REACHING THE KYOTO-TARGETS BY A WIDE INTRODUCTION OF GROUND SOURCE HEAT PUMPS
PART I: METHODOLOGY

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Abstract: The objective of this paper is to present a general methodology to determine green house gas emissions related to different sources of heating. The methodology may be used to estimate the potential for mitigation of green house gas emissions that may be reached, by a wide introduction of ground source heat pumps in the European Union. The generalised methodology may additionally be used to calculate primary energy savings as well as end use energy savings and cost savings. The last part of this paper discusses how the contribution of renewable energy, that relates to the use of heat pumps, may be presented and used in statistics. Part II of this paper applies the methodology to available statistics in the European Union.

Key Words: ***heat pumps, green house gas emission, primary energy efficiency, renewable energy, methodology***

1 INTRODUCTION

This paper explains the development of a methodology to estimate the potential for a reduction of green house gases when heat pumps are replacing conventional heating systems. The main objective of this paper is thus to reveal how the calculations are performed and not to present the overall results that may be achieved by a wide introduction of ground source heat pumps. Some example calculations have however been included in order to increase the readability of this paper. Input data that is used for the example calculations are included in the Appendix

The environmental benefits will be estimated and expressed in terms of the reduction of CO2-equivalents. At local and regional level additional aspects, such as eutrophication, acidification and health hazards have to be considered. These aspects are however, beyond the scope of this study. In addition to the calculations related to the environmental impact, the model is extended to include calculations of primary energy savings, end use energy savings as well as consumer cost savings and renewable energy provided by ground source heat pumps.

The CO2-equivalents are expressed as emission factors, ef (kg CO2eq/kWh). Based on the extraction, refinement, transportation, energy content and chemical composition, emission factors for different fuels may be established for the whole energy chain upstream the final energy conversion at the building site. Emission factors for different fuels and different mixes of electricity generation in this report are based on the values retrieved from GEMIS 4.2 (Oeko-Institut) and stated Appendix I.

2 ENERGY EFFICIENCY

While discussing the efficiency of heating systems, one need to realise that you will end up with different results depending on the interpretation of 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 consumer, but taking 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 for different types of systems, it is essential to address the primary energy efficiency. This study will encompass the energy chain including, extraction, refinement and transportation of the primary energy source as well as conversion, final distribution and final conversion at appliance level. All energy losses upstream the heating appliance will, for practical reasons, be represented by a resulting efficiency factor. Resulting upstream efficiency for the different technologies that will be considered in this study has been compiled and may be found in Appendix II.

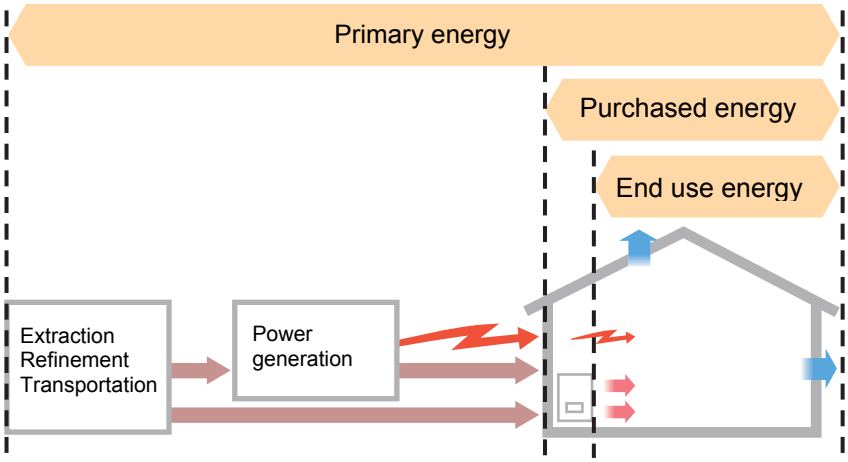


Figure 1: Definition of the system boundary

3 GREEN HOUSE GAS EMISSIONS DUE TO COMBUSTION OF HEATING OIL

The building in Figure 2 requires the net energy demand for heating denoted Ebuilding. This is the useful heat supplied by the heating system, in this case an oil boiler operating at an estimated annual efficiency, ηoil.

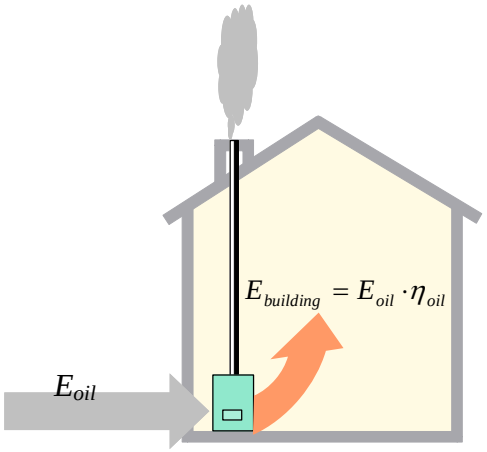


Figure 2: The annual heating demand for the building above is, denoted $E_{building}$. The oil boiler consumes the energy, E_{oil} and operates at an annual efficiency, η_{oil}. The useful heat provided by the oil boiler is given by, $E_{oil} \cdot \eta_{oil}$.

The environmental impact, in terms of green house gas emissions, eimpoil, due to combustion of heating oil and upstream efficiency, ηupoil, may be expressed as:

$$eimp_{oil} = \frac{E_{oil} \cdot ef_{oil}}{\eta_{oil}^{up}} \quad \text{, or} \quad eimp_{oil} = \frac{E_{building} \cdot ef_{oil}}{\eta_{oil} \cdot \eta_{oil}^{up}} \quad \text{(kg)} \qquad (1)$$

4 GREEN HOUSE GAS EMISSIONS RELATED TO THE USE OF HEAT PUMPS

With the exception of a few technologies, the majority of all life cycle assessments carried out on systems for space conditioning or generation of electricity by combustion, confirm that most of the environmental impact stems from the appliance/plant in operation (IEA 2002, Spath, Mann 2000, Halozan et al 1999). Environmental evaluations of heat pump applications need to take into account for indirect emissions related to the generation of electricity that is used to operate the heat pump, as well as direct emissions of the refrigerant. A lot of research has been made on the establishment of an integrated method to calculate the contribution of green house gas emissions from refrigeration and heat pump applications. The most well established method, TEWI (Total Equivalent Warming Impact), was developed at Oak Ridge National Laboratory in the early nineties. A TEWI calculation integrates direct and indirect green house gas emissions over the whole lifetime into a single number expressed in terms of CO_2 mass equivalents. Even though the TEWI concept is well known and accepted it has been developed to evaluate individual units or a defined number of units. It is at current stage difficult to apply the concept in evaluations of very large number of units, which is the case when a whole country is being studied. In this study we will restrict our analyses to the green house gas emissions related to the generation of electricity.

Like many other types of renewable heating systems, heat pumps are sometimes most economical if they are designed for part load, i.e. bivalent system. This fact raises the

demand for an auxiliary heating system, auxhs, to be run in parallel or in series with the heat pump. This practice is more pronounced in the Nordic countries than other parts of Europe, where heat pumps tend to be designed for the peak heating demand, i.e. monovalent system. The annual performance of the heat pump system is called seasonal performance factor (SPFhp). In case of a bivalent system, a factor, exen, is used to denote the relation between the energy provided by the heat pump and the annual heat demand for the building.

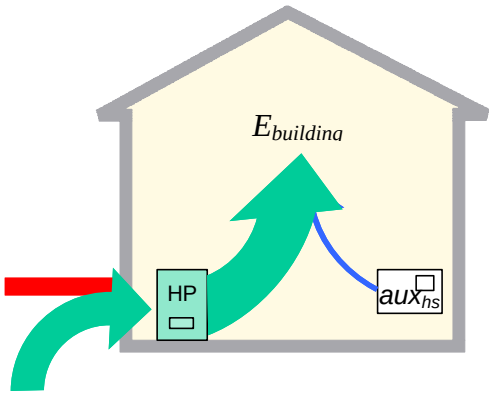


Figure 3: The annual heating demand, $E_{building}$, for interior space and domestic hot water heating is provided by the heat pump and if required by an auxiliary heat source, aux_{hs}. A factor exen is used to denote the relation between the energy provided by the heat pump and the annual heat demand for the building. Thus the auxiliary heat source is providing $E_{building} \cdot (1 - exen)$. For a monovalent heat pump system exen equals to unity.

The overall environmental impact of heat pump operation need, in analogy with oil heating, to take into account for all upstream losses for the electricity and the auxiliary heating device, i.e. distribution losses and losses related to the generation of electricity as well as losses related to extraction and refinement. A final expression for the environmental impact of the heat pump system including the auxiliary heat source may be deducted and yields in:

$$eimp_{hp} = \frac{E_{building}}{SPF_{hp}} \cdot \frac{exen}{\eta_{el}^{up}} \cdot ef_{el} + E_{building} \cdot (1 - exen) \cdot \frac{ef_{aux}}{\eta_{aux} \cdot \eta_{aux}^{up}} \quad \text{(kg)} \qquad (2)$$

This general expression may be used for all types of electric heat pumps.

The net change of CO2-emissions when an oil boiler is replaced by a heat pump system is given by:

$$\Delta eimp_{oil-hp} = eimp_{oil} - eimp_{hp} \quad \text{(kg)} \qquad (3)$$

Using the expression above gives:

$$\Delta eimp_{oil-hp} = \frac{E_{building} \cdot ef_{oil}}{\eta_{oil} \cdot \eta_{oil}^{up}} - \left(\frac{E_{building} \cdot exen \cdot ef_{el}}{SPF_{hp} \cdot \eta_{el}^{up}} + \frac{E_{building} \cdot (1 - exen) \cdot ef_{aux}}{\eta_{auxhs} \cdot \eta_{aux}^{up}} \right) \qquad (4)$$

By use of equation (1) and (4), a final expression for the relative change of CO2-emissions may be deducted.

$$\text{Re}\,l\,emission\,savings = \underbrace{1-\left(exen\cdot\frac{ef_{el}}{ef_{oil}}\cdot\frac{\eta_{oil}^{up}}{\eta_{el}^{up}}\cdot\frac{\eta_{oil}}{SPF}+(1-exen)\cdot\frac{ef_{aux}}{ef_{oil}}\cdot\frac{\eta_{oil}^{up}}{\eta_{aux}^{up}}\cdot\frac{\eta_{oil}}{\eta_{aux}}\right)}_{\text{Introducing a conversion factor, } h_{oil-hp}^{conv}} \quad (-)(5)$$

$$h_{oil-hp}^{conv} = 1-\left(\underbrace{exen\cdot\frac{ef_{el}}{ef_{oil}}\cdot\frac{\eta_{oil}^{up}}{\eta_{el}^{up}}\cdot\frac{\eta_{oil}}{SPF_{hp}}}_{\text{Heat pump operation}} + \underbrace{(1-exen)\cdot\frac{ef_{aux}}{ef_{oil}}\cdot\frac{\eta_{oil}^{up}}{\eta_{aux}^{up}}\cdot\frac{\eta_{oil}}{\eta_{aux}}}_{\text{Auxiliary heat source}}\right) \quad (-)(6)$$

Within the brackets, the conversion factor consists of two parts. One is related to heat pump operation, whereas the other is related to the auxiliary heat source. For a monovalent heat pump system, i.e. the heat pump is designed to provide 100% of the annual heat demand, exen is equal to 1 and evidently the part related to the auxiliary heat source will be superfluous.

As can be seen in equation (6) both parts within the brackets of the conversion factor consists of similar factors, i.e. one factor indicating the share of the annual heating demand provided by the heat source, one giving the relation between the emission factors, one giving the relation between the upstream losses and finally one factor giving the relation between the efficiencies of the heating devices.

Analogous conversion factors may be found for any case, simply by using the relevant indexes in equation (6).

Replacing electricity based heating with a heat pump:

$$h_{el-hp}^{conv} = 1-\left(exen\cdot\frac{\eta_{el}}{SPF_{hp}} + (1-exen)\cdot\frac{ef_{aux}}{ef_{el}}\cdot\frac{\eta_{el}^{up}}{\eta_{aux}^{up}}\cdot\frac{\eta_{el}}{\eta_{aux}}\right) (-) \qquad (7)$$

Replacing a gas boiler with heat pump:

$$h_{gas-hp}^{conv} = 1-\left(exen\cdot\frac{ef_{el}}{ef_{gas}}\cdot\frac{\eta_{gas}^{up}}{\eta_{el}^{up}}\cdot\frac{\eta_{gas}}{SPF_{hp}} + (1-exen)\cdot\frac{ef_{aux}}{ef_{gas}}\cdot\frac{\eta_{gas}^{up}}{\eta_{aux}^{up}}\cdot\frac{\eta_{gas}}{\eta_{aux}}\right) (-)(8)$$

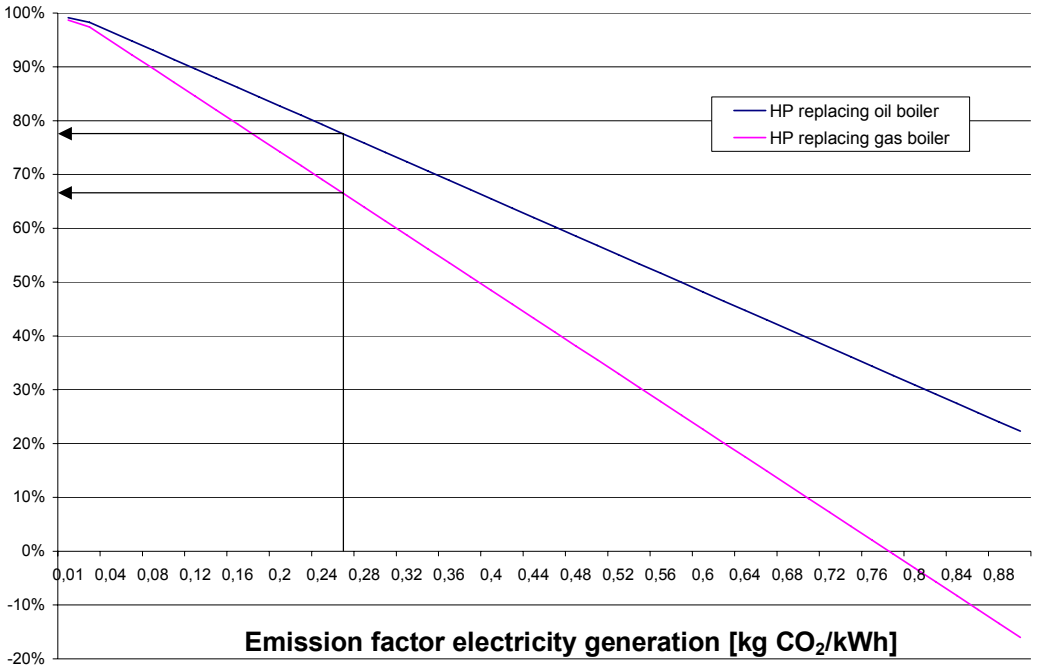


Figure 4: Relative CO2 savings by heat pumps: Conditions used for the example above; gas boiler efficiency 95%, oil boiler efficiency 90%, monovalent heat pump operating with SPF 4.

5 PRIMARY ENERGY SAVINGS

As the previous expressions included upstream losses we may use the same equations to establish an expression for the relative savings of primary energy. The conversion factors for the relative savings of primary energy are given below.

By leaving out the quotient for the emission factors, we end up with a conversion factor for primary energy savings, hprimary energyoil-hp.

$$h_{oil-hp}^{primary\ energy} = 1 - \left(exen \cdot \frac{\eta_{oil}^{up}}{\eta_{el}^{up}} \cdot \frac{\eta_{oil}}{SPF_{hp}} + (1 - exen) \cdot \frac{\eta_{oil}^{up}}{\eta_{aux}^{up}} \cdot \frac{\eta_{oil}}{\eta_{aux}} \right) (-) \quad (9)$$

Replacing electricity based heating with a heat pump:

$$h_{el-hp}^{primary\ energy} = 1 - \left(exen \cdot \frac{\eta_{el}}{SPF_{hp}} + (1 - exen) \cdot \frac{\eta_{el}^{up}}{\eta_{aux}^{up}} \cdot \frac{\eta_{el}}{\eta_{aux}} \right) (-) \qquad (10)$$

Replacing a gas boiler with a heat pump:

$$h_{gas-hp}^{primary\ energy} = 1 - \left(exen \cdot \frac{\eta_{gas}^{up}}{\eta_{el}^{up}} \cdot \frac{\eta_{gas}}{SPF_{hp}} + (1 - exen) \cdot \frac{\eta_{gas}^{up}}{\eta_{aux}^{up}} \cdot \frac{\eta_{gas}}{\eta_{aux}} \right) (-) \qquad (11)$$

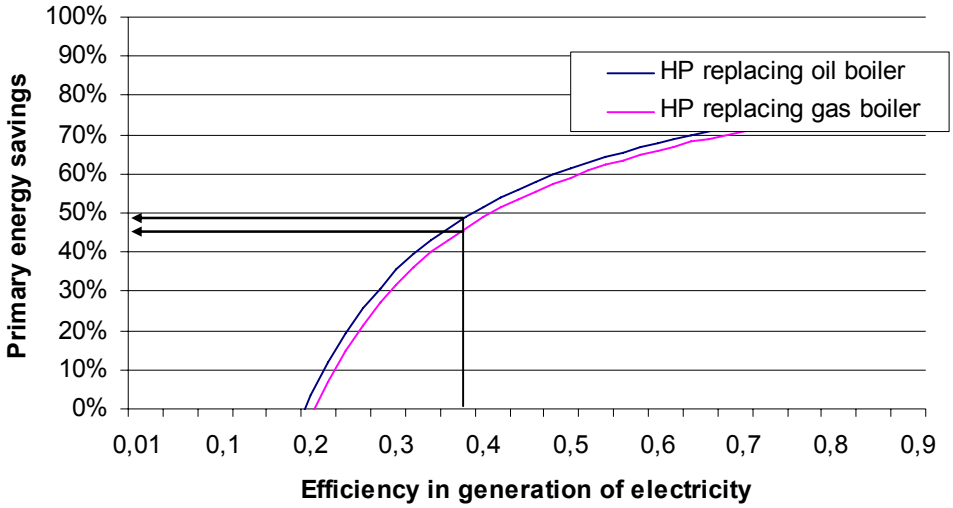


Figure 5: Relative savings of primary energy by heat pumps: Conditions used in the example above; gas boiler efficiency 95%, oil boiler efficiency 90%, monovalent heat pump operating with SPF 4.

6 END USE ENERGY SAVINGS

The step from primary energy savings to the actual energy savings for the end customer may be done by disregarding all upstream losses. The conversion factors for end use energy savings becomes:

$$h_{oil-hp}^{end\ use\ energy} = 1 - \left(exen \cdot \frac{\eta_{oil}}{SPF_{hp}} + (1 - exen) \cdot \frac{\eta_{oil}}{\eta_{aux}} \right) \text{(-)} \qquad (12)$$

Replacing electricity based heating with a heat pump:

$$h_{el-hp}^{end\ use\ energy} = 1 - \left(exen \cdot \frac{\eta_{el}}{SPF_{hp}} + (1 - exen) \cdot \frac{\eta_{el}}{\eta_{aux}} \right) \text{(-)} \qquad (13)$$

Replacing a gas boiler with a heat pump:

$$h_{gas-hp}^{end\ use\ energy} = 1 - \left(exen \cdot \frac{\eta_{gas}}{SPF_{hp}} + (1 - exen) \cdot \frac{\eta_{gas}}{\eta_{aux}} \right) \text{(-)} \qquad (14)$$

7 END USE COST SAVINGS

Whether an electric heat pump installation will render in lower operating costs for the end consumer or not, depends on the appliance efficiency as well as the energy price ratios between electricity and the alternative systems. The relevant energy price ratio is simply the end user price of 1 kWh electricity in relation to the price of 1 kWh of the alternative. The step from end use energy savings to the actual savings of operating costs for the consumer may be done by including the energy price ratios for the systems studied. The conversion factors for savings of operating costs become:

$$h_{oil-hp}^{end\ use\ energy} = 1 - \left(exen \cdot \frac{price_{el}}{price_{oil}} \cdot \frac{\eta_{oil}}{SPF_{hp}} + (1 - exen) \cdot \frac{price_{aux}}{price_{oil}} \cdot \frac{\eta_{oil}}{\eta_{aux}} \right) \quad (-)(15)$$

Replacing electricity based heating with a heat pump:

$$h_{el-hp}^{end\ use\ energy} = 1 - \left(exen \cdot \frac{\eta_{el}}{SPF_{hp}} + (1 - exen) \cdot \frac{price_{aux}}{price_{el}} \cdot \frac{\eta_{el}}{\eta_{aux}} \right) \quad (-)(16)$$

Replacing a gas boiler with a heat pump:

$$h_{gas-hp}^{end\ use\ energy} = 1 - \left(exen \cdot \frac{price_{el}}{price_{gas}} \cdot \frac{\eta_{gas}}{SPF_{hp}} + (1 - exen) \cdot \frac{price_{aux}}{price_{gas}} \cdot \frac{\eta_{gas}}{\eta_{aux}} \right) \quad (-)(17)$$

8 RENEWABLE ENERGY PROVIDED BY HEAT PUMPS

An extensive use of renewable energy is an absolute necessity in order to reach a sustainable energy system. This is already well acknowledged all over Europe and binding targets for the use of renewable energy have already been approved by the European Council, March 2007. The target is set for a minimum of 20% of renewable energy in total energy utilisation by 2020. The calculation of renewable energy provided by monovalent heat pumps is given by the equation below.

$$E_{ren} = E_{building} \cdot \frac{(SPF - 1)}{SPF} \quad \text{(kWh)} \qquad (18)$$

9 REFERENCES

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10 APPENDIX

The table below depicts the emission factors, for various types of energy sources, retrieved from GEMIS 4.2. As the emission factor include emissions occouring upstream it is given as the qvotient of emission factor and upstream efficiency, ef / η^{up}.
The values for electricity Emission factors for electricity does not take into account for grid losses between the power plant and the end users. Thus the values retrieved from GEMIS have been recalculated by use of a general assumption of 4% grid losses. Eventhough this assumption is not valid for Europe as a whole, the error this will induce is small.

Table 1: Emission factors (Source: Gemis 4.2, recalculations: own)

Energy source	**ef/ηup (kg/kWh)**
Fuel oil	0.330
Natural gas	0.238
Hard coal briquettes	0.446
Electricity EU 25	0.486
Electricity Austira	0.242
Elec. Belgium	0.310
Elec. Schweiz	0.041
Elec. Germany	0.622
Elec. Denmark	0.687
Elec. Spain	0.529
Elec. France	0.104
Elec. Greece	0.878
Elec. Italyl	0.542
Elec. Ireland	0.700
Elec. Luxenburg	0.356
Elec. Netherlands	0.623
Elec. Norway	0.014
Elec. Poland	0.627
Elec. Sweden	0.077
Elec. Finland	0.406
Elec. United Kingdom	0.554

Table 2 Depict the upstream efficiencies for different heating systems used in this study. Values are retrieved from GEMIS 4.2. As the GEMIS database does not include gridlosses, the values have been recalculated by assuming 4% losses for all national grids.

Table 2: Upstrem efficiencies

Source of heating	**Upstream efficiency,** η^{up}
Fuel oil	84%
Natural gas	85%
Pellets	91%
Hard coal briquettes	90%
Electricity EU 25	34%
Electricity Austria	58%
Elec. Belgium	29%
Elec. Switzerland	47%
Elec. Germany	33%
Elec. Denmark	38%
Elec. Spain	37%
Elec. France	29%
Elec. Greece	37%
Elec. Italy	41%
Elec. Ireland	39%
Elec. Luxemburg	35%
Elec. Netherlands	36%
Elec. Norway	92%
Elec. Poland	36%
Elec. Sweden	44%
Elec. Finland	29%
Elec. United Kingdom	36%