SELECTION OF LOW GWP REFRIGERANT FOR HEAT PUMP BY ASSESSING THE LIFE CYCLE CLIMATE PERFORMANCE (LCCP)

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Abstract: With the growing concern over global warming and increasing contribution of refrigeration and heat pump systems to climate change, it is necessary to mitigate the greenhouse gases emissions from refrigeration and heat pump system. To evaluate the environmental impact of heat pump system over its entire life cycle, the Life Cycle Climate Performance (LCCP) has been used. Current study presents the LCCP of 30 kW capacity air/water heat pump system, designed for retrofitting of heating systems in European building sector applications. The analysis is performed for selection of low GWP refrigerants with GWP values not greater than 150 (including R152a, R1234yf, R290, R1270 and others). The results are compared with the results of R410A, which is used as a reference refrigerant. In addition to the LCCP evaluation, thermophysical properties are taken into account in the process of refrigerant selection. As there is no perfect refrigerant, the advantages and disadvantages of different refrigerants are discussed. Based on the results of this study, one refrigerant is suggested to be used.

Key Words: refrigerant, LCCP, GWP, heat pump

1 INTRODUCTION

Heat pumps can be used to mitigate global CO_2 emissions. Heat pumps utilise energy required for their operation and complements it with renewable energy extracted from air, ground or water. Thus, heat pumps are able to deliver few times greater amounts of energy than other conventional heating technologies at the same equivalent greenhouse gases (GHG) emission rates.

The emissions from heat pump are strongly dependent on used refrigerant: the selection of refrigerant affects emission rate both directly (through the refrigerant release into atmosphere) and indirectly (by means of energy related emissions). Hence, in order to design environmentally friendly heat pump system, the selection of proper refrigerant is important.

Ideally, a perfect refrigerant should satisfy a number of important criteria, including:

- Non-flammable and non-toxic, easy leak detection
- Chemically and thermally stable, inert
- Suitable physical and thermodynamic properties (critical point and boiling point temperatures appropriate for the application, low viscosity, low vapour heat capacity, high thermal conductivity);
- Compatibility with materials, miscibility with lubricants
- Low cost;
- Low environmental impact.

To be environmentally friendly is no longer an option for refrigerants. It required by common sense and sanctioned by a number of legislations, including the Montreal protocol and

European Directive on mobile air-conditioning systems. The recent European F-gas Regulation proposal also promotes the use of environmentally friendly refrigerant. The proposed measures, among others, suggest that the amounts of newly introduced F-gases, expressed in tonnes of CO_2 equivalent, should be decreased to 21% of current values by 2030 (Council of the European Union, 2014). One way to achieve this goal is to use low GWP refrigerants in new equipment.
Current paper summarizes the selection process of the environmentally friendly low global warming potential (GWP) refrigerant for 30 kW heating capacity heat pump that is designed for retrofitting of heating systems in European building sector.
Life-cycle climate performance (LCCP) analysis is used when overall GHG emissions are estimated over entire lifetime of refrigerating and heat pump equipment system. The approach of estimating entire amount of GHG emissions associated with lifetime of refrigeration equipment, including consideration of equivalent warming impact of refrigerant and heat pump components during their production and end of life, was first introduced by Papasavva and Moomaw (1997) and led into the basis of LCCP methodology as it is used today. A number of studies have been made to estimate LCCP of various refrigeration equipment (Bovea et al., 2007; Horie et al., 2010; Minor et al., 2010; Papasavva et al., 2010). Zhang and Muehlbauer (2012) presented a LCCP model for residential heat pump systems. In their LCCP model, they studied different refrigerants such as R410A, R134a and R1234yf. According to their analysis, R1234yf has the lowest lifetime emissions, compared to the R134a and R410A refrigerants. However, they assume equal heat pump performance for every refrigerant in the analysis and thus underestimate the influence of refrigerant selection on total LCCP of heat pump.

2 PRESELECTING CANDIDATE REFRIGERANT LIST

Refrigerants with GWP of not greater than 150 are considered in the analysis. In addition to low GWP value, it was required that the candidates vapour pressure and compressor discharge temperature should not be greater than the values of the reference refrigerant R410A. These limits have narrowed the refrigerant selection towards four refrigerant options: two hydrocarbons (R290, R1270) and two hydrofluorocarbons (R152a, R1234yf).
Both R290 (propane) and R1270 (propene) are natural refrigerants. They are characterized with good thermo-physical properties and low GWP. They are also quite cheap and widely available on the market. R152a and R1234yf are synthetic refrigerants. Volumetric cooling capacity and pressure levels of R1234yf and R152a are very similar while cycle performance of R152a is more favourable. Pressure levels of preselected hydrocarbons (HCs) are high, but still below the reference values of R410A.
Key properties of the preselected refrigerants are summarized in the Table 1. In comparison to the reference refrigerant R410A, all four preselected refrigerants are flammable, whereas the flammability of hydrocarbons is highest and flammability of R1234yf is the lowest among four refrigerant candidates. Thus, regardless of the selection result, refrigerant flammability needs to be accounted for in the heat pump design.

Table 1: Key properties of the preselected and the reference refrigerants

Refrigerant	Critical temperature, °C	Discharge T*, °C (isentropic compression)	Absolute pressure level at design condensing temperature*, bar	ASHRAE 34 safety group	GWP^, 100yr
R152a	113,3	84,5	14,0	A2	124
R1234yf	94,7	58,0	15,3	A2L	4#
R290	96,7	70,3	19,9	A3	3,3
R1270	91,1	79,5	23,8	A3	1,8
R410A	72.8	93,6	35,8	A1	2088

* Values calculated at T_{evap}=-18℃ T_{cond}=57℃, 5℃ subcooling, 5℃ superheat
^ Source: IPCC Fourth Assessment Report: Climate Change 2007 (IPCC AR4, 2007)
# Source: Nielsen et al. (2007)

3 LIFE CYCLE CLIMATE PERFORMANCE ANALYSIS

Life cycle climate performance of heat pump system is evaluated in order to identify the most environmentally friendly refrigerant out of the preselected ones. LCCP evaluation includes estimation of direct and indirect GHG emissions of the system through its entire lifetime and thus provide holistic picture of environmental impact of different refrigerants. The expression presented on the Equation 1 is used for LCCP calculation in current analysis.

$$LCCP = \text{total lifetime direct emissions} + \text{total lifetime indirect emissions} = (GWP \cdot L \cdot n) + (Ea \cdot \beta \cdot n) + I + D \quad (1)$$

where
GWP – global warming potential of refrigerant
L – annual leakage rate in the system, kg
n – lifetime of the system, years
Ea – annual energy consumption, $kWh \cdot year^{-1}$
β – carbon dioxide emission factor (kg CO_2-eq. emissions per kWh).
I – Other indirect emissions (materials and refrigerant chemical consumption and transport, recycling), kg CO_2-eq.
D – Other direct emissions (manufacturing, transportation and end-of life leakage), kg CO_2-eq.
Thus, in order to obtain LCCP value, each of the components of the Equation 1 needs to be determined for every refrigerant.

3.1 Global Warming Potential

Used Global Warming Potential (GWP) values in the calculation are those that referred in the IPCC Fourth Assessment Report (IPCC AR4, 2007). For refrigerant R1234yf the value is taken from the work of Nielsen et al. (2007). All the values are summarised in the Table 1.
All the selected refrigerants have low GWP values that are many times lower than the reference R410A refrigerant. It can been seen from the table that the global warming potential of R152a at 100 years time horizon is more than 16 times lower than R410A and global warming potential of R290 is more than 630 times lower than R410A.

3.2 Annual Leakage Rate in the System

Refrigeration plants often leak refrigerant into the environment. Data regarding leakage rate varies greatly depending on refrigeration system type, local installation standards and service quality. Annual leakage rate in range of 2-10% of refrigerant charge can be found in literature (AHRTI, 2011). Four litres of refrigerant charge with the annual leakage rate of 3% of the charge was assumed for this analysis.

3.3 System Lifetime and Running Time

Heat pump system is assumed to be located in the central European region with average European climate conditions. The lifetime of the refrigeration system is assumed to be 15 years. Considering that no auxiliary heating is foreseen, the entire heating demand during the year has to be covered by the heat pump, which is assumed to be capable to perfectly match the heating demand of the building throughout the entire heating season. For any location, the length of the heating season is dependent on the local climate conditions. The climate data for three main European climates is listed in the standard EN 14825:2012 which, among others, provides guidelines for calculation of the seasonal performance of heat pumps (ECS, 2012). For average European climate zone location a system running time is 4910 hours per year, whereas the number of hours at any ambient temperature during the heating season is presented in the Figure 1.

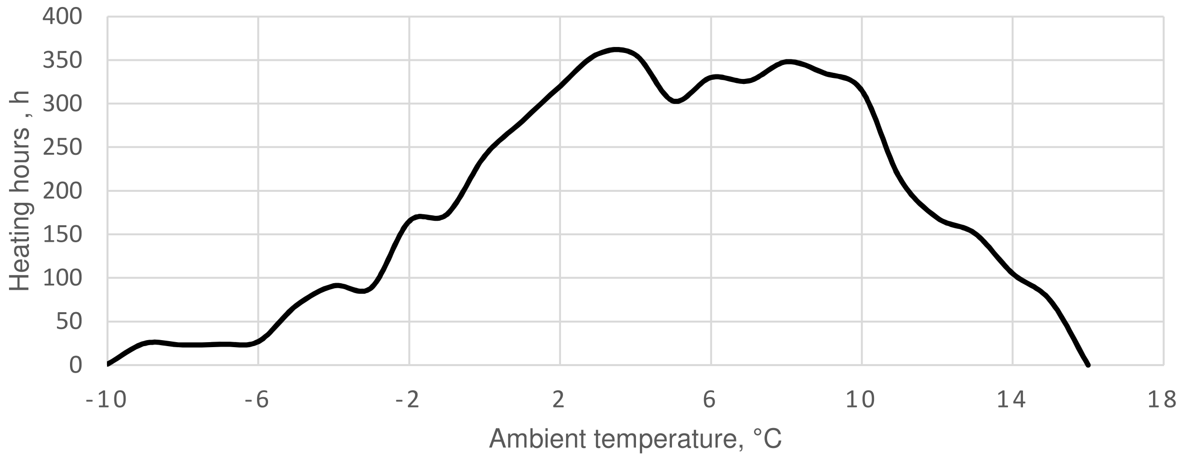

Figure 1: Amount of the heating hours for every temperature bin at the average European climate zone (ECS, 2012).

3.4 Annual Energy Consumption

Energy consumption of the heat pump is an important parameter as affects the amount of indirect emissions from the heat pump operation. The consumption varies during the year and depends on many factors, such as heating demand, ambient temperature and the refrigerant as well.
Annual energy consumption could be calculated by knowing annual heating demand and seasonal coefficient of performance (SCOP), which represents the seasonal efficiency of a heat pump unit. SCOP, in turn, is calculated based on the guidelines of the Standard 14825:2012 (ECS, 2012) for each refrigerant at the chosen location. The seasonal performance of heat pump is calculated by the formula, suggested by the Standard 14825:2012 (ECS, 2012). Taking in account heat pump system design without electrical backup heater, the formula could be rewritten in the form, presented at Equation 2 below:

$$\mathrm{SCOP}_{net} = \frac{annual\ heating\ demand}{annual\ energy\ consumption} = \frac{\sum_{j=1}^{n}\ h_j P_h(T_j)}{\sum_{j=1}^{n}\ h_j \frac{P_h(T_j)}{COP_{PL}(T_j)}} \qquad (2)$$

where
$SCOP_{net}$ – net seasonal efficiency calculated for the reference annual heating demand;
T_j – the bin temperature, ℃; j – the bin number; n – the amount of bins;
$Ph(T_j)$ – the heating demand of the building for the corresponding temperature T_j, kW;
h_j – the number of bin hours occurring at the corresponding temperature T_j, h;
$COP_{PL}(T_j)$ – the COP values of the unit for the corresponding temperature T_j.

Bin temperatures reflect the ambient air temperature conditions and listed as standard for three main heating seasons: “warmer”, “average” and “colder”. The average heating season bin temperatures (as presented in the Figure 1) are used in this calculation.

The heating demand of the building is assumed to vary linearly from being zero at the ambient temperature of 16 °C to 30 kW at the reference design temperature for heating (-10 °C). Thus, the heating demand at any ambient temperature during the heating season is calculated using the Equation 3:

$$P_h(T_j) = P_{design} \frac{T_j - 16}{-10 - 16} \ \% \qquad (3)$$

$COP_{PL}(T_j)$ values of the heat pump system was calculated for each refrigerant at every corresponding bin temperature. The modelled system assumed to operate with scroll compressor with enhanced vapour injection system with both superheating and subcooling of 5°C.
At the design of evaporator and condenser heat exchangers, 5 °C logarithmic mean temperature difference is used at calculation UA values. Additionally, air temperature drop across the air side of evaporator is assumed to be 5°C at any operation condition.
Heating distribution in the building is maintained by radiators with 55 °C/45 °C input/output temperatures at the design conditions. By using Equation 4 the actual heating demand at given ambient temperature is calculated.

$$Q = Q_{ref} * \left(\frac{\Delta T}{\Delta T_{ref}}\right)^n \qquad (4)$$

where
ΔT_{ref} – temperature difference between input to radiators at the design conditions (55 °C) and temperature in the room (20 °C);
Q_{ref} – heating demand at the design conditions (30 kW);
Q – actual heating demand, kW;
ΔT – actual temperature difference, °C;
n – is the radiator constant, which is the characteristics of the radiator (n=1.3 in our analysis).

Figure 2 shows COP values for five refrigerants at different outdoor temperatures. As one can see, at higher ambient temperatures, R152a has higher performance compared to other three refrigerants. However, at ambient temperatures of around -3 °C and lower both R290 and R1270 outperform R152a. R1234yf has the lowest performance at low ambient temperatures, however at higher ambient temperatures its performance improves and at ambient temperatures greater than 5 °C this refrigerant is more efficient than hydrocarbons R290 and R1270. However, even at high ambient temperatures R1234yf is still less efficient than R152a.

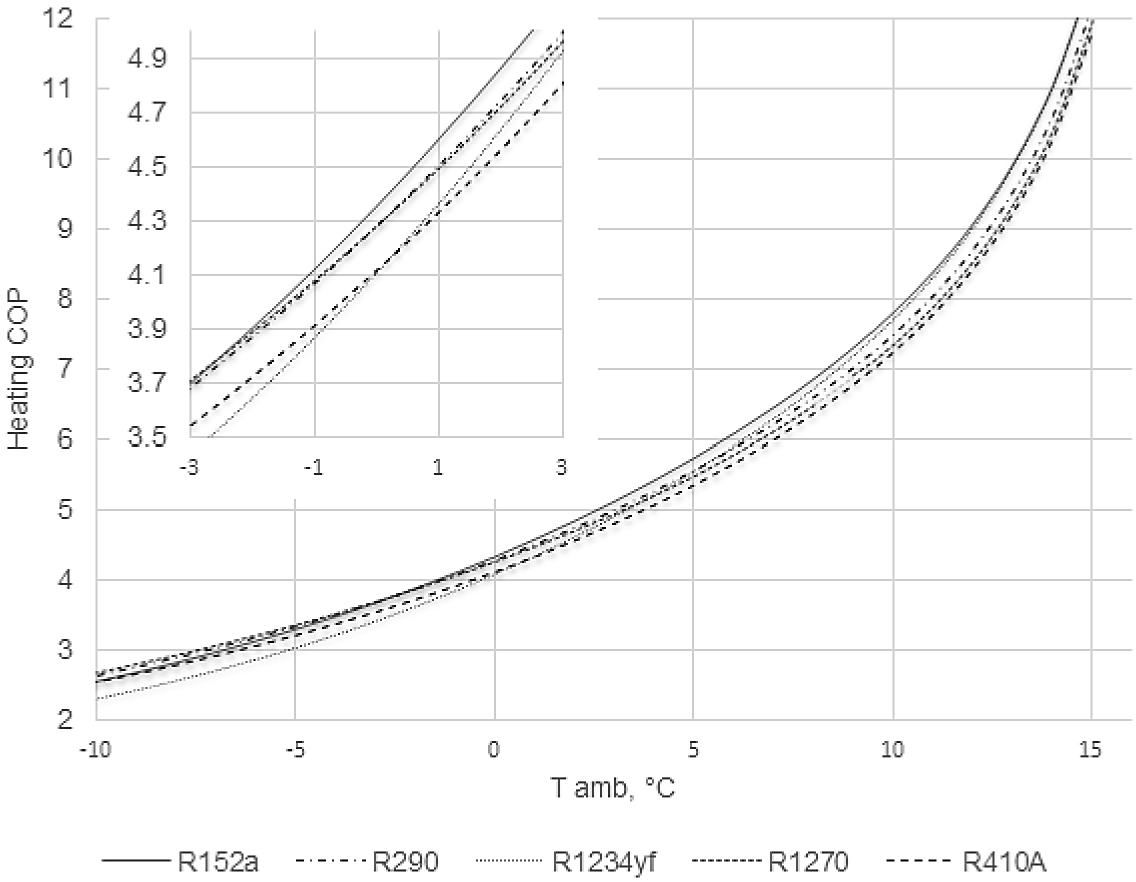

Figure 2: Heating COP of the heat pump over a range of ambient temperatures

Based on the above data, seasonal performance of heat pump system and its annual energy consumption are calculated. R152a shows to be the refrigerant that provides the best performance with resulting value of SCOP of 4.17. Other refrigerants have lower seasonal performance (SCOP) with values of 4.12, 4.11 and 3.88 for refrigerants R1270, R290 and R1234yf respectively. The SCOP of the reference refrigerant R410A is among the lowest and is equal to 3.96. As discussed before the values of SCOP of different refrigerants affects the indirect emissions at the LCCP analysis.

3.5 Carbon Dioxide Emission Factor

Carbon dioxide emission factor of supplied electricity to heat pump is much dependent on the electricity origin. In current study, the heat pump is considered to be connected to UCTE European electricity grid with carbon intensity of electricity distributed within the grid equal to 165 g CO_2-eq per kWh of energy (Ecoinvent Centre, 2007). Although the UCTE grid has been recently integrated into bigger European network of transmission system operators for electricity (ENTSO-E), the selection of UCTE electricity grid will better represent central European location.

3.6 Other Indirect Emissions

Equivalent CO_2 emissions that occur during production of materials are considered in the LCCP analysis. These emissions are estimated based on a typical heat pump material composition which consist of few main materials including, 31 kg of copper, 19 kg aluminium, 76 kg of steel, 1.8 kg of brass and 38 kg of plastics (Zhang et al., 2011). For respective CO_2

equivalent emissions during production Ecoinvent 2.2 database (Ecoinvent Centre, 2007) has been used. For plastics, the value was obtained from the life cycle data of American Chemistry Council (ACC, 2010). All these values are given in Table 2.

Table 2: Specific CO_2-equivalent Emissions During Heat Pump Components Manufacturing

Material	Emissions, kg CO_2-eq./kg mass	Material	Emissions, kg CO_2-eq./kg mass
Aluminium	8.55	Brass	2.45
Copper	1.88	Plastics	3*
Steel	1.72	* Source (Zhang et al., 2011)	

The recycling of heat pump components is also energy intensive and requires 1.7 MJ to recycle one kg metals and 0.15 MJ to dispose one kg of plastics. The energy is than converted to CO_2-eq. emissions, assuming that 100g CO_2-eq. emissions corresponds to every MJ of used energy for recycling of metals and plastics. These values are adopted from the model of Zhang et al. (2011).

3.7 Other Direct Emissions

Apart from global warming of the refrigerants themselves, there are CO_2-equivalent emissions associated with refrigerant manufacturing. For R-410A the value is the highest and equals to 11.4 kg CO_2-equivalent emissions per produced kg refrigerant (Zhang et al., 2011). That follows with other synthetic refrigerants – 8 kg CO_2-eq./kg for R1234yf (Zhang et al., 2011) and 5.45 g CO_2-eq./kg for R152a (Ecoinvent Centre, 2007). Whereas GHG emissions from manufacturing of HCs are among the lowest – 1,43 kg CO_2-eq./kg for both Propene (Ecoinvent Centre, 2007) and Propane (Zhang et al., 2011).
In addition to regular leakage, some refrigerant loss can occurs at the equipment's end of life (EOL). Assuming 5% leakage from the total charge at the EOL, and recovering of 90% of the charge, the assumption of 15% refrigerant loss at EOL can be made (Sand et al., 2001).
Leakage of refrigerant during transportation to the heat pump assembly plant facility is small and assumed to be 0.03% of the transported amount (Papasavva et al., 2010). Indirect emissions of transport itself during transportations are neglected in current analysis.

4 RESULTS AND DISCUSSION

The LCCP analysis of four preselected refrigerants and the reference one has been performed to reveal the one providing the best environmental performance. The indirect emissions associated with the use heat pump are dominant in the total life cycle analysis. 98.5% of the entire amount of the emissions are indirectly originated from electricity consumption during heat pump operation, while only 0.2% – are direct emissions associated with GWP of refrigerants (Figure 3). This results are in agreement with the previous life cycle analyses, where it was claimed that the total lifetime climate performance is very much dependent on system efficiency and the used fuel mix during production of the electricity for operation of the heat pump (Papasavva and Moomaw, 1997; Zhang and Muehlbauer, 2012). However, the direct emissions of the low GWP refrigerants approaches negligible value of less than one present of total lifetime emissions.

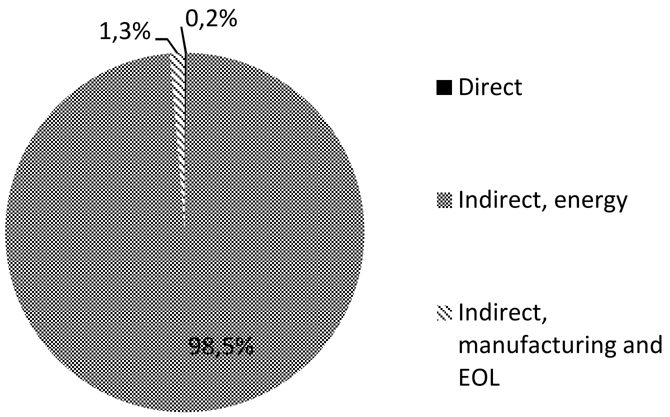

Figure 3: Share of direct, indirect, and indirect during manufacturing and EOL in total emission amount (averaged for the analysed low GWP refrigerants)

The LCCP calculation results are presented on Figure 4. As it is expected based on above discussed SCOP values, R152a has the lowest life cycle climate impact and R1234yf – the highest. The indirect contribution of R410A refrigerant is close to other refrigerants, but due to its significantly higher GWP value, it has higher LCCP.

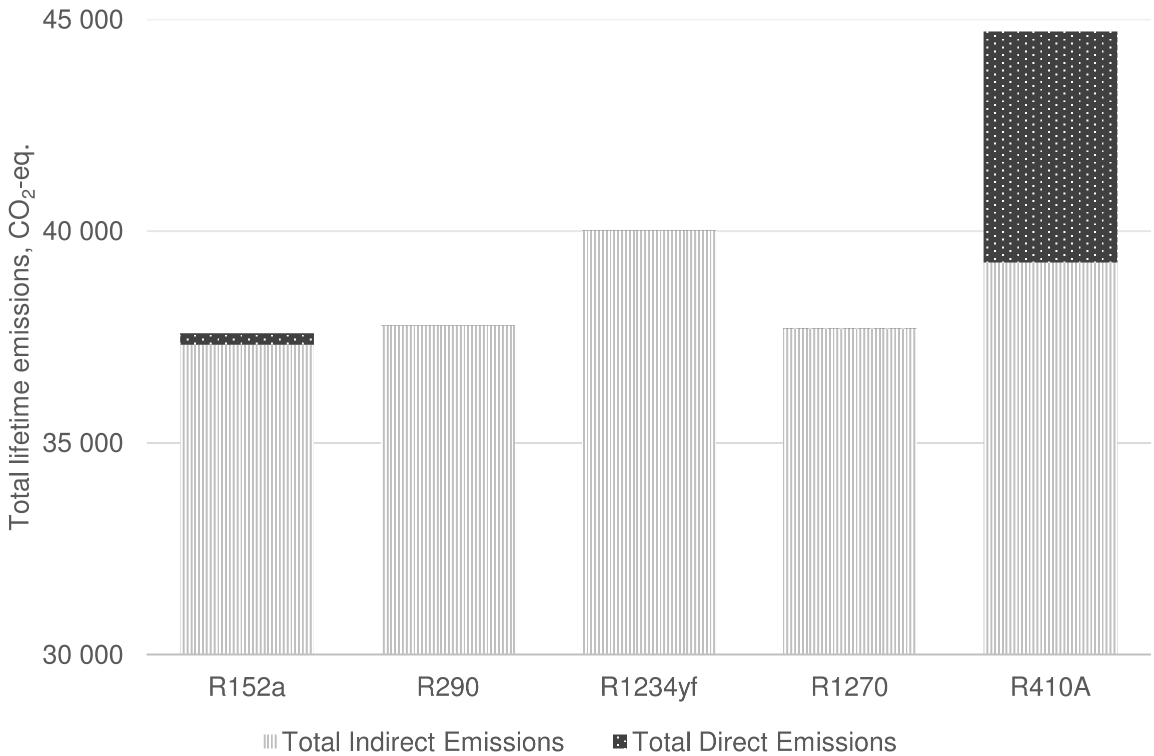

Figure 4: Total lifetime CO_2-equivalent emissions associated with heat pump operation, all refrigerants

Among the low GWP refrigerants, R1234yf has the highest lifetime emissions, whereas R152a, R290 and R1270 have almost equal values, with slightly better performance for the hydrocarbons. The difference between R290, R1270 and R152a is negligibly small and, from

the environmental point of view, R290, R1270 and R152a could be considered as equally good. Thus, the selection of low GWP refrigerant for heat pump application among the R290, R1270 and R152a should be continued based on other selection criteria.
Both propane and propene are good refrigerants; however, the priority can be given to Propane due to lower vapour pressures, which is preferred for the heat pump's heat exchanger design.
Thus, the main selection is to be done between R152a and R290. Both refrigerants are flammable while R152a is less flammable than R290.
In terms of operating pressures, R152a is more beneficial with lower pressure than R290 that affects the design of the heat exchanger. While from compressor design point of view, R290 is a preferred option as it has higher volumetric capacity and will requires smaller compressor.
From environmental point of view, many counties have already implemented or planning to implement in the coming future measures to limit the use of hydrofluorocarbons. Thus, for instance European Union is likely to adopt a regulation to phase-down fluorinated gases usage to 21% of current levels (Council of the European Union, 2014). In face of this regulation, the selection of natural refrigerant as a working fluid for environmentally friendly heat pump is more reasonable.
Based on the considerations above, it could be concluded that R290 is the best refrigerant option to use in 30 kW capacity air/water heat pump system designed for residential heating application.

5 CONCLUSION

LCCP analysis of 30 kW capacity air/water heat pump system has been performed. Refrigerants with low GWP were selected as potential candidates for the heat pump. Results reveal that indirect emissions are dominant in total lifetime emissions amount. For low GWP refrigerants, the dominance of indirect emissions is significant as the share of indirect emissions due to energy consumption reaches 98%. Thus, system performance is of vital importance in order to minimise total lifetime climate impact from heat pump operating with low GWP refrigerant.
LCCP analysis revealed that all the low GWP options have lower life cycle climate emissions, compared to the baseline R410a. Out of the four low GWP refrigerants, the best environmental performance is achieved by the refrigerants with higher seasonal performance. In general terms, the selection of environmentally friendly low GWP refrigerant is a selection of the most efficient one.
While R1234yf has shown the lowest performance, refrigerants R152a R290 and R1270 are considered equally good according to the resulting LCCP values. Thus, any of these refrigerants can be used to design environmentally friendly heat pump system. Taking in account additional considerations, the refrigerant selection has been made in favour of R290 refrigerant.

6 ACKNOWLEDGEMENTS

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