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The role of electric heat pumps in the decarbonisation of the heating sector in Europe

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Abstract

Mitigation of greenhouse gases, dependency of fossil fuel and security of energy supply are on top of the agenda in all energy discussions. This sets the focus on energy efficiency and the use of renewable energy in all sectors. The European Union has set ambitious targets to improve energy efficiency, increase the use of renewable energy and reduce greenhouse gas emissions by 2030. Up until recent years most of the focus has been on the electricity and transport sector. The building sector has largely been overlooked. However as approximately 40% of the total energy use in Europe is related to buildings, this sector has one of the largest potential for reducing greenhouse gas emissions. The objective of this paper is to present a general methodology on how to determine greenhouse gas emissions related to different sources of heating and to what extent a wide introduction of electric heat pumps will contribute to a decarbonisation of the heating sector. The methodology is additionally used to calculate primary energy savings as well as to give an indication of potential operating cost savings by use of available statistics for different energy sources. The results show that electric heat pumps has a significant potential to improve energy efficiency (53 – 81%) and reduce greenhouse gas emissions (57 – 99%) while replacing old inefficient boilers in Europe.

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Keywords: heat pump; decarbonise; greenhouse gas emissions; primary energy; final energy; primary energy factor;

1. Introduction

This paper explains the development of a methodology to estimate the potential for a reduction of green housegas (GHG) emissions when heat pumps are replacing conventional heating systems. The main objective of this paper is to make an assessment on GHG-emission reduction and primary energy savings that may be accomplished while replacing old fossil boilers by electric heat pumps. Other types of heat pumps such as thermally driven and fuel engine driven heat pumps are commercially available but not included in the study that serves as a basis for this paper. At local and regional level emission reduction of particles, SOx and NOx may be just as important drivers to phase out the use of old boilers. The model used for all calculations allow for the use of different assumptions of efficiency at appliance level as well as the generation of electricity on national level. The GHG-emission savings are calculated and expressed in terms of carbon dioxide equivalents (kg CO_2eq). The calculations are performed by use of emission factors (ef_{xx} [kg CO_2eq/kWh]) for different energy carriers and national emission factors for the generation of electricity. The example calculations of primary energy savings are, where existing, based on official primary energy factors for different energy carriers.

2. On how to compare energy efficiency of different heating systems

When we are to compare the energy efficiency of heating systems, we need to realise that the result will depend on the boundaries for the system in view. Different stake holders would set the boundaries from different perspectives. The end user of a heating system would naturally define the efficiency as the useful heat in

relation to the amount of energy that needs to be purchased. This is however not sufficient when energy systems are studied from a broader perspective, as energy losses and emissions from different types of heating systems appear at different stages in the energy chain. An electric boiler might seem very efficient from the perspective of the end consumer, but if we take into account for distribution losses and losses at point of electricity generation and even further up the energy chain, it is evident that electric heating is not as efficient as the customer might perceive. In order to obtain an impartial comparison of the energy efficiency and total emissions for different types of systems, it is essential to extend the system boundary beyond the external wall of the heated building.

If we start with the actual energy needed to heat a building and add all the losses in the heating appliance, distribution and if applicable power generation as well as energy use for extraction, refinement and transportation of fuels we end up at a final value that gives a better representation of the energy needed to supply one unit of heating. The total amount of energy including the energy content of the energy carrier itself and all the energy required for extraction, refinement, transformation and distribution is often referred to as primary energy. An assessment of primary energy use is often required in order to enable a fair comparison of different heating systems using different energy carriers. In order to simplify a primary energy assessment, it is common to use a set of precalculated primary energy factors (PEF) for different energy carriers. The primary energy use is given by the purchased energy multiplied by the PEF for the energy carrier in use. The European standard EN 15603 defines a methodology, including a few alternatives, on how to calculate PEF.

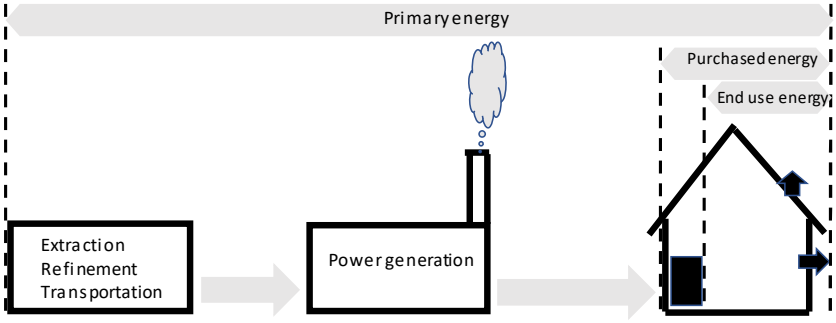


Figure 1 System boundaries for primary energy definition

2.1 The use of primary energy factors, PEF

Within the European Union there are several policy instruments e.g. the Energy Efficiency Directive and the Energy Performance of Buildings Directive [1, 2] that requires the use of PEF for different energy carriers. The default value for the primary energy factor for electricity for all Member States has recently been reviewed and changed from 2,5 to 2,1. The revision was based on a study initiated by the European Commission and finalised 2016 [3]. The study presents 4 principal methods that may be used to calculate the PEF and elaborate pros and cons for each method. It is evident that the applicable system boundaries and time frames chosen for the calculation of the PEF will vary from country to country and thus result in different values. It is however vital that the calculations of the PEFs are made in a transparent manner avoiding arbitrary assumptions chosen to fit a predefined purpose. As this study is focusing on the transformation of the heating in buildings, we have chosen to use the PEFs that have been established for use in the building codes in different countries.

3. Calculation of primary energy savings

While assessing the potential primary energy savings that can be achieved by replacing conventional boilers with electric heat pumps we need to take into account for the efficiency of the appliances we are addressing as well as the primary energy factors for electricity and the energy carrier of the system we are considering to

replace. Even though the model we are describing in this paper is generic and may be used for any type of heating system, the derivation is given for the example of replacement of an existing gas boiler.

The primary energy use of a gas boiler may be expressed as follows;

$$E_{Prim\ Gas} = \frac{Q_H \times PEF_{gas}}{\eta_{gas}} \quad (1)$$

Where;

$E_{Prim\ Gas} = Primary\ \ energy\ \ use\ \ of\ \ a\ gas\ boiler$

$Q_H = Annual\ \ heating\ \ demand$

$PEF_{gas} = Primary\ \ energy\ \ factor\ \ for\ \ gas$

$\eta_{gas} = Annual\ \ efficiency\ \ \ \ of\ \ the\ gas\ boiler$

The primary energy use of an electric heat pump may be expressed as follows;

$$E_{Prim\ HP} = \frac{Q_H \times PEF_{el}}{SPF} \quad (2)$$

Where;

$E_{Prim\ HP} = Primary\ \ energy\ \ use\ \ of\ \ the\ heat\ \ pump$

$Q_H = Annual\ \ heating\ \ \ demand$

$PEF_{el} = Primary\ \ energy\ \ factor\ \ for\ \ electricity$

$SPF = Seasonal\ \ performance\ \ factor\ \ of\ \ the\ heat\ \ pump$

By use of equation 1 and 2 we may now deduce the relative primary energy savings.

$$\frac{\frac{Q_H \times PEF_{gas}}{\eta_{gas}} - \frac{Q_H \times PEF_{el}}{SPF}}{\frac{Q_H \times PEF_{gas}}{\eta_{gas}}} = \frac{\frac{PEF_{gas}}{\eta_{gas}}\left(1 - \frac{PEF_{el}\ \eta_{gas}}{PEF_{gas}\ SPF}\right)}{\frac{PEF_{gas}}{\eta_{gas}}} \quad (3)$$

Thus, the relative primary energy savings are given by the relation between the primary energy factors and the relation between the annual efficiencies of the appliances.

$$Relative\ \ \ primary\ \ energy\ \ savings = \left(1 - \frac{PEF_{el}}{PEF_{gas}}\frac{\eta_{gas}}{SPF}\right) \quad (4)$$

Equation (4) is in its form general and may be used to calculate the relative primary energy savings that may be achieved while replacing any type of heating system with a heat pump. In order to make the calculation for replacement of oil or solid coal the primary energy factor for gas (PEF_{gas}) and the annual boiler efficiency (η_{gas}) shall be replaced by the respective constant for the relevant system.

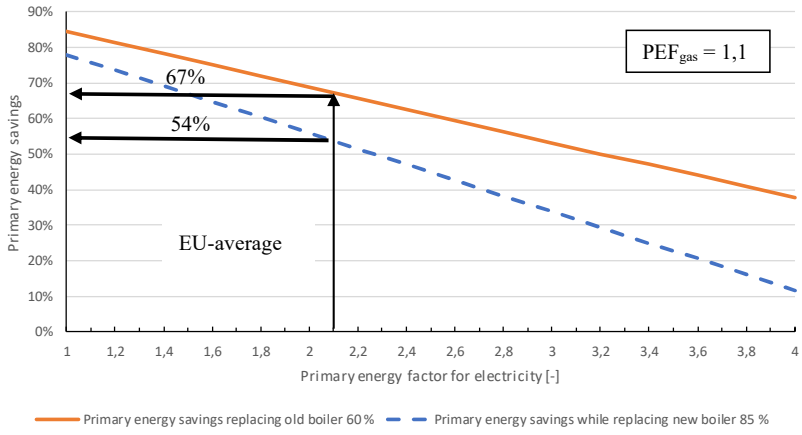


Figure 2 Primary energy savings - heat pump replacing boiler

Figure 2 illustrates the primary energy savings that will be achieved by replacing boilers with an electric heat pump operating at an annual SPF of 3,5. The European Union has established that the average of European electricity generation corresponds to a primary energy factor of 2,1. This value may be used by the Member States to assess national improvements of energy efficiency. However, Member States are free to establish their own primary energy factor based on the national mix of the generation of electricity. The ongoing transition of the electricity sector characterised by an increasing share of renewables is improving the efficiency over time and thus leading to a lower primary energy factor. These improvements enhance the primary energy savings further.

Table 1 below depicts the calculated primary energy savings that will be achieved for 9 different Member States. The calculations are based on the primary energy factors for electricity that has been established in each country to be used in the building codes.

*Table 1 Primary energy savings; old boiler (60%), new boiler (85%), * PEF for Sweden = 1,85 is to be confirmed during 2020*

Country	PEF$_{elec}$	Primary energy savings, old boiler	Primary energy savings, new boiler
France	2,58	60%	43%
Germany	1,8	72%	60%
The Netherlands	2,56	60%	43%
The United Kingdom	1,5	77%	67%
EU-average	2,1	67%	54%
Czech	3,0	53%	34%
Slovakia	2,2	66%	51%
Poland	3,0	53%	34%
Finland	1,2	81%	74%
Sweden*	1,85	71%	59%

The results reveal that significant energy savings may be achieved by replacement of old inefficient boilers (53 – 81%). Furthermore, it can be seen that a replacement of more efficient boilers contributes to an improvement in the heating sector (34 – 74%).

4. Calculation of reduction of greenhouse gas (GHG) emissions

While addressing the greenhouse gas emissions, expressed in the form of CO_2-eqvivalents, we may in an analogous manner derive a general equation as depicted below.

The GHG-emissions generated by a gas boiler may be expressed as follows;

$$GHG_{gas} = \frac{Q_H \times e_{gas}}{\eta_{gas}} \tag{5}$$

Where;

$GHG_{gas} = green\ \ house\ \ gas\ \ emissions\ \ \ \ generated\ \ \ \ by\ a\ gas\ \ boiler$

$Q_H = Annual\ \ heating\ \ \ \ demand$

$e_{gas} = Emission\ \ \ \ factor\ \ \ \ for\ \ gas$

$\eta_{gas} = Annual\ \ efficiency\ \ \ \ \ \ of\ \ the\ gas\ \ boiler$

The GHG-emissions generated by a heat pump may be expressed as follows;

$$GHG_{HP} = \frac{Q_H \times e_{elec}}{SPF} \tag{6}$$

Where;

$GHG_{HP} = green\ \ house\ \ gas\ \ emissio\ \ ns\ \ generated\ \ \ \ by\ a\ heat\ \ pump$

$Q_H = Annual\ \ heating\ \ \ \ demand$

$e_{elec} = Emission\ \ \ \ factor\ \ \ \ for\ \ electricity$

$SPF = Seasonal\ \ \ \ performance\ \ \ \ factor\ \ \ \ of\ \ the\ heat\ \ pump$

By use of equation 5 and 6 we may deduce the relative reduction of greenhouse gases that may be achieved while replacing a gas boiler with a heat pump.

$$\frac{GHG_{gas} - GHG_{HP}}{GHG_{gas}} = \frac{\frac{\cancel{Q_H} \times e_{gas}}{\eta_{gas}} - \frac{\cancel{Q_H} \times e_{elec}}{SPF}}{\frac{\cancel{Q_H} \times e_{gas}}{\eta_{gas}}} = \frac{\frac{\cancel{e_{gas}}}{\cancel{\eta_{gas}}}\left(1 - \frac{e_{elec}}{e_{gas}}\frac{\eta_{gas}}{SPF}\right)}{\frac{\cancel{e_{gas}}}{\cancel{\eta_{gas}}}} \tag{7}$$

Thus, the relative reduction of greenhouse gases is given by the relation between the primary energy factors and the relation between the annual efficiencies of the appliances.

$$Relative\ \ \ \ GHG\ emission\ \ \ \ savings\ \ \ = \left(1 - \frac{e_{elec}}{e_{gas}}\frac{\eta_{gas}}{SPF}\right) \tag{8}$$

Figure 3 below illustrates the reduction of greenhouse gas emissions that will be achieved by a replacement of gas boilers with electric heat pumps (SPF = 3,5) as a function of the emission factor for the generation of electricity. Results show that an electric heat pump that replace a gas boiler will contribute to a reduction of GHG-emission by the order of 65 – 75% if we base the calculation on the European average emission factor for generation of electricity (295,8 gCO_{2eq}/kWh_{elec}) [4].

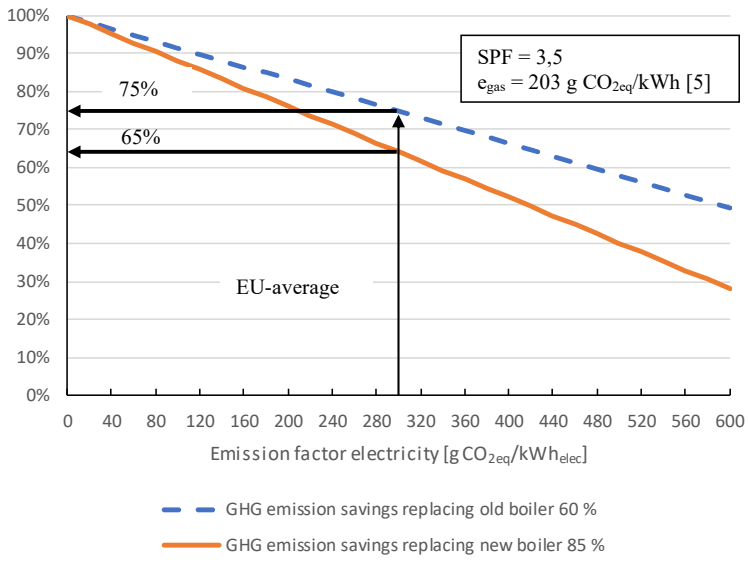


Figure 3 Reduction of greenhouse gases

Figure 3 visualise the impact of the carbon intensity of the electric grid. The reduction of greenhouse gas emissions by retrofitting old boilers with electric heat pumps are significant in all European countries, but varies a great extent depending on the carbon content of electricity. Poland is one of the countries that has one of the highest emission factors for electricity in Europe (773,3 gCO_2/kWh_{elec}) [4] show the lowest potential, but in this case it might be relevant to perform the assessment based on the assumption that the heat pump replace an old coal-fired boiler which is still used to a large extent. In this case a heat pump retrofit will decrease the greenhouse gas emissions by the magnitude of 60% and the benefits will increase over time as the greening of the grid will come into effect. Table 2 below show the potential of reduction of GHG-emissions in 9 European countries, based on the latest available data of the carbon intensity in the national grid. The calculations are based on replacements of gas boilers in the gas dominated countries (France, Germany, The Netherlands, The United Kingdom and EU-average) and a replacement of coal boilers in Czech, Slovakia and Poland. As none of these systems are common in Finland nor Sweden the calculations are based on oil boilers in this case.

Table 2 Reduction of greenhouse gases; old boiler (60%), new boiler (85%), (e_{elec}= emission factor for electricity 2016 [4], e_{gas}= 203 g CO_{2eq}/kWh, e_{gcoal}= 334 g CO_{2eq}/kWh, e_{oil}= 267 g CO_{2eq}/kWh [5])

Country	Energy source being replaced	e_{elec} [g CO_{2eq} /kWh_{elec}]*	GHG-emission reduction, old boiler	GHG-emission reduction, new boil
France	Gas	58,5	95%	93%
Germany	Gas	440,8	63%	47%
The Netherlands	Gas	505,2	57%	40%
The United Kingdom	Gas	281,1	76%	66%
EU-average	Gas	295,8	75%	65%
Czech	Coal	512,7	74%	63%
Slovakia	Coal	132,3	93%	90%
Poland	Coal	773,3	60%	44%
Finland	Oil	112,8	93%	90%
Sweden	Oil	13,3	99%	99%

Table 2 reveal the significant emission reduction that may be achieved by a replacement of boilers with electric heat pumps. Improvements in heat pump technology and the phase out of carbon intensive electricity generation will increase the benefits even further with time. The current trend in the electricity sector is positive and is expected to continue at an even higher pace in several countries. Figure 3 depicts the evolvement of the

national emission factor for the generation of electricity [4]. In 2016 the share of renewable electricity reached 29 % in Europe. The share of renewable electricity is by now higher than coal and lignite. The transition from fossil fuels to renewable electricity in conjunction with increased efficiency has led to a decrease of the emission factor of 43 % between 1990 and 2016.

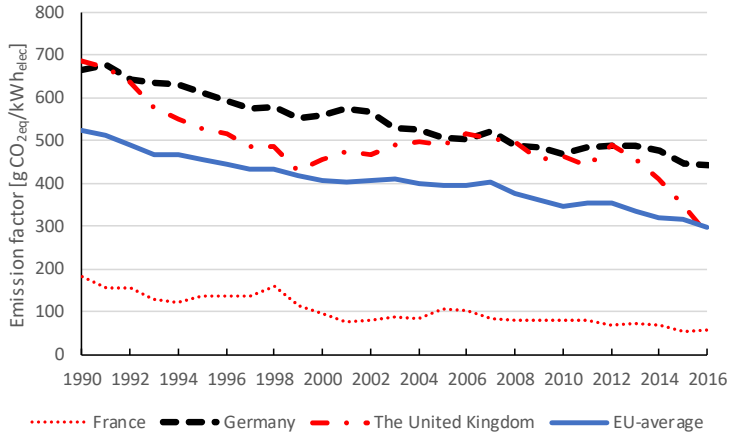


Figure 4 Development of the emission factor for electricity generation 1990 – 2016 [4]

5. Economical aspects

In view of the Paris agreement and binding European targets it is evident that there is an urgent need to transform the heating sector. Up until recently there has been a strong focus on how to decarbonise electricity and transport. The heating and cooling sector has so far not attracted the attention it deserves and requires, but changes are on their way. The European Directive on energy performance of buildings (EPBD) sets a requirement that all new buildings within the European Union need to meet a "nearly zero energy building" definition by 1 January 2021. The member states of the European Union are presently at the point of re-defining their building codes to meet this requirement. The EPBD is expected to serve sufficiently for new construction but as this will only address a minor fraction of the energy use of the whole building stock it is essential to implement comprehensive renovation programs. The European Commission published a "green deal" communication in December 2019 [6] which states that the European Union and its Member States should engage in a "renovation wave". The European Union will enforce the legislation related to the energy performance of buildings that will start with an assessment of the national long-term renovation strategies in 2020. The annual renovation rate of the building stock varies in between the Member States from 0,4 – 1,2 %. This rate will need to at least double in order to reach the energy efficiency and climate targets [6]. Several Member States are aware of the significant benefits that are offered by heat pumps but the economical incentives for end consumers to make a shift differ greatly between the Member States.

The relative savings of the operational costs that may be achieved by a replacement of an existing boiler with an electric heat pump is largely determined by the energy price ratio between electricity and the energy carrier to be replaced. In analogy with the expressions for primary energy savings and reduction of greenhouse gases the potential annual savings of the operational costs may be expressed as;

$$Relative\ \ savings\ \ of\ annual\ \ operation\ \ costs\ \ = \left(1 - \frac{Price_{elec}}{Price_{gas}} \frac{\eta_{gas}}{SPF}\right) \tag{9}$$

Where;

$$Price_{elec} = Price\ of\ electricity \quad \left[\frac{euro}{kWh}\right]$$

$$Price_{elec} = Price\ of\ gas \left[\frac{euro}{kWh}\right]$$

The quota between the energy prices for electricity and the relevant energy carrier we are comparing with constitute the previously mentioned energy price ratio. By use of equation (9) we may draw a chart of the potential savings of the annual operational costs as a function of the energy price ratio.

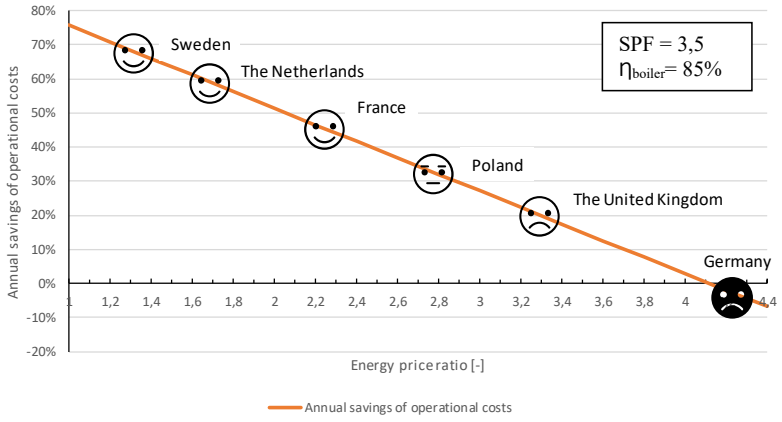


Figure 5 Annual savings of operational costs

Figure 5 depicts the potential annual operational cost savings that may be achieved by a heat pump compared to a modern boiler while taking into account for relevant energy price ratios 2018 [7] on a few selected markets. As these calculations are based on average energy prices and rough estimations on annual efficiencies the results may only be seen as an indication of the level the economic attractiveness of heat pumps. In reality substantial differences may prevail both in terms of energy prices and efficiencies. It is however evident that the low energy price ratio for Sweden has served as the single most important economic driver for the development of the Swedish heat pump market. As of today, heat pumps are used in more 50% of the single-family houses and the use of heating oil that for decades was the dominant source of heating is almost entirely abandoned. The low energy price ratio in Sweden is to a large extent the result of the introduction of a carbon tax 1991. On the other side of the scale the German heat pump market is suffering from high energy price ratios partly because of the energy price policy induced the “energy turnaround” (energiewende) that introduced additional taxes on electricity in order to finance the development of renewable electricity. Given the good example of Sweden it is evident that some sort of progressive energy price policy may play a very important role in order to stimulate the transformation of the heating sector. The energy price policy may as in Sweden be in the form of a carbon tax or as mentioned in EU Green Deal Communication [6] an inclusion of the heating sector into the emission trading system.

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