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Performance analysis of heating systems for low energy houses

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ABSTRACT

The residential sector is responsible for more than 35% of the final energy consumption in the European Union, and is increasingly constrained by thermal regulations, resulting in a significant rise of new efficient heating technologies. This paper presents a comparison of the energetic and environmental performances of six heating systems installed in a low energy house: a gas-fired condensing boiler, a wood pellet boiler, a micro-combined heat and power (MCHP), an air-to-water electric heat pump, an air-to-water gas absorption heat pump and an exhaust air-to-air electric heat pump. The comparison is made with respect to the annual primary energy consumption and the annual greenhouse gas (GHG) emissions, and carried out under various climates and electricity generation mixes. The results indicate that, based on an ideal sizing, the MCHP and the absorption heat pump achieve the highest energy performances. However, both technologies suffer from small size unavailability, leading to significant oversizing which impacts their performances. Based on current size availability, the air-to-water electric heat pump benefits from the previous systems oversizing and thus appears as the most efficient technology. However, current sizing practice also causes significant oversizing which impacts the performances of thermodynamic systems. Without significant sizing practice improvements, the air-to-water electric heat pump merit decreases in favor of the MCHP. In terms of environmental impact, the wood boiler causes the lowest GHG emissions, whatever the electricity generation mix considered.

1. Introduction

Residential sector contributes to more than 35% of the final energy consumption, and to a large part of the GHG emissions in the EU, leading to a significant impact on the environment. In 2010, the EU adopted a Directive on energy performance of buildings [1], aiming for major cut in building sector annual energy consumption. Under this Directive, Member States must establish and apply minimum energy performance requirements for new and existing buildings. In France, this requirement is set to 50 kWh/m^2 of primary energy per year for new buildings including heating, cooling, auxiliaries (pumps and fans), domestic hot water and lighting, with a slight variation depending on local climate, and 80 kWh/m^2 per year for retrofit buildings.

In order to meet these new standards, building insulation, air renewal management, heat production as well as thermal regulation should be carefully addressed. Peeters et al. [2] evaluated the impact of building insulation quality and emitters control strategy on overall heating efficiency. They showed that heating efficiency tends to decrease with building insulation improvement, since heating system oversizing becomes more important. The study also showed the interest of using a modulating boiler, an outdoor air temperature compensation and thermostatic radiator valves. Calvino et al. [3] revealed that the application of a new PID-fuzzy controller instead of a classic on-off controller for indoor thermal comfort could result in energy savings and lower deviation from temperature set point. Badran et al. [4] performed a comparative study of continuous versus intermittent heating in residential buildings. For buildings with high insulation level, continuous operation of the heating system at low water temperature becomes more economical than intermittent operation at high temperature when the operation time per day exceeds 14 h. El Fouih et al. [5] carried out a comparison of the energy performance of three ventilation systems in several types of low-energy buildings. In the case of a residential house, humidity controlled ventilation appears to be the most efficient ventilation system for warm and moderate climates. For cold climates, heat recovery ventilation can become the most efficient system if high efficiency heat exchanger and low specific fan power are used.

Energy performance and environmental impact comparison of heating systems is a major topic that has already led to numerous publications. Cabrol and Rowley [6] estimated the CO_2 emission savings achieved by the use of an air source heat pump instead

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Nomenclature

COP	coefficient of performance
CHP	combined heat and power
EU	European Union
FH	floor heating
GHG	greenhouse gas
HCV	humidity controlled ventilation
HDD	heating degree day (°C-day)
HHV	higher heating value
HRV	heat recovery ventilation
LHV	lower heating value
LTR	low temperature radiators
MCHP	micro combined heat and power
UCTE	Union for the co-ordination of transmission of electricity

Latin letters

a_{nom}	nominal efficiency calculation coefficient (1/K)
$a_{30\%}$	efficiency at 30% of the nominal load calculation coefficient (1/K)
AEWI	annual equivalent global warming impact (kg eq-CO_2/year)
COP_{nom}	coefficient of performance at nominal conditions
COP_{min}	coefficient of performance at minimum load factor of steady-state operation
c_p	mass specific heat of water (J/(kg K))
E_{annual}	annual energy consumption (kWh/year)
F	compressor operating frequency (Hz)
GWP	global warming potential
H_T	transmission heat loss coefficient (kW/K)
H_V	air renewal heat loss coefficient (kW/K)
k	part-load COP correction factor
L	refrigerant leakage rate (kg/year)
m	refrigerant charge (kg)
n	system operating time (year)
P_{aux}	auxiliaries electrical power consumption (kW)
P_{elec}	electrical power consumption (kW)
$P_{elec,nom}$	electrical power consumption at nominal power (kW)
$P_{elec,fan}$	fan electrical power consumption (W)
ΔP_{fan}	total pressure rise from the fan inlet to the outlet (Pa)
P_{FL}	thermal power produced at full-load (kW)
P_n	heating system nominal power (kW)
P_{pump}	circulating pump electrical consumption (W)
P_{th}	thermal power produced (kW)
Q_0	thermal losses at idle (W)
$Q_{0,30}$	thermal losses at idle at reference conditions (W)
Q_v	ventilation airflow rate (m^3/h)
$Q_{v,nom}$	nominal ventilation airflow rate (m^3/h)
ΔT	water temperature increase through the heating system (°C)
$T_{30\%}$	nominal supply temperature set point at 30% of the nominal load (°C)
T_{nom}	nominal supply temperature set point at full-load (°C)
T_{out}	outdoor temperature (°C)
$T_{out,des}$	outdoor design temperature (°C)
T_{in}	house indoor temperature (°C)
T_{water}	water supply temperature set point (°C)

Greek letters

α_{rec}	refrigerant recycling factor
β	CO_2-eq emission factor (kg eq-CO_2/kWh)
$\eta_{30\%}$	nominal efficiency at 30% of the nominal load
η_{elec}	nominal electrical efficiency
η_{fan}	overall efficiency of the fan system (motor + drive + fan)
η_{nom}	nominal efficiency
Φ_{HL}	maximum heat losses (kW)
τ	load factor
τ_{aux}	auxiliaries electrical consumption factor
τ_{min}	minimum load factor of steady-state operation

of a conventional gas boiler. Results vary between 26% and 36%, depending on the building and the climate considered. Kelly and Cockroft [7] also evaluated these savings in the case of heat pumps retrofitted into dwellings. Simulations validated by trial data indicated that heat pumps produce 12% less GHG emissions than equivalent condensing gas boilers. Yang et al. [8] carried out a comparison of hot water and forced air heating systems in terms of annual exergy consumption, life-cycle GHG emissions and life-cycle energy use. Results indicated that hot water heating systems using either electricity or natural gas and coupled with heat recovery ventilation have the lowest annual exergy consumption and life-cycle energy consumption. However, life-cycle GHG emissions depend largely upon electricity mix. Same conclusions have been drawn by Shah et al. [9] while performing a life cycle assessment of an air-to-air heat pump compared to a conventional gas furnace and gas boiler coupled with an air conditioning system. Eventually Dorer and Weber [10] assessed the energy performance and CO_2 emissions of several micro-cogeneration systems and compared them to conventional heat pumps and boilers. The heat pump appeared to offer the maximal CO_2 emissions savings compared to a gas boiler, whereas micro-cogeneration systems can achieve maximal primary energy consumption reductions, up to 34%.

Although these studies have focused on the comparison of heating systems through energetic and environmental criteria, the types of heating systems compared was mainly limited to gas boilers and electric heat pumps, and did not reflect the large range of heating systems currently available for residential heating. While boilers have long constituted the vast majority of the heating systems used in the residential sector, increased regulatory constraints have recently resulted in a significant rise of new efficient heating technologies. Although some studies focus on one of these emerging technologies, none of them has taken into account all these technologies in either an energetic or an environmental analysis. Such study is however essential for addressing their relative merits and for understanding future market development. Furthermore, the sizing issue is rarely discussed. This is of particular interest for low energy buildings as all heating products are not available in the small power range, which may lead to important system oversizing and change the order of merit of the different heating systems.

This study aims to evaluate the energetic and environmental performances of six heating systems installed in energy-efficient residential buildings. The systems studied are: (a) gas-fired condensing boiler, (b) wood pellet boiler, (c) micro-CHP, (d) air-to-water electric heat pump, (e) air-to-water gas absorption heat pump, and (f) exhaust air-to-air electric heat pump. The study intends to compare these six heating systems in terms of annual primary energy consumption as well as annual GHG emissions according to different European climates, while accounting for the effect of sizing and the limit of small size availability.