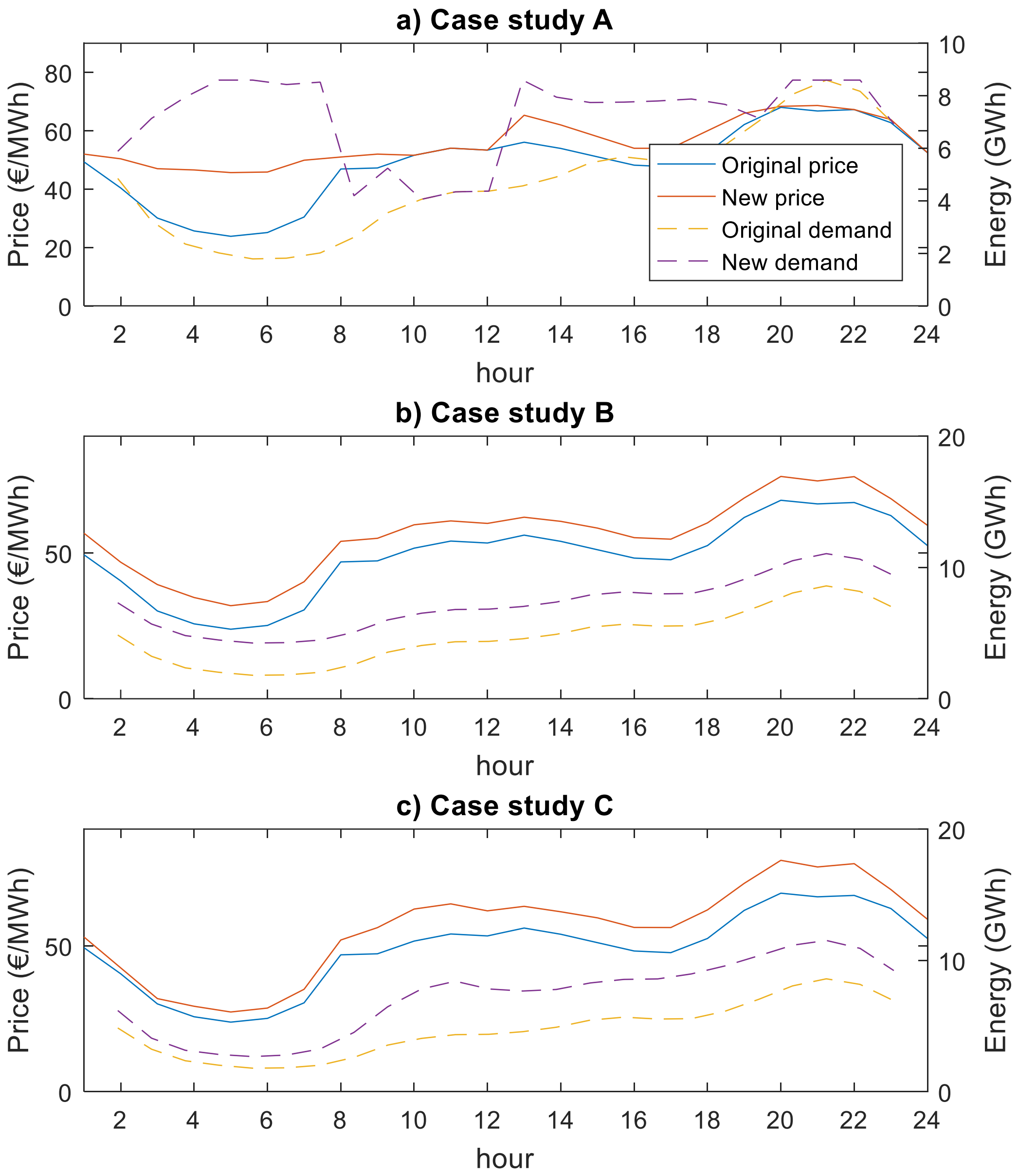

Figure 8. Energy transactions and effect on energy prices for the representative day of July (Sc2).

5.3. Limitations and future work

The analysis developed in this paper intends to be a first step on analysing the implications of a wider electrification of heating on market prices and energy affordability, and to show an example of the potential use of the methodology proposed. However, there are some opportunity areas and limitations, such as the COP average value (lacking seasonal variability) and the homogeneous and somehow artificial heating demand profiles. More realistic representation of these parameters would deliver more accurate operation of the HP systems and thus, the electricity demand change and the market price change computation would be more reliable. Moreover, including technology costs will deliver a better assessment of the actual costs of implementing these systems for the final consumer.

Therefore, the next steps for this analysis include (but not limited to) the following:

- Updated and more heterogeneous heating demand profiles
- Better seasonal representation of the coefficient of performance for HP systems
- More accurate representation of energy efficiency scenarios, analysing the effect of buildings' thermal inertia and thermal storage in HP operation
- Add investment costs for HP systems, thermal storage, and energy conservation measures, for a detailed profitability analysis of such systems
- Adapt all data to analyse the Scottish and UK contexts

6. Concluding remarks

The impact of electrification of heating and energy efficiency measures on electricity market prices has been analysed in this paper, using a price-maker mixed integer linear programming problem. Even though the price-maker model used is a simplified representation of the market (other agents' reactions to new prices are not considered), it provides potentially useful insights on the expected energy cost changes due to the electrification of heating and potential savings due to residential energy efficiency measures, not only by straightforwardly reducing electric demand, but also by allowing a smarter heating management, which could be done with the assistance of energy conservation measures and thermal storage.

Results show that the electrification of services such as heating increases electricity prices, directly affecting the affordability of such services for consumers. In this study, a cost increment of up to 32.7% was found. In addition, the effect on the energy price change due to the heating profile was also analysed. The conventional heating profiles, with higher demand in the evening and lower demand overnight, partly coincides with the typical electricity market price curves. Therefore, the extra load, especially in peak hours, tends to increase the peak price (approximately 35% in this analysis) and the difference between off-peak and peak prices (off-peak price is approximately 65% lower than peak prices). Conversely, an 'optimal' heating demand profile, able to choose (within certain limits) the best time to produce heat according to the market price, tend to flatten the energy price curve. These effects are likely to impact the supply side, potentially changing the merit order of generators. With a flatter demand, there is less need to shut down and start up generators, and generators can work at their optimal performance, improving efficiency.

It is important to remark that for relatively small numbers of clients (a few thousands) a price-taker approach could be used to achieve sensible energy cost results (due to the small impact on market prices). However, when a large-scale change on the system is expected, such as the electrification of heating or transport, a price-maker model is likely to give more realistic outcomes. In this paper, an equivalent price-taker market methodology presented around 14% difference in energy costs relative to the price-maker results, and around 25% difference if conventional residential tariffs were used. These differences should be taken into account as they could translate to inaccurate assessments.

The outcomes obtained provide insight on some of the economic challenges of heating electrification. This insight could be relevant for policy makers and stakeholders, to understand better the potential impacts of decarbonisation of services and energy efficiency measures in the residential sector, also providing awareness on potential conflicting targets, such as decarbonisation of heat vs energy affordability.

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