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Implementation of biomass boilers for heating and domestic hot water in multi-family buildings in Spain: Energy, environmental, and economic assessment

Jesús Las-Heras-Casas [a], Luis M. López-Ochoa [a,*], José P. Paredes-Sánchez [b], Luis M. López-González [a]

[a] TENECO Research Group, Department of Mechanical Engineering, University of La Rioja, Calle San José de Calasanz, 31, 26004 Logroño, La Rioja, Spain
[b] University of Oviedo, School of Mining, Energy and Materials Engineering of Oviedo, Department of Energy, Calle Independencia, 13, 33004 Oviedo, Principado de Asturias, Spain

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A B S T R A C T

In the residential sector, biomass offers great potential to achieve the goals of the Europe 2020 strategy for climate and energy. With their policies, the different countries of the EU encourage actions in building stock such as the replacement of boilers with more efficient boilers and a greater use of renewable energy. This article explores the substitution of central fossil fuel boilers (heating oil, liquefied petroleum gas, and natural gas) with central biomass boilers to cover all heating and domestic hot water needs in multi-family buildings in Spain. Typical buildings from five cities located in each different climate zone of peninsular winter were chosen for this study. A thorough energy, environmental, and economic analysis is conducted. A reduction by as much as 93% in primary non-renewable energy consumption can be achieved, and CO_2 emissions can decrease as much as 94%, resulting in better and higher energy performance certificate ratings. Despite the required investment, savings in all cases studied are achieved. The savings are greater with the increasing severity of winter weather, with a substantial reduction in energy costs.

1. Introduction

The biomass sector covers any organic matter used to produce energy. In particular, Spanish Association of Standardization and Certification (2016) uses the definition for categorizing biomass as any material of biological origin, excluding those that have been covered in geological formations that undergo a mineralization process (Montoya et al., 2014). The implication is that biomass resources come from diverse and heterogeneous sources. The technology currently available allows the obtained bioenergy products to replace any conventional energy, including solid, liquid, or gaseous fuels. Biomass can be used in combustion plants of all sizes: stoves and small boilers in single-family homes, central heating in small dwellings, and medium and large thermal power plants (Scarlat et al., 2011). In addition, biomass is the third largest primary energy resource in the world (Bilgen et al., 2015). In the European Union, in 2014, the primary energy consumption of solid biomass was 89.1 Mtoe, with a heat consumption of 69.9 Mtoe and a gross electricity production of 84.8 TWh. Spain accounted for 5.95% of this primary energy consumption. The consumption of heat amounted to 3.7 Mtoe, and 3.8 TWh of electricity was produced (EUROBSERV'ER, 2015).

In the residential sector, with the use of biomass for heating and domestic hot water (DHW) solutions, a substantial reduction in CO_2 emissions is expected. This reduction contributes to the European goal of reducing greenhouse gas emissions by 20% compared to 1990 (European Commission, 2009a). On the other hand, with the promotion of these solutions and with biomass being a renewable energy source, biomass helps achieve the European goal of achieving a 20% contribution of renewable energy to total energy consumption (European Commission, 2009b). In addition, biomass is a key factor to consider in achieving a 20% reduction in primary energy consumption compared with 2005 (European Commission, 2012), as biomass has a lower conversion factor from final energy to primary energy than fossil fuels (Spanish Ministry of Industry, Energy, and Tourism and Spanish Ministry of Development,

* Corresponding author.
E-mail address: luis-maria.lopezo@unirioja.es (L.M. López-Ochoa).

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2016). All of these goals are included within the Europe 2020 strategy for climate and energy (European Commission, 2010). By 2030, these demands will be much more ambitious (European Commission, 2014a, 2014b, 2016a). Therefore, these solutions are very important in light of this new 2020–2030 scenario.

With their National Energy Efficiency Action Plans (European Commission, 2016c), EU countries have studied and analyzed their building stock. In this manner, they have been able to evaluate what type of renovation and rehabilitation actions are the most appropriate to achieve energy savings. These actions for existing buildings may consist of improving the building thermal envelope, increasing the contribution of renewable energy, or replacing installed boilers with more efficient boilers. In addition, EU countries are developing policies to encourage these actions.

According to ENTRANZE (2016), in Spain, 70% of the residential building stock includes multi-family dwellings, with a total of 11,780,660 dwellings in multi-family blocks. A total of 9% were built before 1945; 46% between 1945 and 1979; and 45% between 1980 and 2008. Biomass is currently used for heating and DHW in 648,970 Spanish households, consuming 2.1 Mtoe per year. From the total average consumption of a Spanish home (heating, cooling, DHW, lighting, and appliances), 47% correspond to heating and 19% to DHW (Pablo-Romero et al., 2013).

Spain has been one of the countries with the highest energy dependence in Europe. Biomass exploitation is considered an important driving force in reducing energy dependence (Dinica, 2009). The existence of technical, economic, and even market barriers has restrained the development of the use of thermal biomass. This study explains the potential development of thermal biomass by exploring alternative boiler diffusion patterns to those based on traditional fossil fuels. It is assumed that, by studying the patterns of diffusion, one can better understand the various types of obstacles and the benefits that affect the expansion of biomass in thermal applications.

The impact of using biomass boilers on housing has been evaluated in several studies: Kattan and Ruble (2012) conducted a study for multi-family dwellings in Lebanon; Stolarski et al. (2013, 2016), for single-family houses in Poland; Michopoulos et al. (2014), for multi-family dwellings in Greece; and Carpio et al. (2013), for multi-family dwellings and single-family houses in the Iberian Peninsula. Moreover, the use of biomass in hybrid systems for heating and DHW in residential buildings is of great interest. In this field, there are many possibilities: solar hot water systems and a biomass boiler (Berković-Šubić et al., 2014); combined cooling, heating, and power (CCHP) system utilizing biomass and solar energy (Wang and Yang, 2016); the integration of deep geothermal energy and woody biomass resources in urban energy systems (Moret et al., 2016); and the use of biomass in organic Rankine cycles (ORC) for solar-based multigeneration systems with hot and cold thermal storages and hydrogen production (Almahdi et al., 2016). On the other hand, evaluating the energy, environmental, and economic impact of biomass district heating can contribute to strengthening its settlement and development, as Madlener (2007), Madlener and Koller (2007), and Paredes-Sánchez et al. (2016) studied. Additionally, the possibilities of combining energy conservation measures with biomass district heating systems (Lundström and Wallin, 2016) and using low temperature biomass district heating systems (Baldvinsson and Nakata, 2016) should be considered. Finally, enhancing these solutions can help achieve important benefits in rural regions and villages, as Stephen et al. (2016), Hendricks et al. (2016a, 2016b) showed in their studies.

The goal of this study is to evaluate, at the energy, environmental, and economic level, the substitution of existing central boilers for biomass pellet central boilers to cover all heating and DHW requirements in typical multi-family buildings in Spain. To that end, five buildings have been chosen; each building is located in a representative municipality of the five different Spanish winter climate zones (WCZs), with the typical thermal envelopes of the 1981–2007 period. The used fuels are heating oil, liquefied petroleum gas (LPG), and natural gas. In all cases, the final energy consumption (FEC), non-renewable primary energy consumption (NRPEC), CO_2 emissions (as well as the corresponding ratings), and other significant emissions are evaluated. Understanding the diffusion barriers of thermal biomass and the factors that affect its development and expansion is important for the evaluation of decision-makers. In the economic study, the feasibility of the implementation of the biomass-fueled boiler is evaluated through a net present value (NPV) analysis.

2. Materials and methods

2.1. Selected cities

In Peninsular Spain, the five WCZs are distinguished according to the winter weather severity. These winter climate zones are arranged from the lowest to the highest weather severity: A, B, C, D, and E (López-González et al., 2016b). When research has focused on the impact of implementing biomass boilers for heating and DHW, a representative city of each WCZ is chosen (Spanish Ministry of Development, 2013): Cádiz (WCZ A), Valencia (WCZ B), Cáceres (WCZ C), Madrid (WCZ D), and León (WCZ E). Cádiz corresponds to a temperate winter and León a very cold winter (Table 1). In this manner, the selected cities cover all winters of Peninsular Spain. In Fig. 1, the map of Spain with the different WCZs and the cities under study are presented.

2.2. Geometry and thermal envelope of the studied buildings

To compare the results among the different cities, a representative multi-family building of 1981–2007 period is chosen for the study in each city. This representative building with different thermal envelopes was used by López-Ochoa et al. (2017) to assess the impact of the Energy Performance of Buildings Directive in residential buildings in Spain. The building includes a ground floor and five floors. Its base is square, with an area of 484 m^2, and the height of each floor is 3 m. The main façade faces north. On the ground floor, there is the main entrance and a space that is dedicated for commercial purposes; and in each of the five floors, there are four different housing types, with a total living area of 2216.57 m^2. The typical floorplan is shown in Fig. 2, and the spaces of each type of dwelling are detailed in Table 2.

The thermal envelope for the building of each city complies with the maximum thermal transmittances allowed by NBE-CT-79 (Presidency of the Government of Spain, 1979), effective in its construction time. CE3X (Institute for Energy Diversification and Saving, 2012), which is a Spanish official energy certification tool for existing buildings, uses these thermal transmittances by default for residential buildings built between 1981 and 2007. The composition of the different elements that compose the building enclosures and their main characteristics are presented in Table 3 for Cádiz and Valencia, Table 4 for Cáceres, Table 5 for Madrid, and Table 6 for León. There are two types of windows or openings for all living spaces in the studied buildings and in all locations. Both types are composed of the same frame and glass material in each city; in addition, type 1 has 21.21% of the opening covered by frame and type 2 has 23.27%. On the one hand, a metallic frame without a thermal bridge break and single glass is used in Cádiz, Valencia, and Cáceres. On the other hand, in Madrid and León, a metallic frame with a thermal bridge break between 4 and 12 mm