7th International Conference on Advances on Clean Energy Research, ICACER 2022 April 20–22, 2022, Barcelona, Spain

Energy and economic analysis of domestic heating costs based on distributed energy resources: A case study in Spain

Olaia Eguiarte[a,b,*], Pablo de Agustín-Camacho[a], Luis del Portillo-Valdés[b]

[a] *TECNALIA, Basque Research and Technology Alliance (BRTA), Derio, Spain*
[b] *ENEDI Research Group, Thermal Engineering Department, University of the Basque Country (UPV/EHU), Bizkaia, Spain*

Abstract

Energy electrification is part of the European strategy for the decarbonization of the building sector and energy transition in cities. The present paper compares the heating costs of covering the heating demand by different systems: (i) domestic gas boiler and an air-to-air heat-pump, (ii) without and (iii) with local PV backup; in order to analyze the effects of the electric price volatility along with the weather condition dependency of the renewable systems. The study presents a heat pump model and a PV generation model to estimate the hourly performance of both systems. These models are then applied in an average dwelling in Bilbao, Spain, in November 2020, and November 2021. Results show that in November 2020 the combined use of a heat pump with PV generation to cover the heat demand was 66% cheaper than covering the same demand with a natural gas boiler. By contrast, the combined use of the PV and heat pump resulted in a 15% higher energy bill compared to the natural gas in 2021 due to the increase of the electricity prices (3 times higher), the lower temperatures (25%) and less solar radiation (70%).

1. Introduction

Because of the weight of the energy consumption of the building sector in EU's, the EU established a legislative framework updating the Energy Performance of Buildings Directive (2018/844) [1] and the Energy Efficiency Directive (2018/2002) [2], seeking to promote a high energy efficient and decarbonized building stock by 2050.

As part of the decarbonization strategies, the mentioned directives promote the use of renewable energy resources to cover the residential energy demand, with special interest in heat pumps as an alternative for space heating. Additionally, the EU is also widely promoting the figure of the prosumer. Prosumers are small consumers who are also producers of electricity for their own consumption or participation on the market [3].

---

* Corresponding author at: TECNALIA, Basque Research and Technology Alliance (BRTA), Derio, Spain.
  E-mail address: olaia.eguiarte@tecnalia.com (O. Eguiarte).

Several studies can be found along the state-of-the-art demonstrating the feasibility of the combined use of heat pumps and PV (Photovoltaic) generation system [4,5]. Rinaldi et al. [4] show that heat pumps do not only decarbonize heat but also increase local PV self-consumption. Moreover, Schreurs et al. [5] demonstrate that replacing gas heating with heat pumps and PV in European multifamily houses reduces CO_2 emissions. De Agustín-Camacho [6] points out how the coupling between generation and demand, on off-grid or without surplus compensation schemes, conditions the exploitation share of a domestic PV facility.

However, European electricity market entered a period of unprecedent change in 2021 reaching new price records day after day. This has exposed electric market's volatility, which is directly dependent of the gas, coal and CO_2 prices; renewables intermittency; and demand uncertainty from electric vehicle charging for example [7]. This volatility can endanger EU's electrification strategy when heat pumps become more expensive to use discouraging consumers to switch their heating system.

In consideration of all the above, the proposed study presents a comparison of the heating costs of covering the heating demand through different technologies: (i) domestic gas boiler and an air-to-air heat-pump, (ii) without and (iii) with local PV backup. The heating costs are calculated hourly taking into account the outdoor weather conditions and regulated energy market prices. Moreover, a physical model of the HP has been developed to obtain the hourly performance according to the outdoor temperature, and the PV generation is also hourly estimated. As an application case, the methodology is applied on a dwelling in Bilbao, Spain, in November 2020 and 2021.

2. Methodology

In order to analyze the economic feasibility of the combined use of PV and HP to cover the heating demand of a household different modules have been developed. Those modules allow the estimation of the heating demand, electric consumption, and PV generation in an hourly basis considering the weather conditions, the electric tariff, and the performance of the systems. Outdoor weather conditions, temperature and horizontal radiation, are obtained from the open-source Basque meteorological agency [8]. Moreover, selected tariffs have an indexed price (Real-Time-Pricing combined with Time-of-Use periods) regulated by the Spanish government.

2.1. Heating demand

The hourly heating demand is calculated using a simplified method, as described in [9]:

$$Q_T = UA_{efec} \cdot (T_{in} - T_{out}), \tag{1}$$

Where the heating demand (Q_T) is determined by the overall heating transfer coefficient (UA_{efec}), the indoor temperature (T_{in}) and the outdoor temperature (T_{out}). For this study, it is assumed the indoor temperature is maintained to a constant comfort value of 20 ºC.

2.2. Heat pump model

A heat pump model was developed using the EES (Engineering Equation Solver) software. Such model calculates the hourly COP of the heat pump considering the outdoor temperature at each time [10,11].

2.3. PV generation

The hourly PV generation injected into the domestic grid is estimated as:

$$P_{PV} = A \cdot I_T \cdot \eta_c \cdot \eta_{system}, \tag{2}$$

where, A is the area, I_T the total radiation, η_c the modules efficiency and η_{system} the overall efficiency of the system. Total solar radiation and modules efficiency are hourly estimated as follows:

- First, the metered horizontal radiation (I) is obtained from the nearest weather station to the selected location [8]. Then, the HDKR (Hay, Devies, Klucher, Riendl) [12] anisotropic model is applied to calculate the total radiation on a tilted surface (I_T). The model assumes that the total radiation is the sum of the beam, ground reflected and diffuse (isotropic, circumsolar, horizon brightening components) radiation.

To calculate those components, it is necessary to obtain the hourly horizontal extraterrestrial radiation (I_o) and the clearness index (k_T). The former is calculated as:

$$I_o = \frac{12 \cdot 3600}{\pi} \cdot G_{sc} \cdot \left(1 + 0.033 \cos \frac{360n}{365}\right) \cdot \left[\cos \varnothing \cos \delta \left(\sin \omega_2 - \sin \omega_1\right) + \frac{\pi \left(\omega_2 - \omega_1\right)}{180} \sin \varnothing \sin \delta\right],$$

(3)

where G_{sc} is the solar constant, n the day of the year, $\varnothing$ the latitude, δ the declination and, ω_i the hour angle. The latter, is calculated dividing the metered radiation I and the extraterrestrial radiation I_o and I:

$$k_T = \frac{I}{I_0}.$$

(4)

This particular model is chosen because despite of being a simple model the obtained results are close to measured values as stated in [13,14].

- Finally, PV module's efficiency is estimated as a function of the cells temperature [15]. Furthermore, cell temperature is calculated following the equation proposed by Duffie and Beckman in [12]. If both elements are combined, constant values integrated, and wind speed is assumed as an average value, the following equation is obtained for the selected panels (datasheet [16]):

$$\eta_c = 0.20 - 1.77 \cdot 10^{-5} \cdot I_T - 7.14 \cdot 10^{-4} \cdot T_{out},$$

(5)

where, I_T is the total radiation and T_{out} the outdoor temperature.

3. Case study

The methodology is applied to an average dwelling in Bilbao, Spain, of 80 m^2 which thermal characteristics are explained in [10]. Calculations are made to evaluate the heating costs of November for both 2020 and 2021. For both years, the electric heating costs of the heat pump, with and without adding a self-consumption PV solar system, are compared to cover the same heat demand with a conventional natural gas boiler, the most widely used system [17] in the country.

A summary of the main characteristics can be found in Table 1.

Table 1. Characteristics of the case study.

	Nov 2020	Nov 2021
UA_{efec} (W/K m^2)	5.07	5.07
Mean temperature (ºC)	14.54	10.9
Total radiation (kWh/m^2)	90.7	53.67
Natural gas boiler efficiency (%)	90	90
Natural gas price (c€/kWh)	3.732 [18]	4.128 [19]
Electric tariff type	RTP 2 periods	RTP 3 periods
mean value (c€/kWh) [20]	8.41	25.16
PV installation (kWp)	1.2	1.2
Slope (°)	35	35
System efficiency (%)	97	97
Mean PV surplus compensation price (c€/kWh) [20]	4.17	19.32

It is important to point out several aspects for a sound understanding of the results of the study. On the one hand, even though the study is done for the same month of the year, the weather conditions are noticeably different. Mean temperature of 2020 was 2 ºC higher compared to normal climatological values. In 2021, by contrast, mean temperature was 1.5 ºC lower than normal values [21]. A similar phenomenon happened with the solar radiation with 70% more radiation in 2020 than 2021.

On the other hand, electricity prices have drastically increased from one year to another, being 3 times higher in 2021. Several market, geographic and political factors have altered these prices which are breaking records every day [22]. However, these factors have not affected in the same scale the natural gas prices, for which the regulated consumer price has just increased 10% in 2021. Additionally, regulated electric tariffs changed on June 2021 from a two-period RTP tariff to a three-period RTP tariff.

4. Results and discussion

In the following subsections obtained results are analyzed in detail highlighting the most relevant aspects. Finally, in Section 4.3 total results are displayed.

4.1. November 2020

Fig. 1 shows the hourly costs of covering the heating demand with the different systems throughout the first week of November 2020. Those moments where the values are 0 mean that there is no heating demand.
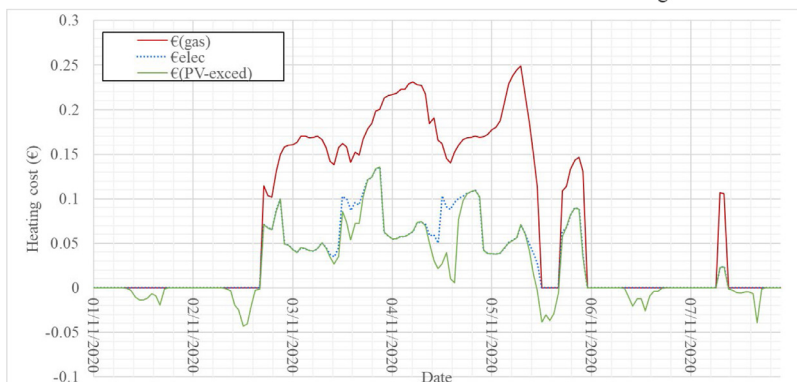

Fig. 1. Natural gas (Red line), heat pump (Blue line), and heat pump with PV (Green line) hourly heating costs of the first week of November 2020 with the different systems.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Covering the heating demand of the first week of November 2020 with a natural gas boiler is always more expensive than covering it with a heat pump with a maximum hourly cost of 0.25€(05/11/20 at 7:00). At the same time, since the electric price is still in night period, along with the higher efficiency of the heat pump compared to the boiler, the electric cost is 0.07€. The results also show that in the central hours of the day electric costs are reduced when adding PV generation to the system. Moreover, when there is no significant heating demand the solar generation is economically compensated (negative values of the green line).

4.2. November 2021

Fig. 2 shows the hourly costs of the different systems throughout the first week of November 2021.
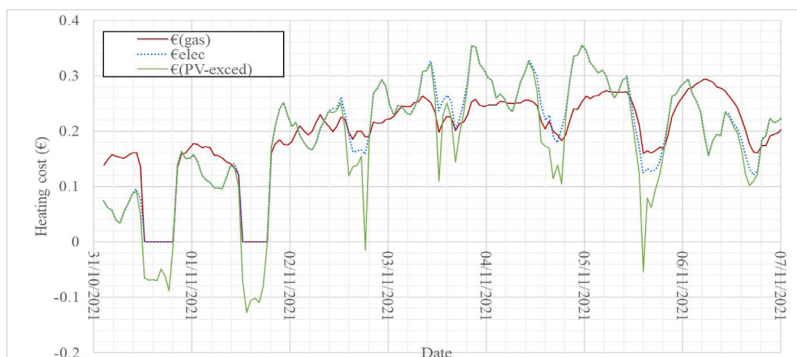

Fig. 2. Natural gas (Red line), heat pump (Blue line), and heat pump with PV (Green line) hourly heating costs of the first week of November 2020 with the different systems.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Unlike for the 2020 results, the higher efficiency of the heat pump does not compensate the high electricity prices of November 2021. For that reason, covering the heating demand with a heat pump is only cheaper when the temperatures are high, and the electricity prices are low. During central hours of the day, the PV generation also benefits the reduction of the electric cost. In fact, it is even economically compensated the few hours this generation is bigger than the electricity consumption.

4.3. Total results

Finally, total results are shown (Table 2) and discussed in the present section.

Table 2. Total results of November 2020 and 2021 of covering the heating demand with a natural gas boiler, a heat pump, and a heat pump with PV generation.

	Nov 2020	Nov 2021
Total heating demand (kWh)	1410.11	2611.06
Total PV electricity generation (kWh)	105.60	64.03
Total natural gas consumption (kWh)	1566.79	2901.17
Total electric grid consumption with the heat pump (kWh)	382.78	716.44
Total electric grid consumption with the heat pump + PV systems (kWh)	357.08	672.85
Total cost with the natural gas boiler (€)	70.71	144.63
Total cost with the heat pump (€)	29.97	183.04
Total cost with the heat pump + PV system (€)	24.11	168.86

As explained in the case study, the selected months have several differences in terms of weather and energy prices, which are reflected in the obtained results. First, the total heating demand of 2020 was 1410.11 kWh while in 2021 the demand was 85% higher, 2611.06 kWh. The total electricity generated with the PV panels was 105.6 kWh in 2020 and 64.03 kWh in 2021 because of the less solar radiation.

If energy consumptions are evaluated, it can be seen that both years the gas consumption is significantly higher than the electric consumption, both with and without the PV panels. In 2020, natural gas consumption was 4 times higher compared to the electric consumption of the heat pump, and 4.4 higher if the heat pump is combined with a PV system to cover the heating demand. Similar proportions are obtained in the energy consumptions of 2021.

It is important to mention that not all the PV generation is directly used by the heat pump. In 2020, only 24% of the electricity generated by the solar system was self-consumed, 25.7 kWh, and the remaining electricity was fed into the grid and economically compensated, 79.9 kWh. In 2021 up to 68% of the generation was self-consumed.

Despite those proportions are similar in both year, these are not translated in the economical results. In 2020, the natural gas bill was in the amount of 70.71€, while the electric bills were 29.97€ and 24.11€, without and with solar generation respectively; this is, 60% and 66% less. In 2021, however, both electric bills were more expensive than the natural gas. Total natural gas cost for the whole month was 144.63€, 22% less than using a heat pump to cover the same heating demand, 183.04€. Furthermore, even if the use of the heat pump is combined with a PV system to reduce the electricity consumption from the grid, the electric cost is still 15% higher than the natural gas cost.

5. Conclusion

Electrification of the energy demand is part of the European strategy for the decarbonization of the building sector and energy transition in cities. This strategy could be jeopardized by electricity prices if the price hike occurred in the EU markets during the last quarter of 2021 is maintained. This study compares the heating costs of covering the heating demand by different systems: (i) domestic gas boiler and an air-to-air heat-pump, (ii) without and (iii) with a PV system in order to analyze the effects of the electric price volatility along with the weather condition dependency of the renewable systems.

Results show that in 2020 the combined used of a heat pump with PV generation to cover the heat demand was 66% cheaper than covering the same demand with a natural gas boiler. By contrast, the combined use of the PV and heat pump resulted in a 15% higher energy bill compared to the natural gas in 2021 due to the increase of the electricity prices. Those results stress out the importance of increasing local and distributed renewable energy generation against the price volatility of international and fossil-fuel dependent electric markets.

It is important to remark that increasing the size of the PV installation would not lead to a proportional increase on the self-consumption. Results show that in 2020 only the 24% of the electricity generated was self-consumed, while in 2021 68% was self-consumed. This is the result of the mismatch between solar generation and the heating demand. The former having its maximum during central hours of the day and the latter having its peak during night hours when there is no solar radiation.

There are several possibilities to reduce the effect of the mismatch between the generation and consumption. The installation of electric batteries would lead to increase the self-consumption of the system by storing the electricity surplus for its later use than injecting it to the grid. Furthermore, if solar electricity generation and the energy demand are estimated in advance, along with the day-ahead electricity prices, the energy consumption could be optimized exploiting the thermal flexibility of the building. Thus, heating load would be shifted to daylight hours increasing the self-consumption of the system while reducing heating costs.

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.

Data availability

Data will be made available on request.

References

[1] European Parliament. Directive (EU) 2018/ of the European Parliament and of the Council of 30 may 2018 amending directive 2010/31/EU on the energy performance of buildings and directive 2012/27/EU on energy efficiency. 2018.

[2] European Parliament. Directive (EU) 2018/ 2002 of the European Parliament and of the Council - of 11 december 2018 - amending directive 2012/ 27/ EU on energy efficiency. 2018.

[3] Parag Y, Sovacool BK. Electricity market design for the prosumer era. Nat Energy 2016;1:16032. http://dx.doi.org/10.1038/nenergy.2016.32.

[4] Rinaldi A, Soini MC, Streicher K, Patel MK, Parra D. Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation. Appl Energy 2021;282:116110. http://dx.doi.org/10.1016/j.apenergy.2020.116110.

[5] Schreurs T, Madani H, Zottl A, Sommerfeldt N, Zucker G. Techno-economic analysis of combined heat pump and solar PV system for multi-family houses: An Austrian case study. Energy Strategy Rev 2021;36:100666. http://dx.doi.org/10.1016/j.esr.2021.100666.

[6] Pablo de agustín camacho. Photovoltaic self-consumption heating system: Analytical model, experimental results and autonomy prospects. Universidad Carlos III de Madrid; 2015.

[7] Samseth E, Stockhausen F, Veillard X, Weiss A. Five trends reshaping European power markets. McKinsey & Company; 2021.

[8] Euskalmet | Agencia vasca de meteorología. 2021, https://www.euskalmet.euskadi.eus/inicio/. [Accessed 13 December 2021].

[9] Izquierdo M, Moreno-Rodríguez A, González-Gil A, García-Hernando N. Air conditioning in the region of Madrid, Spain: An approach to electricity consumption, economics and CO2 emissions. Energy 2011;36:1630–9. http://dx.doi.org/10.1016/j.energy.2010.12.068.

[10] Eguiarte O, Garrido-Marijuán A, de Agustín-Camacho P, del Portillo L, A. Romero-Amorrortu. Energy, environmental and economic analysis of air-to-air heat pumps as an alternative to heating electrification in Europe. Energies 2020;13:3939. http://dx.doi.org/10.3390/en13153939.

[11] Eguiarte O, de Agustín-Camacho P, Garrido-Marijuán A, Romero-Amorrortu A. Domestic space heating dynamic costs under different technologies and energy tariffs: Case study in Spain. Energy Rep 2020;6:220–5. http://dx.doi.org/10.1016/j.egyr.2020.11.112.

[12] Duffie JA, Beckman WA, Blair N. Solar engineering of thermal processes, photovoltaics and wind. John Wiley & Sons; 2020.

[13] Loutzenhiser PG, Manz H, Felsmann C, Strachan PA, Frank T, Maxwell GM. Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. Sol Energy 2007;81:254–67. http://dx.doi.org/10.1016/j.solener.2006.03.009.

[14] Padovan A, Del Col D. Measurement and modeling of solar irradiance components on horizontal and tilted planes. Sol Energy 2010;84:2068–84. http://dx.doi.org/10.1016/j.solener.2010.09.009.

[15] Evans DL, Florschuetz LW. Cost studies on terrestrial photovoltaic power systems with sunlight concentration. Sol Energy 1977;19:255–62. http://dx.doi.org/10.1016/0038-092X(77)90068-8.

[16] Datasheet: DualSun flash 300 black. 2020.

[17] Honoré A. Oxford institute for energy studies. Decarbonisation of heat in Europe: Implications for natural gas demand. 2018.

[18] Ministerio para la Transición Ecológica y el Reto Demográfico. Resolución de 29 de Septiembre de 2020, de la Dirección General de Política Energética y Minas, por la que se publica la tarifa de último recurso de gas natural. vol. BOE-A-2020-11426. 2020.

[19] Ministerio para la Transición Ecológica y el Reto Demográfico. Resolución de 26 de septiembre de 2021, de la Dirección General de Política Energética y Minas, por la que se publica la tarifa de último recurso de gas natural. vol. BOE-A-2021-15778. 2020.

[20] Welcome | ESIOS electricity · data · transparency. 2021, https://www.esios.ree.es/en. [Accessed 14 December 2021].

[21] Meteorología AE de. Bilbao aeropuerto: Bilbao aeropuerto - agencia estatal de meteorología - AEMET. Gobierno de españa. 2021, http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos. [Accessed 14 December 2021].

[22] Liboreiro J, Filippis de A. Why Europe's energy prices are soaring and could get much worse. Euronews 2021. 2021, https://www.euronews.com/2021/10/28/why-europe-s-energy-prices-are-soaring-and-could-get-much-worse. [Accessed 14 December 2021].