The Performance Potential of Domestic Heat Pumps in a Temperate Oceanic Climate

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Abstract. Domestic purpose heat pumps are commonly rated based on a manufacturer specified single Coefficient of Performance (COP). The performance of heat pumps however, is known to vary widely for different seasons and for varying climate conditions. This study is part of an in-depth analysis of nZEB homes through the nZEB101 project funded by the Sustainable Energy Authority of Ireland (SEAI). In advance of undertaking a large-scale monitoring project, preliminary studies of nZEB technologies are being undertaken. This paper outlines a simplified method for calculation of the heat pump's seasonal performance factor over six heating seasons in a modelled nZEB dwelling in Ireland using real hourly weather data. The study has found that while Seasonal Performance Factor (SPF) values of 4.5 (as often claimed by manufacturers) are achievable, favorable operating conditions are required to achieve these high values. In a new building where under floor heating and modern convective radiators are installed, the primary energy associated with the space heating is approximately 40% that of a natural gas boiler. The total CO_2 emissions are also 47% less. However, in a retrofit nZEB building where existing radiators (which require higher outlet temperatures of approximately 65°C) are used, the difference in CO_2 emissions from a heat pump and gas boiler is almost negligible. The potential for heat pumps can be improved further by decarbonizing the grid and improving grid and plant production efficiencies.

Keywords: Air source heat pump, Coefficient of performance, Energy savings

1 Introduction

The energy use and CO_2 emissions associated with buildings continue to be significant and solutions are needed to reduce their impact. In the EU, building's account for approximately 40% of the total final energy consumption and 36% of the total CO_2 emissions [1]. Of this building energy consumption, two thirds is made up of residential buildings. In Irish residential buildings the greatest consumer of energy is space heating [2].

Heat pumps are becoming the standard for the supply of space heating in Irish residential buildings as a result of their high efficiencies and grant to support. Between 2007 and 2008 the total heat pump sales increased by approximately 50% in Europe according to the European Heat Pump Association [3].

They function by moving low-temperature thermal energy from outside to higher temperature thermal energy on the inside of a building using a relatively small amount of external work. This work is powered by electrical energy from the grid and is often three or four times less than the thermal energy supplied to the building.

Mackay [4] estimates that replacing fossil fuel heating with heat pumps in conjunction with high performance building envelopes and heating control systems would reduce the primary energy consumption for heating by 75% in the United Kingdom (UK), a promising reduction if achieved.

This study presents likely SPF values for a standard air-to-water heat pump operating in an Irish climate by using real hourly weather data. The study also assesses the primary energy requirement and CO_2 emissions for the space heating of a sample nZEB building. Five different heating systems are compared including four heat pumps operating at different outlet temperatures and one condensing natural gas boiler. The objective of the study is to identify the conditions for which air-to-water heat pumps are a sustainable solution to provide space heating to Irish buildings.

2 Heat Pump Performance

The performance of a heat pump system is typically measured by a single coefficient known as the coefficient of performance (COP). This is simply the ratio of heat power output to electric power input under specific conditions.

The conditions which determine the COP are presented graphically in Fig. 1 and listed below:

- The heat pump's efficiency curve
- The heat source
- The application temperature
- The climate
- The control system
- The occupant's behavior

As the climate and operating conditions change regularly, the COP will change regularly, and so, this ratio is often averaged over a period of time, which is known as the Seasonal Performance Factor (SPF) [5]. SPF values of 4.5 and more are often quoted by manufacturers. This study investigates if over an average 6 year period this is possible and, if so, under which conditions.

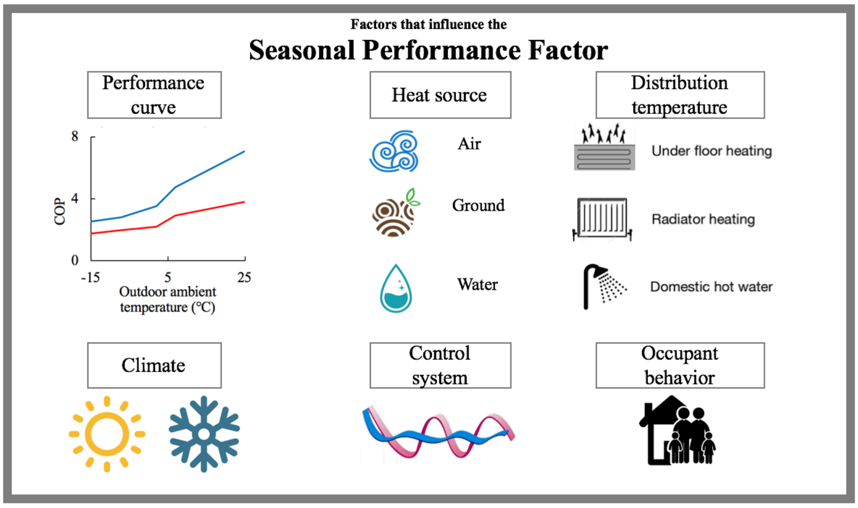

Fig. 1. Factors affecting the seasonal performance factor.

2.1 Performance curve

The mechanical performance of the heat pump itself is determined by the refrigerant used and the efficiency of the individual components including the compressor, evaporator, expansion valve and condenser. The limit on heat pump performance is based on the theoretical maximum coefficient of performance or Carnot coefficient of performance. The COP of an actual heating system is approximately half the Carnot value [6].

All heat pumps are tested to evaluate their performance. The test requirements in the EU for an air-to-water heat pump with outdoor unit operating to provide space heating are as follows:

- The heat pump should be tested at a dry bulb temperature of 7°C and a wet bulb temperature of 6°C as set out in Tables 12-14 of EN 14511-2 [7] for a 35°C, 45°C and 55°C outlet temperatures for space heating application temperatures.
- In Table 1 of EN 14511-4 [8] the relationships between wet and dry bulb temperatures are provided for definition of relative humidity.
- Test data is required at a minimum of two sink (outlet application) temperatures, but usually at least three are provided by the manufacturer for space heating (35°C, 45°C and 55°C) with an additional application of 65°C if Domestic Hot Water (DHW) is to also be supplied by the heat pump.
- Additionally, for application use (i.e. most cases) additional data points are required at:
  - Dry = 2°C ; Wet = 1°C.
  - Dry = -7°C ; Wet = -8°C.
  - Dry = 12°C ; Wet = 11°C.
  - Dry = -15°C; Wet = NA

For example, to be listed on the SAP Product Characteristics Database (PCDB) temperatures are required at dry bulb/wet bulb temperatures of 7/6, 2/1 and -7/-8 °C).

2.2 Heat source

The source of heating is typically either a ground source or air source, and less commonly water. Ground source heat pumps extract heat from the ground with vertical or horizontal heat exchangers and are more efficient than air source heat pumps as a result of the more stable heat source. They are, however, costly and in areas of high density housing these heat pumps are not an option. Air to water heat pumps, are particularly relevant for retrofit, as they do not require a significant amount of space. In the UK approximately 40% of the housing stock is comprised of high density housing according to [9].

2.3 Distribution temperature

The outlet temperature from the heat pump has a significant impact on its performance with lower temperatures (requiring a smaller temperature lift), resulting in higher COPs. The usual heating supply temperature operation for radiators in Germany is c. 55°C [10] and is c. 80°C in the UK for old smaller radiator systems [6], while a typical under floor heating system requires an output temperature of c. 45°C.

Results from a study on the performance of a domestic low temperature heating system with a heat pump [11] showed that the building construction and its dynamic behaviour are of significant importance when opting for a heat pump system. Tight building construction (low infiltration heat losses) with heavy insulation (low U-values) allows for low-temperature heat distribution systems. Low temperature distribution is possible in nZEB buildings which have high performance.

2.4 Control Strategy

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2.5 In-use performance

Kelly and Cockroft [9] measured the performance of an air source heat pump using field trial data. Results showed that the average annual COP (SPF) was approximately 2.7 (in contrast to its nominal COP of 3). Results also showed that the air source heat pump system alone produced 12% less CO_2 than a condensing gas boiler. These figures don't appear promising but are based on the CO_2 intensities of 0.19kg/kWh for gas and 0.54kg/kWh for grid electricity. The figure of 0.54kg/kWh has since been reduced with the increasing amount of renewable electricity generation.

One recent European study has already assessed the validity of European Labels and found that there were significant differences (of between +80% and -24%) between the real working conditions and test procedures carried out according to regulations [12].

3 Methodology

To holistically assess heat pumps, considering all these discussed parameters, monitoring of a significant sample of occupied dwellings over a number of years is required. This is the objective of the SEAI funded project nZEB101. This study forms the foundation for this greater body of work by assessing the potential performance of a sample air-to-water heat pump's SPF and the primary energy consumption and CO_2 emissions associated to it. The SPF is calculated as follows:

- A sample 9kW heat pump performance curve is taken as the baseline and the COP is modelled as a linear piecewise function of temperature difference between outside ambient and heat pump outlet (or application) temperature.
- A heating period from the beginning of October to the end of April is assumed and for simplification it is assumed that the temperature is kept constant for 24 hours.
- Hourly weather data for Ireland over the past 6 years is used [13].
- The COP at individual hourly intervals is calculated using the linear piecewise model of the heat pump's performance.
- The SPF is calculated by taking the average hourly COP value over the entire heating period.

The SPFs are calculated for four different operating conditions (35°C, 45°C, 55°C and 65°C) and the associated primary energy consumption (kWh) and CO_2 emissions for these four operating conditions are compared with that of a natural gas boiler (91% efficiency).

The application temperature is dependent on a number of factors but primarily it depends on the type of heaters used, for example under floor heating or convective wall heaters. The exact outlet temperature can only be estimated on a case study basis with real performance data.

To compare the five heating systems (four heat pumps and one gas boiler) the hourly heat demand for a sample nZEB home is simply calculated with Eq 1. The dimensions and specifications used to calculate the dwelling's specific heat loss coefficient, H (W/K) , are taken from [2]. The heat loss is simplified by assuming fabric heat loss only, which for the assumed dwelling equates to a total heat loss of 46.5 W/K. In any case the heat loss coefficient does not affect the relative differences between the compared heating systems. The ambient air temperature, T_a, is taken from the hourly weather data and the base temperature, T_b, is set to 15°C and which is lower than the set point temperature as it accounts for internal gains.

$$Q_H = H(T_b - T_a) \tag{1}$$

The Primary Energy Factor (PEF)and CO^2 emissions factors of the two energy sources are presented in Table 1. These values are all multiplied by the delivered energy for heating to calculate the total primary energy consumption (kWh) and total carbon emissions ($kgCO^2$).

Table 1. Sources of energy taken from the SEAI [14].

Energy source	PEF	gCO^2/kWh
Natural Gas	1.1	204.7
Electricity	2.06	436.6

The PEF is calculated by the SEAI by dividing the total energy used to generate electricity divided by the total delivered electrical energy. The total energy used is the sum of the gross calorific values of the fuels (including an additional 5% for processing and transport to the plants) used and the renewable sources. The PEF is the inverse of the combined efficiency of the grid and Irish generator plant. The PEF has improved in recent years as shown in Fig. 2. The impact of this improvement in Ireland will be assessed in the context of the air-to-water heat pump.

The CO_2 conversion factor is calculated by the Sustainable Energy Authority of Ireland (SEAI) by dividing the total CO_2 emissions from the GCV of the various fuel sources by the total delivered electrical energy. The CO_2 figures are calculated for the individual sources of fuel and renewable energy is assumed to have zero CO_2 emissions.

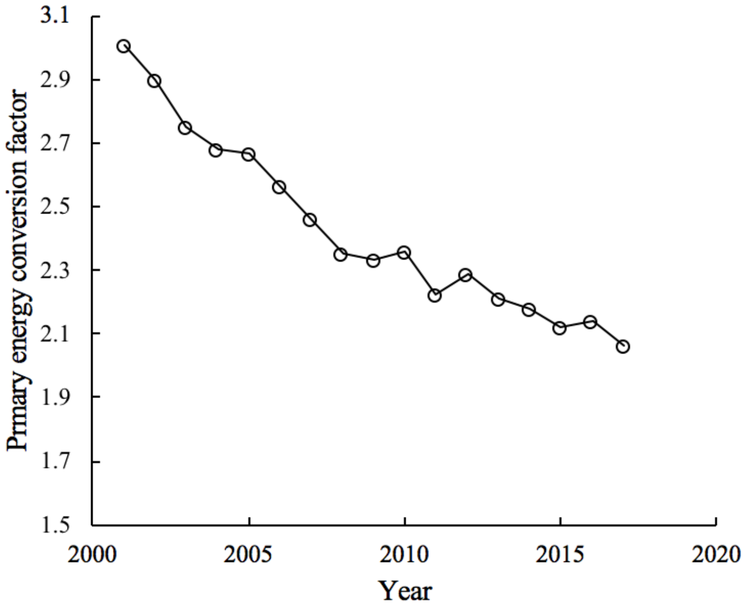

Fig. 2. Historical primary energy conversion factors for Ireland.

4 Results

Both national energy assessment procedures for Ireland and the UK require a minimum number of data points for assessment of air to water heat pumps from test conditions set out in EN 14511-2 [7]. An example of the data for a commercially available high performance 9kW heat pump is presented in Fig. 3. This heat pump is selected for analysis as the manufacturer's also prove additional data points at -15°C and 25°C.

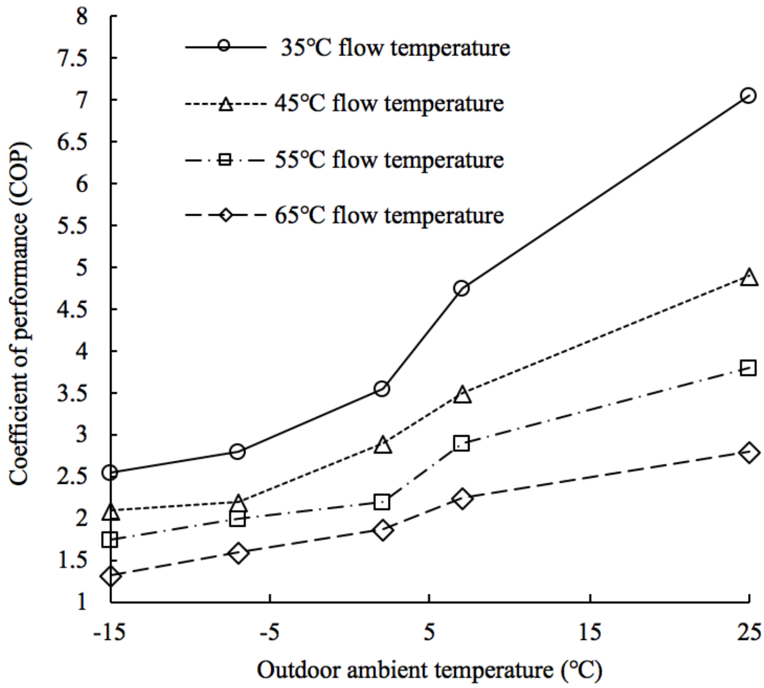

Fig. 3. COP vs Ambient temperature for a typical 9kW heat pump tested to in accordance to EN14511-2 [7].

The performance is compared for six separate heating periods from 2013 to 2018 and the average temperature as well as the six-year average temperature for this heating period is presented in Fig. 4. Over the six-year period there is no significant change in average temperature with a six-year average heating period temperature of 6.8°C. The heat pump performance curves from Fig. 3 are compared for these six years to estimate the SPF.

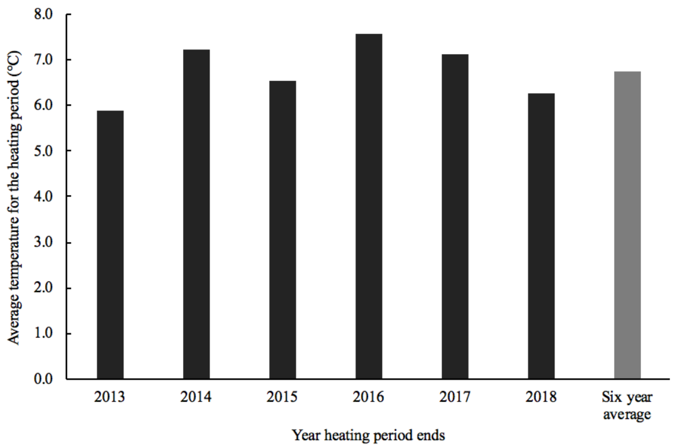

Fig. 4. Average outside air temperature for the heating period in Ireland for six years (2013 to 2018).

The SPF for the four different operating conditions for the six years are presented in Fig. 5. Six-year average SPFs of 4.53, 3.4, 2.74 and 2.17 are calculated for the four operating conditions (35°C, 45°C, 55°C and 65°C respectively). High SPF values are therefore achievable but specifically when the heat pump operates under optimum conditions. The total final energy consumed is proportional to the SPFs which for the air source heat pump running at an outlet temperature of 35°C results in 22% the energy consumption of a modern gas boiler with a 91% efficiency. In a retrofit scenario where the radiator temperature would be 65°C or higher there is a 44% reduction in final energy consumption compared with a gas boiler.

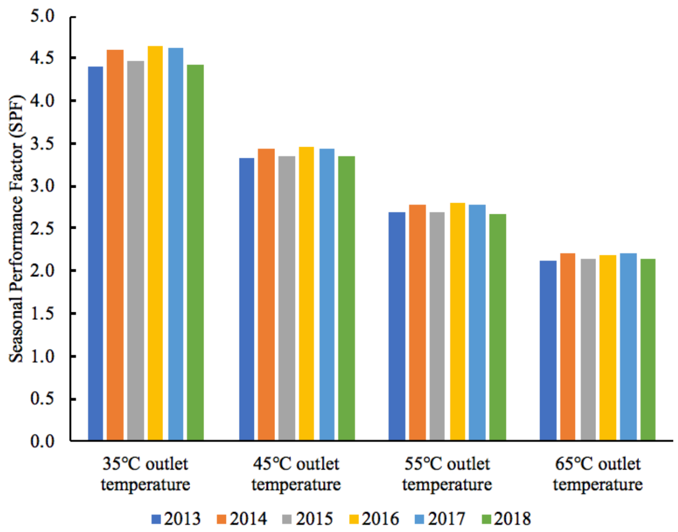

Fig. 5. Average COPs at four different outlet temperatures for six different years.

However, the sources of energy are different for a natural gas boiler and a heat pump which uses electricity. The primary energy associated to the different systems is calculated by applying the conversion factors from final energy consumed to primary energy which is higher for electricity than gas (Table 1). The primary energy required by the four heat pump heating systems are compared for a sample dwelling built to nZEB standards and are presented in **Fig. 6**.

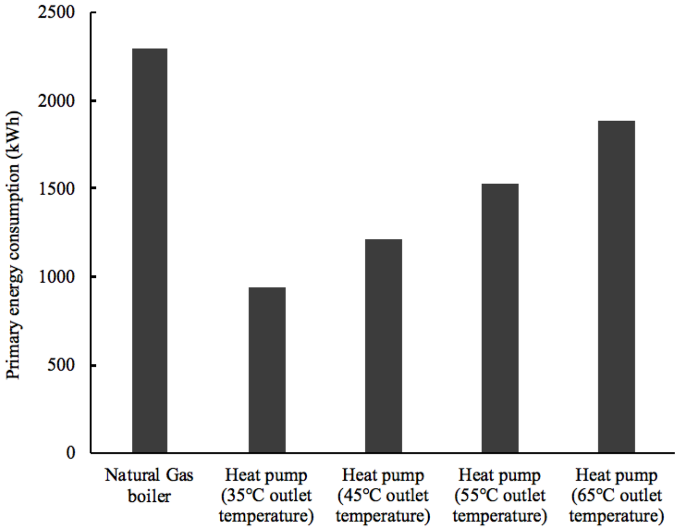

Fig. 6. Six-year average primary energy consumption for heating using five different heating systems.

In each case the primary energy requirement is less for the heat pump. The relative difference between primary energy requirement of the heat pumps and the gas boiler are, however, higher than the final energy consumed (as a result of the lower efficiency of the transformation, transmission and distribution process currently for electricity). For the air source heat pump running at an outlet temperature of 35°C the total primary energy required is 41% of the energy consumption of a modern gas boiler with a 91% efficiency.

In recent years effort has been made to increase the efficiency of the Irish grid and generation plants as is shown in the trend of reducing primary energy factor over time in Fig. 2. The effect of reducing the primary energy factor with primary energy consumption is compared in Fig. 7 which shows that only if the primary energy factor is kept low can heat pumps be regarded as more efficient than the gas boiler.

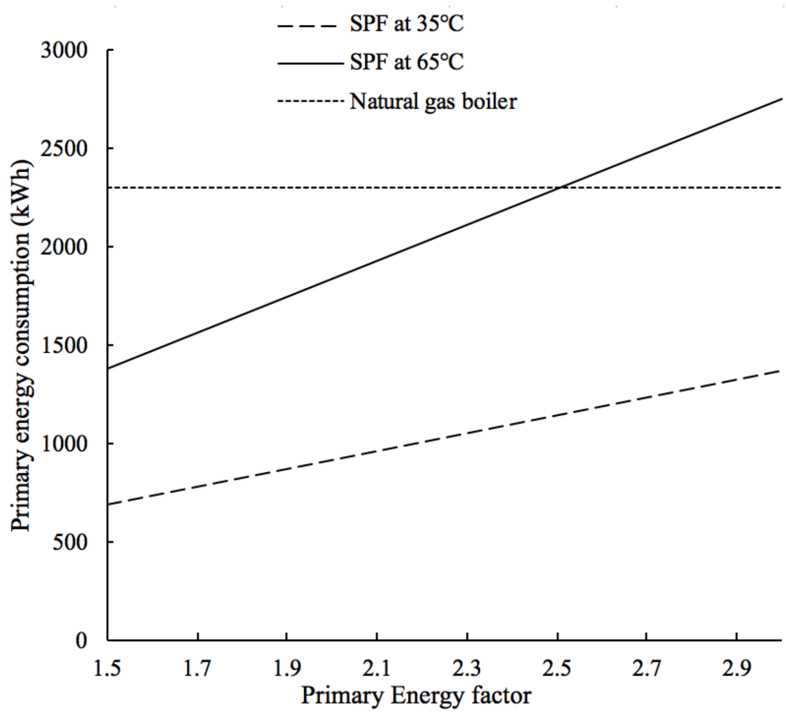

Fig. 7. Change in primary energy required for heating consumption with respect to the primary energy factor.

The CO2 emissions associated with the heat pumps operating at the various outlet temperatures are presented in Fig. 8. The CO2 emission factors, taken from Table 1, are applied to the final energy consumption for the five different heating systems. The results reveal that in a retrofit scenario where cast radiators are not replaced (65°C outlet temperature), there is only a very small difference in the total CO2 emitted for heating with a natural gas boiler. Further effort to decarbonise the grid is required if heat pumps are to provide a real solution for space heating in an Irish climate to combat climate change.

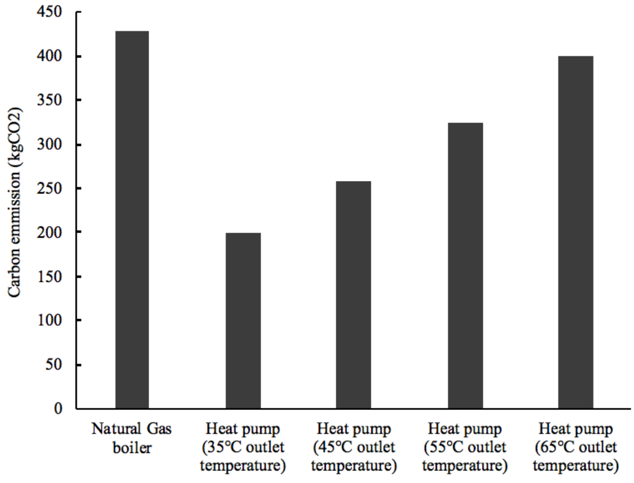

Fig. 8. Six-year average CO2 equivalent for heating using five different heating systems.

5 Discussion

The heat pump has been compared on a seasonal basis for different operating conditions using four different metrics:

- Final energy consumption in the dwelling
- Primary energy consumption
- CO_2 emissions

The performance of the heat pump and gas boiler are compared using these four metrics in Fig. 9 to summarise the findings. The figure shows that

- if the heat pump is operating with a COP lower than 2.0 the CO2 emission for a gas boiler is actually less,
- if COP is operating lower than 1.7 the primary energy of a gas boiler is less and
- A COP of 4.1 equates to the air source heat pump supplying an outlet temperature of 35°C when it is 5°C.

A heat pump operating with an outlet temperature of 35°C when it is -15°C still outperforms the natural gas boiler when comparing both primary energy and CO_2 emissions.

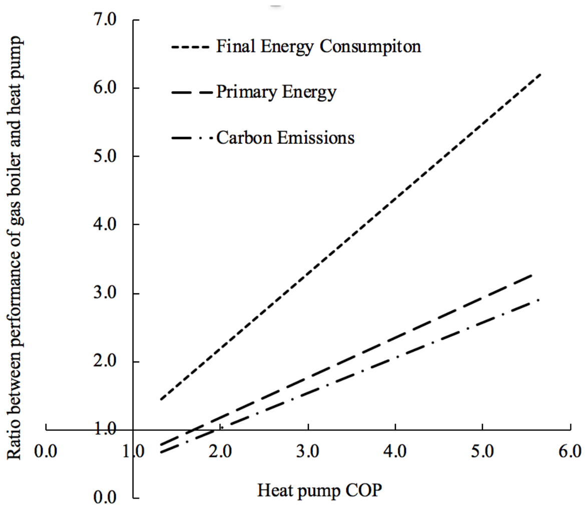

Fig. 9. Ratio between the performance of a heat pump and gas boiler for three different metrics, final energy consumption, primary energy and carbon emissions.

6 Conclusion

Heat pumps reduce energy consumption and are operated using electricity, meaning that they have great potential as a possible renewable solution for the supply of space heating to buildings. However, this potential can only be fully capitalised on by continuing to increase the grid efficiency and by switching to greener alternatives such as wind and solar.

This study found that, based on a simplified methodology, air-to-water heat pumps are a viable technology for Irish buildings, particularly if operated at low temperature applications. If operated at high temperatures, they perform similarly to natural gas boilers in terms of total carbon emissions.

Uncertainties still remain over the actual operating conditions such as the impact of relative humidity, installation quality, maintenance, type of heating system and overall building performance. To obtain this information the monitoring of real case study buildings is required. The nZEB101 project, funded by the Sustainable Energy Authority of Ireland, aims to validate the results of this work by monitoring the performance of heat pumps in-use over a two/three year period.

Acknowledgements

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