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Absorption and compression heat pump systems for space heating and DHW in European buildings: Energy, environmental and economic analysis

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ABSTRACT

The selection of the proper device for space heating and domestic hot water for a building is crucial to achieve good energy and economic performances. For a single-family house, the most common heating device is the condensing boiler. Solar systems, electric heat pumps and gas driven sorption heat pumps represent suitable alternatives for improving the efficiency. Although the performances of each technology are well known, their ability to operate efficiently in bivalent heating plants depends on several variables and the choice of the most suitable heating system for a specific building is not straight-forward. The aim of this paper is to compare, under conditions typical of the European region, the seasonal performances of six system configurations that are obtained by combining the most commonly used heating technologies. The comparison is carried out in terms of primary energy consumption for three climatic conditions, changing the quality of the building envelope and the emission system typology. Although the results are sensitive to the primary energy factor for electricity, electric heat pumps generally result the most promising technology for conditions with low thermal lift, while gas heat pumps have the higher performances at high lift. Additionally, the systems are compared in terms of yearly CO_2 emissions and economic feasibility, finding scattered results among countries, due to large differences in the local energy mix and energy prices.

1. Introduction

It is estimated that in 2013 European buildings used 644 Mtoe of final energy, corresponding to about 41% of the overall consumption in EU28 [1]. Of this share, two thirds were used in households [2], where about 80% of the energy was dedicated to Space Heating (SH) and Domestic Hot Water (DHW), while cooking, lighting, electrical appliances and cooling together accounted for the remaining 20% [3]. Therefore, to be effective, any strategy aimed at significantly reduce the energy consumption and the related emissions in Europe must include space heating and DHW production in residential buildings. On this path, the EU has introduced several measures to ensure the progressive reduction of energy consumption in buildings [4–6].

Actions aiming at the reduction of the energy need for space heating can be focused on the overall performances of the building or on the efficiency of system components [7]. These measures will assure relevant results only in the long-term, since in Europe the new buildings share is about 1% of the actual stock every year and the renovation rate of existing buildings ranges between 0.5% and 1.2%, according to the country [8]. While building renovation takes place slowly, the heating system renovation may represent an option to fasten the reduction of the energy consumption in the residential sector, thanks to its higher renovation rate, estimated at about 3.6% [9]. Moreover, the renovation of the system may be less costly and less impacting on occupied buildings, especially if the renovation action does not imply the replacement of the existing emission system.

Since gas boilers are capable to provide SH and DHW without a storage and auxiliaries, they usually represent the cheapest solution in terms of first costs, given the low price of the appliance itself and the simple system required. Currently, in Europe a relevant share of heating systems is based on gas boilers. In the last decades, the need of reducing the energy consumption for space heating, driven by environmental and economic issues, promoted the improvement of the boilers efficiency, with the introduction of modulating boilers and condensing boilers. In

Abbreviations: AEH, Auxiliary Electric Heater; AEF, Auxiliary Energy Factor; COP, Coefficient Of Performance (heating mode); CR, Capacity Ratio; CFR, Compressor Frequency Ratio; CB, gas Condensing Boiler; DHW, Domestic How Water; EHP, Electric Heat Pump; EU, European Union; GCV, Gross Calorific Value; GHP, Gas absorption Heat Pump; GUE, Gas Utilization Efficiency (heating mode); HS, Hydraulic Separator; IAM, Incidence Angle Modifier; LF, Load Factor; MCHP, Micro Combined Heat and Power; N, New building; NZEB, Net Zero Energy Building; O, Old building; PEF, Primary Energy Factor; PER, Primary Energy Ratio; R, Refurbished building; SFH, Single Family House; SH, Space Heating; SS, Solar thermal System; y, year

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Nomenclature

I_T	global radiation Incident on the solar collector, W/m^2
Q_{DHW}	domestic hot water heat demand, kWh or kWh/m^2
$\dot{Q}_h$	heating capacity, kW
Q_{gas}	gas input energy referred to the Gross Calorific Value, kWh or kWh/m^2
$\dot{Q}_{gas}$	gas input power referred to the Gross Calorific Value, kW
Q_{SH}	space heating energy, kWh or kWh/m^2
T	temperature, °C
W_{in}	electric energy input, kWh or kWh/m^2
$\dot{W}_{in}$	electric power input, kW

Greek symbols

η	thermal efficiency

Subscripts

air	outdoor air
aux	auxiliaries' electric devices
avg	average
ext	external ambient conditions
gen	generator
h	heating mode
in	inlet water
max	maximum
out	outlet water
min	minimum
nom	nominal conditions
th	thermal

2015 condensing boilers accounted for the 78% of the European gas boiler market [9], with a growing trend, fostered by the Ecodesign Directive [7], come into force in September 2015, which banned from the market the less efficient heating devices.

The need for further reduction of the energy consumption for space heating and DHW promoted the diffusion of more efficient technologies, as heat pumps, or combinations of two or more heating devices. These options still represent a small fraction of the installed appliances, but they experience a growing trend.

The vapour compression heat pumps market reached in 2015 a size of 900,000 units, of which about one third is made of air-to-water heat pumps for space heating purposes [10]. Heat pumps may have lower primary energy consumption on seasonal basis, especially if ground sourced and coupled with an underfloor heating system [11], but they require a more cost intensive and complex system. Additionally, their efficiency is strongly influenced by the sizing of the appliance, the heating system features and the adopted control strategy.

Hybrid systems, i.e. a combination of a gas fired unit and a vapour compression heat pump, are considered a possible solution to cope with the drawbacks of heat pumps [12–14]. The market share of these systems is currently low, although it is expected to gain relevance after 2020 [9].

Gas driven absorption heat pumps (GHP) represent a further alternative to gas boilers, without some of the drawbacks of vapour compression units. In particular, GHP are capable to operate with high temperature emitters, as radiators, with good efficiency [15]. Moreover, for countries with a capillary gas distribution infrastructure, they offer the possibility to exploit renewable energy in the heating sector without imposing a load shift from gas to the electricity and, thus, affecting the operation of the electricity grid.

For what concerns solar systems, they can be effectively used for the DHW production. However, when applied for SH, their output is in counter phase with building demand, especially in cold climates. Thus, it is possible to cover a significant share of the heating needs only oversizing the system, with the related additional costs.

The high number of variables affecting the system performances makes the choice of the best technology strongly dependent on the characteristics of the application, such as the climatic conditions, the type of emission system, the space heating and DHW load profiles.

Several studies about the development, optimization and integration of efficient heating devices are available in the literature [16], often addressing buildings with very low heating demand or NZEB [17–19]. Most of these works deal with electric heat pumps [20], often ground sourced to improve the seasonal efficiency [21,22]. Advanced system configurations are also investigated, with heat pumps coupled with other technologies, as internal combustion engines [23], solar thermal or photovoltaic-thermal systems [24].

However, only few works provide an exhaustive comparison among heating systems based on different technologies. In [25] gas condensing boiler, wood pellet boiler, micro-combined heat and power (MCHP), air-to-water electric heat pump, air-to-water gas absorption heat pump and exhaust air-to-air electric heat pump are compared on primary energy consumption for heating low energy houses. The comparison is made for various climatic conditions and considering for each appliance the size available on the market.

Purpose of this work is to provide a wide and in-depth view of the performance of different heating systems in Europe, addressing both space heating and DHW production. The analysis focuses on the residential market and on single-family houses, which represent 66% of the residential buildings in EU28, in terms of floor area [1]. To provide results of general applicability, the comparison is performed for several cases, changing two of the variables, which mostly can affect the performances of heating systems, i.e. the climatic condition and the quality of the building envelope. Care is given to simulate the part load behaviour of the appliances, which

As for the selection of the heating systems the criteria of low cost, simple installation, low maintenance and large potential market have been followed. The six resulting heating system layouts are the following:

- Condensing boiler (CB);
- Condensing boiler with solar system for DHW production (CB + SS);
- Electric heat pump with electric back-up (EHP + AEH);
- Hybrid system with electric heat pump and gas back-up (EHP + CB);
- Gas absorption heat pump monovalent (GHP);
- Gas absorption heat pump with gas fired back-up (GHP + CB).

With the purpose of providing relevant and exhaustive results, the comparison has been carried out based on three indicators: primary energy, CO_2 emissions and economics.

By means of numerical simulations, the seasonal performances of the six alternative systems are compared under nine different conditions, obtained by the combination of three climatic conditions and three building standards. Unlike in [25], the heating devices have been sized according to the building requirement, assuming that appliances of different capacity will be available on the market as soon as each technology increase its market share. Moreover, this choice allows the scalability of the results to larger or smaller buildings than the one used for the presented calculations.

Since the different technologies have a different level of maturity, a direct comparison of their life cycle costs is not meaningful. Therefore, the seasonal operating costs are calculated for different countries and are used to provide an indication of the affordable investment cost,