Comparative analysis of energy demand and CO_2 emissions of residential buildings

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Abstract

Rapid expansion of solar thermal energy for increasing energy efficiency of buildings has been adopted in short/medium and long-term energy strategies of EU countries. Within this context, the overall objective of this work is to develop an innovative high performance and cost effective hybrid solar heat and power system. The initial application is to be implemented in individual dwellings and small business residential buildings for on-site electricity and heat generation using solar thermal energy. It is estimated that the proposed technology will deliver 60% of domestic energy requirements and provide 20% reduction in energy costs and greenhouse gas emissions compared to the best existing low carbon energy technologies. The aim of this study consists in performing a comparative analysis of the different building typologies, which can host this technology, and their energy demands for heating and domestic hot water, as well as their CO_2 emissions.

Keywords: Solar thermal energy, Micro-organic Rankine cycle, Phase change materials, Energy savings, Building energy demand, Residential building typology.

1. Introduction

In Europe the building sector represents 41% of the final energy consumption and the 40% of the total GHG emissions of end-use sectors (Directive 2010/31/EU). The Renewable Heat Incentive and similar schemes, which are deployed across a number of EU countries (e.g. UK, Germany, France, Italy, Spain), encourage uptake of renewable heat technologies to support the ambition of 12% of heating coming from renewable sources by 2020.

The present work is part of the Innova MicroSolar project, which is funded within the framework research and innovation programme Horizon 2020. The overall objective of this project is to develop an innovative high performance, cost effective and solar high durability 2-kW_{el}/18-kW_{th} heat and power system for on-site heat and power supply to individual dwellings and small business residential buildings using solar thermal energy. The proposed technology will be built around a small scale solar concentrating collectors which supply thermal energy to power the small high performance organic Rankine cycle (ORC) turbine with 2-kW_{el} output. To control the energy input and output, a thermal energy storage unit with phase change materials (PCM) will be designed. The system will provide 60% of the required building energy and reduce 20% the energy costs and greenhouse gas (GHG) emissions compared to the best existing low carbon energy technologies.

Figure 1 shows the preliminary scheme design of the system that mainly consists of the following parts:

- Concentrating solar collectors (CSP): The CSP system is based on linear Fresnel mirrors which are considerably easier and cheaper to manufacture than their parabolic equals. The system incorporates a sun tracking mechanism and can supply heat transfer fluid (HTF) flow at 295ºC.

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- PCM thermal energy storage: the storage block has two different main components, the PCM tank and the enhanced heat sink, which are connected by heat pipes. The novelties of this unit are the PCM compound with the tuned melting temperature for heat storage, and the reversible heat pipes capable of transferring heat at the required high heating rate in both directions.
- Micro-organic Rankine cycle plant: micro-ORC technology is equipped with a high speed permanent magnet AC alternator able to supply 2.3 kW_{el}.

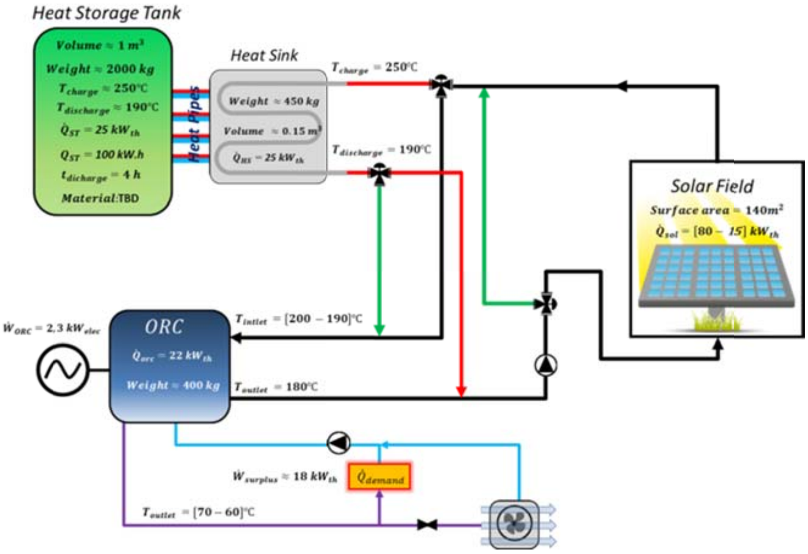

Fig. 1: Innova MicroSolar system diagram

The aim of this study consists in providing information on types of domestic residential buildings for Spain, Italy, UK, France, and Germany. This information will include specification of details on their architecture, building envelope, range of dimensions of living space, their insulation properties, hydronic domestic hot water (DHW), and space heating systems, seasonal and annual energy demands for DHW, heating, and electricity. This information will be used as input data to define and adapt the final design of the system, which will include different building typologies, climate conditions, and energy demand among other technical requirements.

2. Comparative evaluation of building typology, energy demand and CO_2 emissions

From the literature review, projects funded by the IEE agency such as DATAMINE, TABULA, and EPISCOPE (episcope.eu/iee-project) have previously studied the energy performance of the EU building stock by using the energy performance certificates and the different building typology approaches based on the DATAMINE structure and previous experiences of typological classifications used in European countries. The main outcome of these projects was an interactive database named TABULA WebTool created to share valuable information with the scientific community and building experts from European countries.

After performing a comprehensive analysis of these consecutive EU projects (2006-2016) a standardized building classification was identified. In addition, the energy demand for heating and DHW and the related CO_2 emissions sorted by building typology, age classes, and different climatic conditions were compared. Table 1 shows the classification that divides the EU building stock into four general typologies: single family house (SFH), terraced house (TH), multifamily house (MFH) and apartment block (AB). Since databases present different age classes by country (six in Spain, 12 in Germany, ten in France, eight in Italy, and eight in UK), an overall building classification grouped into three different age classes, from 1970 to 1985, from 1986 to 2000, and from 2001 to 2016 was used to unify and compare all the countries within the same age bands. Also, the climatic conditions inside a country were divided into three different classes: hot, temperate, and cold, representing the hottest, the average, and the coldest climatic conditions of a country, respectively.

Tab. 1: Example of standardized building classification for Germany from 2001 to 2016 divided in four typologies by TABULA

Single family house (SFH)	Terraced house (TH)	Multifamily house (MFH)	Apartment block (AB)
			

3. Results

Up to 14 different climatic conditions have been analysed and treated for the different analysed countries (Spain, France, Italy, UK, Germany, and Sweden). However, due to the huge variation on climatic conditions across Europe, the scope of this study is focused only on the representative temperate climatic conditions of the countries in Table 2. The results are organized according to the main outcomes from the aforementioned findings divided in energy demand for heating and DHW and the derived CO_2 emissions.

Tab. 2: Temperate climates of the analysed countries

Country	Spain	Italy	France	Germany	U.K	Sweden
Climate	Atlantic	Middle	H2	Kassel	England	Zone 2

3.1. Annual energy demand for heating and DHW

Figure 2 shows the energy consumption for heating and DHW in temperate climatic conditions by country. As it was expected, the energy demand is lower in apartment blocks in comparison to single family houses and terraced houses for all the EU countries analysed. These results emphasize the importance of the building shape that presents higher compactness (lower form factor between the building surfaces in contact with the non-heated areas and total air volume of the building) in apartment blocks and multifamily houses, so requiring less energy for heating. Additionally, many variations in terms of energy demands for heating and DHW were observed for the same building typology when countries and building construction periods were compared for temperate regions.

Figure 2 also highlights the reduction of the energy demand of buildings over time, for each type of building. Since poor construction systems and low insulation levels were common in old building typologies (1970-1985), European energy policies towards more efficient buildings had a direct impact on reducing the energy demand of buildings. For instance, nowadays newest types of buildings in Spain (2001-2016) consume around 50 % less energy for heating and DHW compared to old building typologies (1970-1985). Similar energy trends were observed in Italy, UK, France, and Germany, but not in Sweden where higher insulation levels were implemented before the considered period in this study.

Regarding to examples of different thermal transmittance coefficient of buildings envelopes, the walls of a single family house in Germany (1986-2000) has 0.35 $W/m^2 \cdot K$ while in Spain the same building characteristics and period shows the double (0.60 $W/m^2 \cdot K$). However, as shown in Figure 2, for the specific construction period of 1986-2000 the German single family house consumes 190 $kWh/m^2 \cdot year$ for heating and DHW in temperate climatic conditions while in Spain the same building typology requires only 60 $kWh/m^2 \cdot year$. As expected, northern countries such as Sweden, UK, and Germany show higher energy demands for heating purposes than southern countries such as Spain and Italy, even using higher insulation levels on building skins. That fact highlights the relevant impact of the climatic conditions in the final energy consumption of a building.

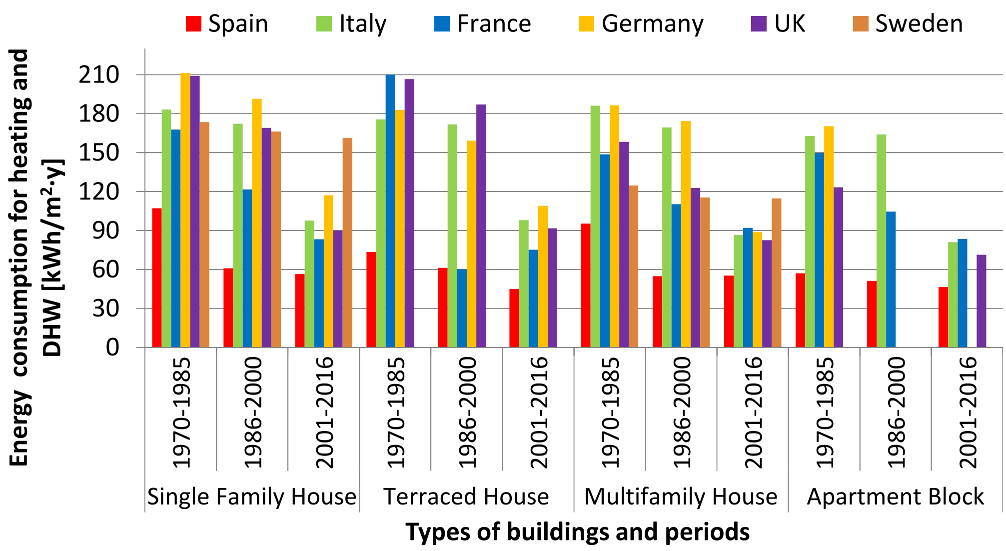

Fig. 2: Energy consumption for heating and domestic hot water in temperate climatic conditions by country

In southern countries such Spain, Italy, and some regions of France, in which Mediterranean climatic conditions are hot, the domestic hot water can account for more than a half of the total energy consumption of a building. As an example, a single family house in Spain (1986-2000) accounted for 41.8 kWh/m^2·y of consumed energy to cover heating and DHW demand (Figure 2) and 20.2 kWh/m^2·y come only from DHW requirements. However, in the opposite site, northern countries such as Germany or Sweden have higher rates in terms of energy consumption for heating in comparison to the energy consumption for DHW. For a similar case scenario in Germany, the calculated delivered energy for heating & DHW of a single family house, from 1986 to 2000, was 188.5 kWh/m^2·y while only 21.1 kWh/m^2·y were for DHW requirements.

These results highlight the wide application potential of new and innovative technologies such as the micro solar heat and power system in different countries and different building typologies.

3.2. Annual CO2 emissions

The expected trends in reducing the CO_2 emissions in all studied countries can be seen in Figure 3. All the building typologies show a reduction of the CO_2 emissions throughout the years, being the newest period (2001-2016) the lowest emissions. These results could be directly related to the reduction in the energy demand for heating purposes. However, Figure 3 shows that in UK, multifamily houses have a higher CO_2 emissions levels despite the fact that their energy consumption is lower than other building typologies. That difference is due to the heating technology considered on TABULA WebTool. Terrace houses supply the heating by condensing boilers while multifamily houses (from 1970 to 2000) use electrical heaters; and the CO_2 emissions per electrical kilowatt in UK is high because of the energy mix. For that reason, the Innova MicroSolar project can achieve its energy savings goal but depending on the current technology installed it may not fulfil the CO_2 emissions required. For instance, multifamily houses located in UK which were built from 1970 to 1985 emit 0.58 CO_2 kg/kW, these emissions go down to 0.28 CO_2 kg/kW in multifamily houses built from 2001 to 2016 due to the implementation of condensing boilers to provide the heat & DHW demand.

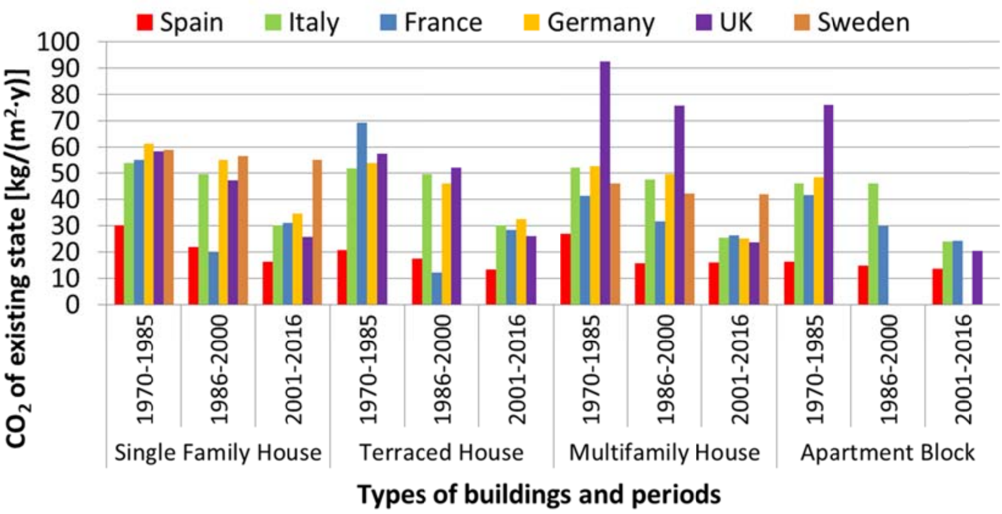

Fig. 3: CO_2 emissions in temperate climatic conditions

4. Conclusions

After performing an estimation of the energy demand for the most common domestic residential buildings in different European countries, the following are the main outcomes of this study:

- The energy policies proposed in many European countries towards more sustainable buildings are being a direct impact in reducing the energy demand in buildings.
- After a literature review, four main typologies of domestic residential buildings have detected for the aforementioned European countries: single family house (SFH), terraced house (TH), multifamily house (MFH) and apartment block (AB).
- The DHW demand of a building is mainly related to the human behaviour and the performance of the system while the heating demand is mainly attributed to the climatic conditions and the building insulation level.
- The estimated range of the energy consumption for heating and DHW was from 46.5 kWh/m^2·y for new apartment blocks in a temperate Spanish climate to 210 kWh/m^2·y for old French terraced house (1970-1985) in the same climatic conditions.
- The CO_2 emissions savings are related with the energy savings. However, the CO_2 emissions saved by the project depend on the current technology installed to supply the heat & DHW demand.

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