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Domestic space heating dynamic costs under different technologies and energy tariffs: Case study in Spain

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Abstract

Dynamic energy tariffs facilitate engaging domestic consumers on demand management, contributing to grid's stability, but requires of informed decision enabling tools. This paper presents a domestic heating costs calculation method for different heating technologies (gas boiler, heat-pumps) and a range of energy tariffs. Based on physical modeling, effect of outdoor temperature in the COP of heat-pumps is assessed. The methodology is applied to the 2018/19 heating season in Madrid (Spain), calculating the heating costs under four diverse energy tariffs (static gas tariff, static electricity tariff, real-time-price electricity tariff, dynamic time-of-use electricity tariff) for a typical home demand. The hourly results for two representative days are detailed, along with the aggregated results for the whole season. Along the season, the continuous changes in energy wholesale market prices and weather conditions make one heating technology and/or tariff more convenient each time. For the whole season, the dynamic time-of-use tariff considered would imply heating costs up to 40% lower than the static gas tariff. The results are strongly conditioned by climate conditions and national energy market evolutions. Day-ahead information on the actual heating costs might lead to domestic end-users to adapt their behavior and consumption patterns for more cost-effective use of the energy.

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Keywords: Consumer empowerment; Demand management; Dynamic tariffs; Heating costs

1. Introduction

Due to the well-known weight of building sector in EU's energy consumption and carbon footprint, and pursuing its energy and environmental goals, the EU has established a legislative framework recently 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, to create a stable environment for investments decisions, and to enable consumers and businesses to take informed choices to save energy and money.

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As part of the decarbonization strategy, the share of electricity generated from renewable sources in Europe increased to 30% of the total electricity consumption in 2018 ([3], n.d.). Thus, with a more decarbonized electricity, the electrification of building's energy demand would help to reduce Greenhouse Gas (GHG) emissions and mitigate global warming [4].

Focusing on the residential sector, where the heating represents the main share of energy consumption and which technologies are currently dominated by fossil fuels, several authors have demonstrated that GHG emissions are reduced using electricity based systems to cover the heating demand instead of conventional technologies [5–8]. Moreover, the mentioned directives promote the use of renewable energy resources to cover the residential energy demand, with special interest in Heat Pumps (HPs) as an alternative for space heating due to their better performance compared with common heating systems [9].

As a result of the large-scale integration of renewable energies, along with the electrification of the energy use, the European energy market is evolving towards more decentralized, less predictable and flexible operating models. Those changes require additional efforts to maintain the reliability and stability of the grid. Hence, an improvement of the energy management from the demand side is needed. Although commercial and industrial consumers are engaged in Demand Response (DR) programs [10], the medium/small tertiary and residential consumers are not such active players in the energy market [11]. Under this context, EU funded HOLISDER [12], in which framework the present work is included, aims to develop a set of components and tools to enable DR in this sectors, empowering end-users.

For the domestic consumers, one of the most common methods for their participation in demand management is the offer of different electricity tariff schemes to be chosen by the energy consumers. There are currently three main pricing schemes in the electricity markets [13]: Time Of Use (TOU) tariffs, which can be either static or dynamic (dTOU), Real-Time Pricing (RTP), and Critical Peak Pricing (CPP). TOU tariff is the simplest pricing scheme where the electricity prices are set in peak and off-peak hours, while dTOU tariff's particularity is that the level of the electricity prices changes regularly. In RTP tariffs, the price changes occur on an hourly basis based on the wholesale market.

Finally, the CPP involves raising the electricity prices significantly during specific periods of time, e.g. excessive demand. However, consumers require of interpretation of these dynamic tariffs and their implication in term of costs on domestic appliances, HVAC equipment and loads, in order to take informed decisions for their consumption patterns optimization. The costs of feeding constants loads as lighting or some appliances are proportional to their nominal power and time used, while some heating system, as heat-pump, present a weather dependent coefficient of performance (COP), which combined with dynamic energy tariffs lead to a not clear relation of costs for non-technical consumers.

In consideration of all the above, the proposed study presents a method to calculate the costs of satisfying the heating demand through different technologies (domestic gas boiler and an air-to-air heat-pump) under different energy tariffs, identifying dynamically the cheapest operation mode. The heating costs are calculated hourly taking into account the outdoor temperature and electricity tariff variables. Moreover, a physical model of the HP has been developed to obtain the hourly performance according to the outdoor temperature. The methodology is applied in Madrid, Spain, where is common to have these two heating technologies in a dwelling (due to the spread of split units for air-conditioning). The study is applied from 01/10/18 to 31/03/19. Furthermore, dTOU, RTP and a commercial static electricity tariffs are compared to a commercial static natural gas tariff.

2. Methodology and case study

2.1. Methodology

The proposed methodology, calculates the space heating cost for different technologies in an hourly basis, taking into account outdoor temperatures, energy tariffs, and the energy performance of the chosen technologies. For the case of air-to-air HPs, the coefficient of performance (COP) is calculated for each hour.

In order to characterize the hourly COP of the heat pump under different outdoor temperatures, a complete model of the system is developed using the EES (Engineering Equation Solver) software.

First, an ideal thermodynamic single stage cycle of an air-to-air HP is modeled.

Second, the COP is calculated under the pressure and temperature conditions established in the EN 14825 [14]. Then, since the ideal cycle is far from the real operational cycle, the calculated ideal COP is modified to obtain a more realistic value considering the isentropic efficiency and heating and pressure losses, [15]. As a result, the following polynomial regression of the COP is obtained, as a function of Tout, for an air-to-air HP with R32 working fluid:

$$COP = 2.85633 + 0.072432 \cdot T_{out} + 0.000546578 \cdot T_{out}^2 \tag{1}$$

Once the performance of the system is calculated, the value is multiplied by the selected energy tariff obtaining the hourly heating cost.

2.2. Case study

The methodology is applied to an average dwelling in Madrid, Spain, calculating which would be the seasonal costs to cover the heating demand (from 01/10/18 to 31/03/19) through different technologies. A conventional gas boiler and a HP are selected; additionally, three different electric tariffs are selected: dTOU, RTP and a static tariff.

The selected heating season in Madrid has an average temperature of 9.6 °C. The maximum temperature is 27.5 °C, which happens in early October, and the minimum value −3.3 °C, happening in February which is, overall, the coldest month of the whole season. The temperature varies around 10 °C between days and nights, having mild temperatures during daylight (14.7 °C) and with a significant heating demand during nighttime (4.2 °C).

With regards to the space heating systems' performance, a constant efficiency is applied in the case of the natural gas boiler, 90%, and the efficiency of the HP is calculated for each hour using Eq. (1). Both Natural Gas and electric static tariffs, are commercial tariffs. The dynamic tariffs are the General tariff (RTP) and the Nighttime tariff (dTOU) from the "Volunteer Price for Small Consumer" (PVPC in Spanish) government regulated tariffs that relate wholesale prices evolution to retail prices. These tariffs have two components:

- The cost of producing electricity obtained from the Day-Ahead market and
- a fixed amount to pay for all the activities necessary to bring the electricity supply, as well as other costs.

Finally, the heating demand is calculated as shown in [16] for a constant indoor temperature of 20 °C.

3. Results and discussion

Before showing the result for the whole season, two significant days, an average cold day and the coldest day, have been selected to analyze them in dept for a better understanding of the proposed study.

3.1. Average cold day

The selected average cold day shown in Fig. 1, which corresponds to the 5th of December 2018, has an outdoor temperature going from 3.8 °C to 15.3 °C. As a result, the COP of the HP (Fig. 1a) varies from a minimum value of 3.14 to a maximum of 4.1. Regarding to the energy prices (Fig. 1b), the Natural Gas price and the static electric price are 0.0536€ and 0.1906€, respectively. RTP prices variation is from 0.1615€ to 0.1828€, and the dTOU has a minimum price at nighttime of 0.0884€ to a maximum price of 0.1949€.

Fig. 1c shows the calculated heating cost for the natural gas boiler and the HP. It can be observed that having a HP with either dTOU or RTP tariff is cheaper than using a Gas boiler during the whole day. In the case of having a HP with the selected static tariff, the coldest hours of the day, the heating cost of the system is higher than the heating cost of the gas boiler due to the low COP.

3.2. The coldest day

The selected average cold day shown in Fig. 2, which corresponds to the 6th of February 2019, has an outdoor temperature going from −3.2 °C to 10.2 °C. As a result, the COP of the HP (Fig. 2a) varies from a minimum value of 2.63 to a maximum of 3.65. Regarding to the energy prices (Fig. 2b), the Natural Gas price and the static electric price are 0.0536€ and 0.1906€, respectively. RTP prices variation is from 0.1515€ to 0.16932€, and the dTOU has a minimum price at night-time of 0.0902€ to a maximum price of 0.1935€.

Fig. 2c shows the calculated heating cost for the natural gas boiler and the HP. It can be observed that the lower COP of the cold hours affects in the heating cost of the HP. However, the low-price during night-time of the dTOU tariff compensates the lower performance of the HP reducing the heating costs, making it the cheapest option.

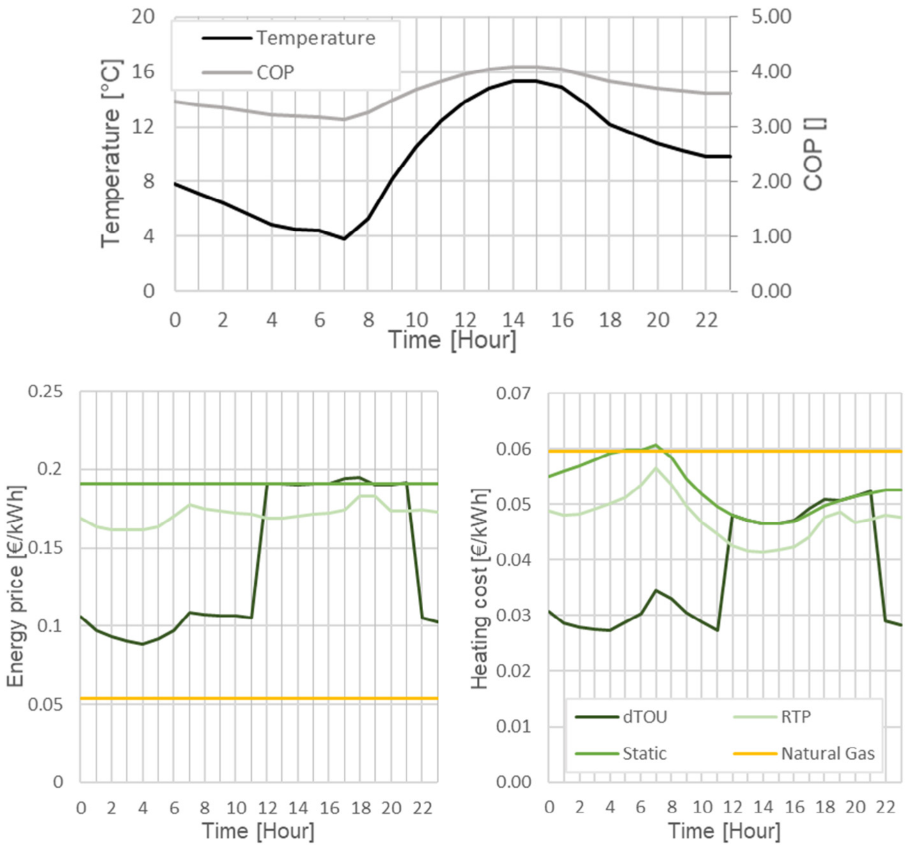

Fig. 1. Result for the average cold day: (a) The hourly temperature with the calculated COP for the HP, (b) The hourly energy price of each energy carrier and electric tariff (c) The hourly heating cost of each energy carrier and electric tariff.

3.3. Seasonal results

The results of the whole heating season are shown in Table 1. First, it is important to address that using a heat pump instead of a natural gas boiler reduces the total heating energy consumption up to 72%. The lowest costs are obtained covering the heating demand with a HP having dTOU tariff, being 40% lower than covering the demand with a gas boiler. This is mainly because during nights where the heating need is higher due to the low temperatures, the electricity prices are reduced in this particular tariff.

Table 1. Seasonal heating demand, energy consumption and total costs to cover the heating demand through the selected technologies and energy tariffs for a typical dwelling in Madrid.

		Heating demand [MWh]	Energy consumption [MWh]	Total costs [€]
Electricity	dTOU	19.20	5.83	694.95
	RTP			912.18
	Static			1110.90
Natural gas	Static		21.33	1144.46

RTP tariff is cheaper than both electric and Natural Gas static tariffs, 18% and 21%, respectively. It is important to mention that both dTOU and RTP tariff are variable and prices could raise during some period, i.e. low share of renewable energies, reducing the cost difference.

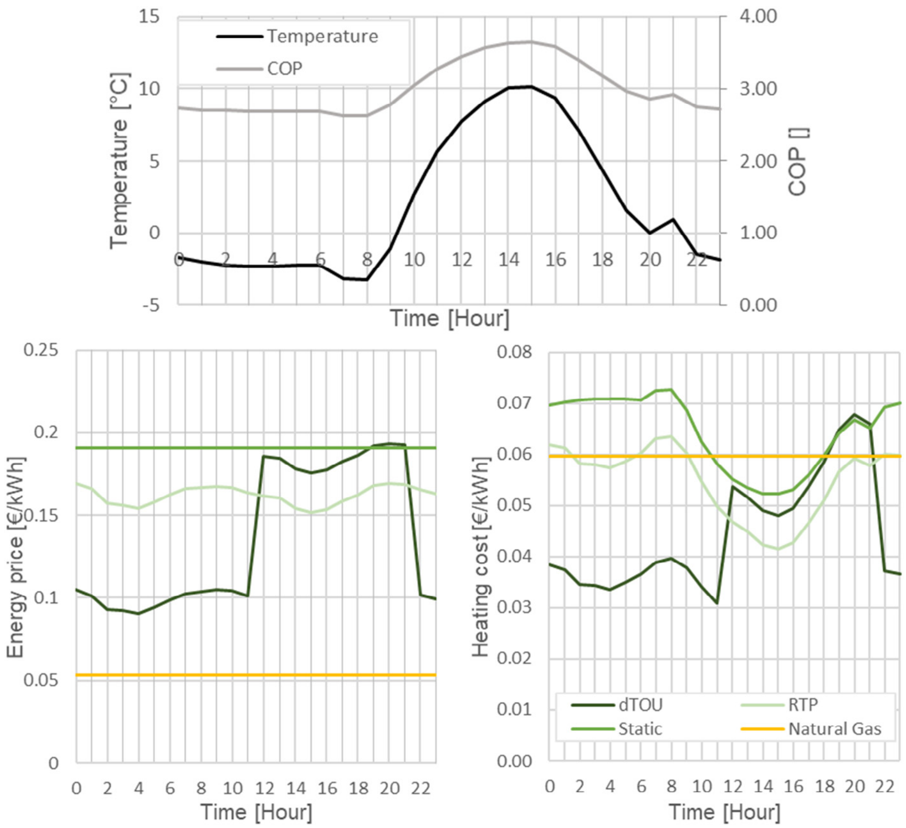

Fig. 2. Result for the coldest day: (a) The hourly temperature with the calculated COP for the HP, (b) The hourly energy price of each energy carrier and electric tariff (c) The hourly heating cost of each energy carrier and electric tariff.

4. Conclusions

This paper presents a space heating dynamic costs calculation methodology for different technologies and energy tariffs. The methodology is applied to analyze the heating costs to cover the demand of a dwelling in Madrid with a gas boiler and a heat pump from 01/10/18 to 31/03/19. Additionally, three different electric tariffs are applied for the heat pump, one static and two dynamics.

The results show how the outdoor temperature affects in the performance of the heat pump, from 2.63, for the coldest temperature, to 5.27 for the highest. It can also be observed how the energy price makes one system or the other more suitable each time. In the case study, having a dynamic time-of-use tariff reduces the cost up to 40% compared with a natural gas boiler. The results are particular for this case study and the weather and market conditions during the 2018/19 heating season, but the methodology is replicable in other markets and other technologies (i.e. District Heating) and lead to diverse values. This fact demonstrates how relevant it is to choose the proper energy system and electric tariff.

Providing this information along with non-technical recommendations to energy consumers would help to empower them to participate more actively in the electric markets and demand response programs. The presented calculation method will be implemented in an app for domestic end-users in two pilot sites of HOLISDER project: residential apartments in Belgrade and Athens. Further developments will be also done in the methodology in order to investigate strategies to reduce not just the cost, but also, the energy consumption.

CRediT authorship contribution statement

O. Eguiarte: Investigation, Formal analysis, Validation, Writing - original draft. **P. de Agustín-Camacho:** Conceptualization, Supervision, Writing - review & editing. **A. Garrido-Marijuán:** Support in modeling and programming, Data curation. **A. Romero-Amorrortu:** Project administration , Funding acquisition.

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.

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