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Review

Greenhouse gas emission savings of ground source heat pump systems in Europe: A review

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ABSTRACT

An overview is presented on the last decade of geothermal heating by ground source heat pumps (GSHPs) in Europe. Significant growth rates can be observed and today's total number of GSHP systems is above 1 million, with an estimate of about 1.25 million mainly used for residential space heating in 2011. These systems are counted among renewable energy technologies, though heat pump operation typically consumes electricity and thus only a fraction of the energy produced is actually greenhouse gas (GHG) emission free. Consequently, only in the most mature markets of the Scandinavian countries and in Switzerland, calculated emission savings reach more than 1% compared to standard heatings. However, Sweden shows that more than 35% is possible, with about one third of these systems in Europe concentrated in this country. Our calculations demonstrate the crucial role of country-specific heating practices, substituted heat mix and primary electricity mix for country-specific emission savings. For the nineteen European countries studied in 2008, 3.7 Mio t CO_2 (eq.) are saved in comparison to conventional practice, which means about 0.74% on average. This reveals that many countries are at an early stage with great potential for the future, but even if the markets would be fully saturated, this average would barely climb to about 30%. These numbers, however, take the current conditions as reference, and when extrapolated to the future can be expected to improve by greener electricity production and increased heat pump performance.

Contents

1. Introduction

Nowadays, it is widely accepted that greenhouse gases (GHGs) influence global climate. To impede this development, in March 2007, the European Council made a commitment to reduce GHGs until 2020 by at least 20% compared to 1990 [1]. This means a net

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GHG reduction of 368 million tons of CO_2 per year. The new Europe 2020 Strategy [1,2] represents the current roadmap of the European Union for economic renewal, which was adopted in June 2010 and replaced the Lisbon Strategy [3]. The program's main goals are to evenly decrease GHG emissions by 30%, if the conditions are right, to reach a 20% share of total energy consumption from renewable energy, and to raise the energy efficiency. In March 2011, the EU launched a new Energy Efficiency Action Plan with more details on specific actions to be taken. Particular focus is set on minimizing energy consumption of buildings, given that this sector accounts for 40% of total energy consumption in Europe [4]. GHG savings by use of renewable energy sources are considered an elementary component to achieve the ambitious targets. Among others, heat pump systems for the heating (and cooling) of buildings are recommended as high-efficiency alternative systems [5].

In the present study, focus is set on an increasingly popular heat pump system variant for heating and cooling of residential buildings: the ground source heat pump systems (GSHPs) [6–9]. In this study, we ask, what is the contribution of such systems in saving emission of GHGs in the residential heating sector? Furthermore, we examine their future potential in Europe.

GSHP systems are the most frequent applications of geothermal energy use, which is counted among those renewables with the most potential for supplying the future societies' energy needs [10]. They are not only common as small scale applications for residential heating, cooling and hot water provision, but of increasing importance also for larger buildings such as schools, industrial and office buildings, and in district heating systems (e.g. [11,12]). Meanwhile, these systems already contribute to strategic low carbon emission plans of cities (e.g. [13,14]) and even entire countries (e.g. [15–18]). Accordingly, their spread is fuelled by grant programs and government incentives (e.g. [19–23]), special electricity heat pump tariffs, and even without extra subsidy funds they show economic and environmental advantages [24–27].

Bristow and Kennedy [28] recently presented a comprehensive analysis of the competitiveness of alternative heating technologies in Canada, and included the risk of future energy price development. GSHPs turned out to be exceptionally good and sustainable investments, not just with respect to energy efficiency and GHG emission savings, but especially in terms of life cycle costs. This was demonstrated for both small residential homes with substantial grants of 61% for the capital costs and for larger buildings even without any financial support. In other countries, the economic virtues will depend on the specific conditions encountered there. Obviously, a major role is played by the competitive heating technologies as well as by the practical experience with GSHP installation and maintenance.

The European Heat Pump Association, EHPA [29] defined a traditional heat mix for Europe (50% gas, 30% oil, 10% solid fuel, 10% electricity) to approximate standard heating practice and related emissions. This served as a basis to roughly evaluate GHG savings potential by (all) heat pump applications in Europe. These are dominated by air source heat pump (ASHP) systems but also include GSHP systems. Extrapolating currently observed growth rates of 5.4 million heat pump units per year, a number of 70 million installed units in Europe is expected for 2020. Given these assumptions, all heat pumps would yield an avoidance of 230 million tons of GHGs in comparison to standard heating practices. Accordingly, heat pumps would contribute over 20% of the EU energy saving goal, 20% of the renewable energy input and 20% of the CO_2 emission target. This forecast is only based on the most frequent application of heat pumps in single family houses. EHPA [29] hypothesizes that this number could be even higher when including multi-family houses, commercial buildings, as well as accounting for improvements in power production efficiency, and including efficiency of heat pumps and improved insulation standards.

Rybach [30] presents a discussion on the prominent role of GSHPs among the heat pumps based on the EHPA study. However, this role is not quantified, and no details on the relative contribution of GSHPs for achieving Europe's CO_2 emission targets are given. In this study, he emphasizes the difference between CO_2 emission reduction and saving. New GSHP installations alone do not reduce, they only avoid (i.e. save) additional emission. Real emission reduction is achieved only when at the same time a fossil-fired burner – with the same capacity – is taken out of service. This is for example the case in renovation/refurbishment.

The objective of our study is to build up on Rybach [30] and estimate actual, as well as, potential GHG savings (or avoidance) by GSHPs in Europe. In the following chapters, we will review the development of GSHP technology in Europe since 2000 and contrast the installed numbers and capacities of different countries. This includes members of the European Union, as well as, Norway and Switzerland. By far most GSHPs are installed for residential heating (e.g. [31]). Accordingly, in countries with appreciable GSHP numbers common heating practice in the residential sector is further examined. Estimates of the typical country-specific heat mixes are used to quantify the GHG savings achieved by applying GSHPs instead of standard heating technologies. Although in countries with moderate climate GSHP systems are now increasingly used for space cooling too, here we consider only space heating since statistical data on GSHP cooling are currently very limited. In Chapter 4, using the most recent data basis from 2008, the country-specific situation is scrutinized, and the most important factors for reducing GHG emissions with GSHPs are elaborated. During the time of our study, more recent data did not exist or accessible information was incomplete, and therefore the year 2008 is taken as reference. Finally, by assuming an idealized saturated case with complete replacement of conventional heating technologies, we reveal the maximal potential of geothermal heating in Europe's residential sectors.

2. GSHP installed capacity and performance

2.1. GSHP technology

GSHPs use the earth's interior as a source and extract heat from the subsurface at low depth, subsequently called "shallow geothermal energy" [7,22,32], and enhance it in order that it is usable for space and domestic hot water heating. A GSHP system consists of two parts: the heat source, in most cases a borehole heat exchanger (BHE), and the heat pump. While the heat exchanger makes the energy stored beneath the surface accessible, the heat pump is needed to enable heating, because temperatures in the shallow depths (<400 m) are most often too low for direct use. Heat exchange with the ground is accomplished by circulating a heat carrier fluid (closed systems) or, if feasible, directly with groundwater (open systems). The heat pump increases the incoming temperature from the ground or groundwater to a level suitable for the in-house (hydronic or air-blown) heating systems. Hence, auxiliary energy, typically in the form of electricity, is still needed for the operation of the heat pump. There are also other possibilities to provide the additional energy, for example, via natural gas. In this study, electricity driven compression heat pumps are considered, by far, the most common variant [32,33].

The ratio of supplied heat to the electricity consumed by the entire GSHP system is called the seasonal performance factor (SPF) (e.g. [34–36]). By technological advancements GSHP specific SPFs have been continuously improved during the last decade. Characteristic values for the SPF of modern GSHPs are commonly assumed to be about 4, meaning that four times the amount of heat is gained per unit of consumed electricity [30]. Saner et al. [37] assume an average value of SPF = 3.5 for all currently installed GSHPs, which is based on a review of available studies and performance reports on previously installed systems. EHPA [38] suggests an SPF of 3.6 for central European countries, and SPF = 3.2 representative for Scandinavia. Apparently, the SPF can vary significantly in each GSHP system depending on a variety of parameters. It is governed, for example, by local factors such as the climate, the geology, the geothermal gradient, which describes the temperature increase with depth, operation mode, and building parameters such as the heating system, e.g. radiators or in-floor heating [36,39–43]. Several simulation procedures are available for in-depth analysis of GSHP performance and to support single or multiple GSHP planning [44–48].

The SPF is a measure of energy efficiency and thus determines the GHG emissions during system operation. Several studies have reported reduced and avoided emissions compared to conventional, fossil fuel based heating technologies (e.g. [6,16,24,49–53]). The calculated savings vary substantially and, in particular depend on the case-specific electricity mix for running the heat pump, and the alternative heating technology the comparison is made with. Saner et al. [37] showed that when contrasting the conditions in different European countries, emission savings of up to 88% are possible, with a median value of about 35% compared to oil fired boilers. This study also proves that GHG emissions serve as good proxy for the environmental assessment of the entire life cycle of the GSHPs, including all potential direct and indirect (i.e. from so-called "background processes") environmental impacts from manufacture, installation, operation and final disposal.

Note that savings here are calculated by comparison to conventional practice, independent from the fact, if old systems have been replaced in retrofitted houses or GSHPs are installed in new buildings. In essence, savings thus stand for reduction in comparison to conventional practice. This does not inevitably mean an overall emission reduction, since no emissions are reduced by building new houses. In this case, it would be more concise to speak of avoidance of additional emissions [30].

2.2. GSHP installed numbers and capacity

The worldwide number of GSHPs is rapidly growing, and GSHPs are gaining more importance, especially in Europe (e.g. [54,55]). This is stimulated by the search for environmental alternatives to traditional heating technologies, both for new and retrofitted buildings. Regional incentive programs raise the economic advantages of using geothermal energy for heating. Today, GSHPs are established in most European countries. EHPA [38] provides detailed statistical data for heat pumps of eight European Countries (Austria, Finland, France, Germany, Italy, Norway, Sweden and Switzerland). A share of 20% of GSHPs was calculated in 2008, with the majority of heat pumps using air as the energy source. The annual GSHP sales in these countries from 2005 to 2008 ranged between 75,000 and 110,000. The EHPA calculates 6.74 Mt GHG annual emission savings by all heat pumps installed during this period, with about 40% (2.7 Mt) originating from GSHPs.

The sales report by the EHPA [38] as well as the worldwide reviews on direct geothermal energy by Lund and co-workers from 2000, 2005 and 2010 [31,56,57], reports by the EurObserv'er [58], and by Rybach and Sanner (2000) [34] are consulted to obtain estimates on the stock of GSHPs in Europe. We identified nineteen European countries, for which significant numbers of GSHPs were reported. The results are listed in Table 1 and show a continuous, overall exponential increase in installed GSHPs throughout Europe (annually 23% in numbers, 28% in produced TJ). The numbers represent averages from available statistics and thus may slightly differ from exact values due to the heterogeneous origin of the country-specific numbers, the difficulty of separating residential applications from others, and differences in the respective reporting periods. Since not all of the reported GSHPs are employed for residential heating, the country-specific GSHP stocks in Table 1 and the capacities in Table 2 may slightly overestimate their role as household appliances. In 2008, about 880,000 GSHPs were in operation in these nineteen European countries. Using the significant growth rates as illustrated in Fig. 1, the current number of GSHPs can be expected to be well above one million (about 1.2–1.3 million). Rough extrapolation indicates that within one decade from 2000 to 2010 this number increased by about one order of magnitude. Nevertheless, even if exponential growth rates were predicted in 2007 [6], recent European heat pump sales show a minor decrease in 2009 and 2010 [54].

The 2008 sales data shows that with regard to direct geothermal energy use, Sweden is the most advanced country, and it hosts about one third of all GSHPs in Europe. Heat pump manufacturers report that 97% of newer Swedish houses are built with heat pumps [59]. About 75% of European GSHPs are installed in Sweden,

Table 1
Average reported number of ground source heat pumps in European countries in the years 2000, 2005, and 2008 [31,56–58]; average size is 12 kW (n.a., no reliable data available).

Country		Year		
		2000	2005	2008
Austria	AUT	19,000	35,810	48,641
Belgium	BEL	n.a.	6000	9500
Czech Republic	CZE	390	3727	9168
Denmark	DNK	250	6000	11,250
Estonia	EST	n.a.	3500	4874
Finland	FIN	10,000	29,106	46,412
France	FRA	4000	63,830	121,900
Germany	DEU	18,000	61,912	148,000
Hungary	HUN	20	230	4000
Ireland	IRL	n.a.	1500	9500
Italy	ITA	100	6000	12,000
Netherlands	NLD	900	1600	14,600
Norway	NOR	500	14,000	26,000
Poland	POL	4000	8100	11,000
Slovenia	SVN	66	300	3440
Spain	ESP	n.a.	n.a.	7000
Sweden	SWE	55,000	230,094	320,687
Switzerland	CHE	21,000	38,128	61,000
United Kingdom	GBR	40	550	10,350
Total		133,266	510,387	879,322

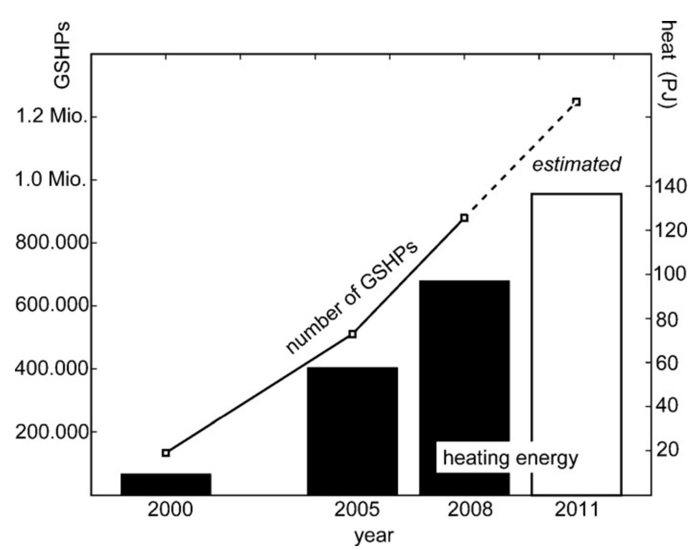

Fig. 1. Development of total number of GSHPs and provided energy for space heating ("heat", 1 PJ = 1000 TJ) in European countries (2000–2011) [31,56–58,61].

Table 2
Final demand of (total) space heating energy (rounded to thousands) and supply by GSHPs in residential sector in European countries in the years 2000, 2005, and 2008 [31,56–58,61]. The relative energy contributions of GSHPs are given in per cent.

	Heating demand (TJ)			GSHP (TJ)			Relative contribution		
	2000	2005	2008	2000	2005	2008	2000	2005	2008
Climate corrected									
AUT	224,000	207,000	209,000	1275	2050	3229	0.6%	1.0%	1.5%
BEL	310,000	333,000	295,000		312	495	0.0%	0.1%	0.2%
CZE	166,000	181,000	186,000	44	301	927	0.0%	0.2%	0.5%
DNK	165,000	165,000	173,000	24	525	1859	0.0%	0.3%	1.1%
EST	27,000	24,000			257			1.1%	
FIN	125,000	129,000	139,000	575	2157	9852	0.5%	1.7%	7.1%
FRA	1,368,000	1,311,000	1,268,000	277	3925	7784	0.0%	0.3%	0.6%
DEU	2,232,000	1,969,000	2,044,000	1308	4309	11,237	0.1%	0.2%	0.5%
HUN				24	240	593			
IRL					92	777			
ITA	711,000	788,000	816,000	7	521	1157	0.0%	0.1%	0.1%
NLD	349,000	305,000	298,000	66	747	1080	0.0%	0.2%	0.4%
NOR	94,000	94,000	91,000	37	3495	8588	0.0%	3.7%	9.4%
POL	598,000	544,000	615,000	127	510	1193	0.0%	0.1%	0.2%
SVN	41,000	30,000	30,000	53	65	387	0.1%	0.2%	1.3%
ESP	258,000	281,000	286,000			408	0.0%	0.0%	0.1%
SWE	269,000	249,000	257000	5292	39,025	52,251	2.0%	15.7%	20.3%
CHE	123,000	113,000	138,000	2287	2836	7403	1.9%	2.5%	5.4%
GBR	1,277,000	1,296,000	1,152,000	3	50	783	0.0%	0.0%	0.1%
Total/average	8,337,000	8,019,000	8,021,000	11,400	61,419	110,005	0.1%	0.8%	1.4%
Without climate correction									
Total/average	7,462,000	7,782,000	7,400,000	9405	57,611	96,464	0.1%	0.7%	1.3%

Germany, France and Switzerland. Thus, an apparent concentration can be observed in Scandinavia and central Europe, i.e. in the countries with colder climate in contrast to, for instance, the Mediterranean countries with warmer climate.

Comparing the total final consumption in the residential sector for space heating to that fraction supplied by GSHPs, geothermal heating plays an important role only in Scandinavia (Table 2). In 2008, Sweden provided 20.3%, Norway 9.4% and Finland 7.1% of space heating by GSHPs. Switzerland reaches a remarkable, although lower value of 5.4%. In all other countries, the fraction is about 1%, and thus we calculate a mean proportion of GSHP heating of only 1.4% for the studied European countries. Table 2 also demonstrates that for all these countries GSHP numbers are continuously on the rise. For 2011, a figure of about 140,000 TJ is estimated for total heating energy provision by GSHPs in Europe. Assuming the growth rate during the period 2005–2008 is also valid in the future, it will take at least until the year 2025 until a share of more than 5% in European space heating is reached. This extrapolation, however, is rather hypothetical, as the country-specific GSHP markets are at different maturity stages. In fact, increasing growth rates such as those observed in the past, incentive programs and premeditated further decrease of European space heating energy consumption may even accelerate the market penetration of GSHPs.

3. GHG emissions and savings

3.1. Calculation of GHG emissions

The purpose of our study is to elaborate the potential of GSHP application in the residential sector to save GHG emissions. The underlying calculation essentially represents a straightforward comparison of GSHP operation versus standard practice. For this, first, the GHG emissions from GSHPs have to be determined. Second, the emissions of the substituted heating technologies are quantified. Saved (i.e. avoided) or increased GHG emissions, thus, are computed by the difference between substituted and GSHP systems. Due to the diversity in each country with respect to heating practice, direct geothermal energy use by GSHPs, and primary energy sources for electricity, calculations are provided on a country-specific resolution. Subsequently, the individual calculation steps, as well as data used are described in detail.

The annual heating energy provided by GSHPs is defined as E_{GSHP}. The annual primary energy consumption from heat pump electricity use then is

$$E_{power} = \frac{E_{GSHP}}{SPF} \tag{1}$$

This may involve unit conversion of E_{GSHP} (TJ) in E_{power} (kWh). As electricity consumption by the heat pump is considered the most important source for GHGs [37], we neglect other potential contributors (e.g. heat pump life cycle, heat pump refrigerant, borehole construction). This simplifies the calculation and GHG emission factors of GSHPs can be approximated by division of electricity emission factors by the SPF value (e.g. [49]). Applying an emission factor γ_{power} (kg CO_2/kWh), we obtain the annual GHG emissions (kg CO_2) from GSHP operation

$$G_{GSHP} = \gamma_{power} E_{power} \tag{2}$$

The emission factor typically varies among different countries and characterizes the GHG intensity of electricity production. For example, it is higher if a fraction of low-voltage power from the grid is produced from fossil fuels, whereas nuclear power tends to decrease γ_{power}. Note that although CO_2 represents the most important greenhouse gas, there exist several other compounds that contribute similarly to climate change. Their combined impact is commonly normalized to the specific effect of CO_2, and all emissions are expressed in CO_2 equivalents. Also in our study GHG emissions other than CO_2 are considered. For the sake of readability, however, we omit further distinction and express emissions only in kg CO_2.

Theoretical emissions G_{sub} (kg CO_2) from the substituted energy are determined by E_{GSHP} and the emission factor representative for the substituted heat mix γ_{sub}

$$G_{sub} = \gamma_{sub} E_{GSHP} \tag{3}$$

For direct comparison, γ_{sub} may be expressed in heat units (kg CO_2/TJ) or power units (kg CO_2/kWh). The substituted heat is a mix from different energy carriers, *i*. The emission factor thus depends on the portion $e_{sub,i}$ of each energy carrier in the substituted heat mix:

$$\gamma_{sub} = \sum_i e_{sub,i}\gamma_{sub,i} \quad (4)$$

The portions $e_{sub,i}$ $\left(\sum_i e_{sub,i} = 1\right)$ are also termed substitution factors [60]. A high portion typically characterizes obsolete technologies (i.e. energy carriers) that are replaced in retrofitted buildings and not competitive anymore on the market.

The annually saved emissions (kg CO_2) are obtained by

$$G_{sav} = G_{sub} - G_{GSHP} \quad (5)$$

According to Eq. (5), $G_{sav} = 0$ indicates no savings and negative values denote increased GHG emissions from GSHPs in comparison to standard heatings.

3.2. Space heating data and synthesis

The calculation of emission savings is based on the figures of GSHP heat provision (E_{GSHP}) reported in Table 2, and we focus on the most recent year with complete data available, that is, 2008. The GHG emissions are directly dependent on the efficiency of a GSHP as expressed by the SPF (Eq. (1)). Typical SPF values vary between Northern and Southern European countries, mainly due to longer heating periods. Having in mind that technological innovation also improved the average SPF over the years, finding an accurate temporal and spatial resolution of characteristic SPF values is a challenging task. Thus, it is not elaborated in such detail here and instead, in the first instance a fixed value of 3.5 is chosen, which is considered representative for the average GSHPs currently in operation in Europe. The influence of this assumption for future predictions is however examined in more detail in Chapter 4.

The emission factor γ_{power} is multiplied by the primary energy consumption to obtain GSHP related emissions (Eq. (2)). This factor depends on the electricity mix consumed, which is different among different locations. Commonly, electricity mixes are expressed on a country-level, which allows comparison of the regionally variable carbon intensity of the generated electricity. Trading of electricity across the borders blurs these differences, and this has to be acknowledged when emission factors are applied. This was demonstrated by Saner et al. [37], and accordingly here we adopted the values of γ_{power} from this study.

The main question is, in order to estimate the emission savings achieved by GSHPs in the European residential sectors, which heating technologies have been substituted? This substituted heat mix, however, is difficult or even impossible to quantify accurately. Hence, exact country-specific values for γ_{sub} (Eqs. (3) and (4)) are not readily available. Representative statistical data does not exist, pan-European surveys on heat-pump specific substitution are not on hand, and thus it remains speculative, which alternative heating technology would have been chosen for each specific case. Comprehensive polls with house owners would be necessary to reflect the decision criteria and technological alternatives during the planning of each individual space heating system, which to our knowledge is not available in sufficient detail for the European market.

The actual heat mix, which characterizes the composition of energy carriers in residential space heating in each country, may serve as a first proxy for the substituted heat mix. This means GSHPs would replace the average of currently applied energy carriers. We used data from the Odyssee database to calculate the space heating consumption in European countries for the years 2000, 2005, and 2008. This database is provided by Enerdata [61] and consists of various energy statistics and indicators for the industry, service, residential, and transport sectors. From the database we derived the final consumption of six different energy carriers used for residential space heating in Europe. The energy carriers distinguished in Odyssee are coal, oil, gas, district heat, wood, and electricity for direct heat generation. This data was complemented with the final consumption of heat from GSHPs as given in Table 2, and the derived actual heat mix composition for 2008 is depicted in Fig. 2. Obviously, substantial differences exist between the countries.

Odyssee does not provide final space heat consumption data for Switzerland, therefore, this data was derived from the National Register of Buildings and Dwellings [62]. This register holds energy carrier, floor area, and construction period information for each building in Switzerland. The final annual energy demand for each

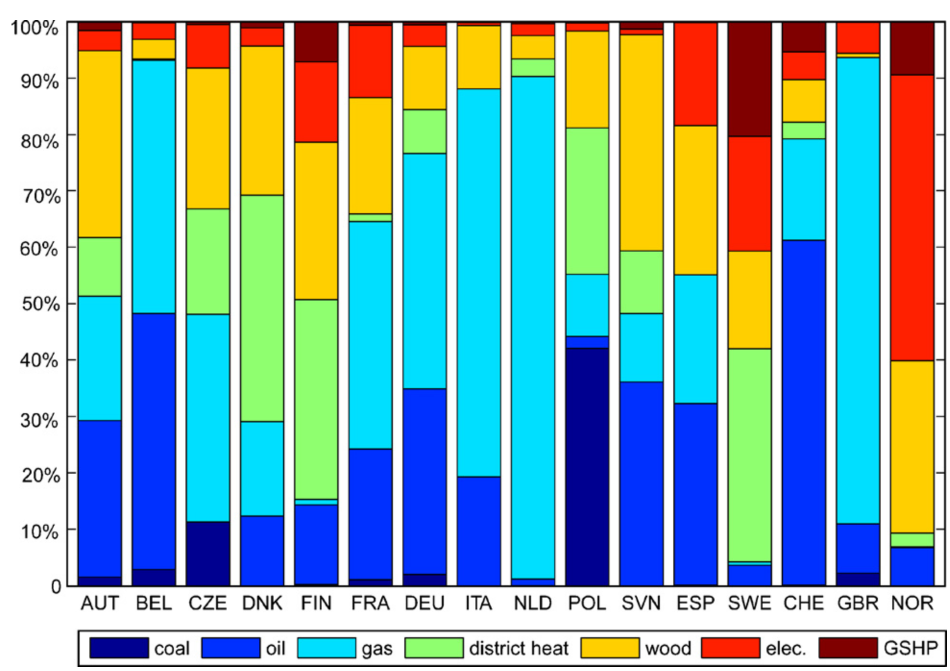

Fig. 2. Heat mix as for the year 2008 of residential sector in various European countries.

considered energy carrier was calculated by multiplying the specific floor areas [m^2] with construction period and energy carrier specific space heating demands [MJ/(m^2 a)] [63]. This was added to Fig. 2.

Aside from using the actual heat mix, the substituted heat mix we search for may be approximated with alternative methods. For instance, following the empirical estimation by Linkohr et al. [60], in Germany, a GSHP is most likely to replace an old heating system such as oil or gas heating. They estimated that a GSHP replaces 45% of gas heatings, 44% of oil heatings, 5% of electrical heatings and 3% of both coal and district heat. These fractions represent substitution factors $\gamma_{sub,i}$ (Eq. (4)), which might be valid for the German heat market, however can hardly be transferred to conditions in other European countries. The findings by Linkohr et al. [60] also indicate that the substituted heat mix differs from the actual heat mix, with a higher proportion of fossil-based technologies in the substituted portfolio. In contrast, when new buildings are equipped, GSHP systems compete with more modern and energy efficient systems than the average of the installed conventional technologies. Thus, in terms of substitution by GSHPs, more efficient technologies than the average in place would have to be considered. Accordingly, considerable uncertainty exists as to what extent the actual heat mix or alternative substitution factors are a good approximation of the substituted heat mix.

In order to reflect the uncertainty in the subsequent calculations, we account for potential ranges of the substituted heat mixes in different countries. As one (i.e. lower emission) bound, a "modified actual heat mix" is chosen. This means the actual heat mix is considered, but slight modification is necessary because it is unlikely that GSHPs are replaced by other GSHPs. Thus, these are dropped from the actual heat mix. Since supply by district heating, if available, is considered advanced and favorable to GSHPs in practice, this technology is also neglected. This decision is also supported by the very small substitution factors for district heating given by Linkohr et al. [60]. Consequently, after omitting district heatings and GSHP systems, the remaining portions of oil, coal, gas, wood and electricity as energy carriers are upscaled to arrive again at 100%. These portions then represent the substitution factors for the modified actual heat mix.

The other (i.e. higher emission) bound, the "removed heat mix", is based on the real changes in the heat mixes as reported for the individual countries. It represents the higher bound as it reflects the trend of replacing carbon intense heatings with more modern and environmentally friendly alternatives. Accordingly, bulk emission factors can be expected to be higher than the modified actual heat mix. To estimate the removed heat mix, a comparison of the actual heat mixes from the years 2000 and 2008 is made. Those heating technologies that decreased their capacities are of major interest, assuming that these trends reflect the changes in the heating markets and thus the substitutions. The technology-specific proportions are determined by the decline, and these proportions are scaled up to a bulk substitution of 100% $\left(\sum_i e_{sub,i} = 1\right)$.

CO_2 equivalent emissions for the final consumption of space heat were calculated within a life cycle assessment (LCA) framework. LCA is a standardized methodology that describes the assessment of environmental impacts of a product over its entire life cycle [64]. The life cycle includes all phases from first extraction of raw material, the use phase and maintenance until the final disposal of the product. LCA has been widely applied in the last two decades to assess the environmental impacts of various products, as well as services (e.g. [65–67]). Saner et al. [37] describe the application of the methodology for the assessment of space heating provided by GSHP. The strength of LCA lies in calculating the direct, as well as the indirect GHG emissions of the heat supplying technologies. Direct GHG emissions, for instance, are generated by incinerating a heat carrier (e.g. oil); indirect emissions are emitted in the supply chain of the heat carrier (e.g. refining and transportation of oil).

We determine GHG emissions represented as CO_2 equivalents. They are induced by the final consumption of residential space heating. We use life cycle inventory data from the Ecoinvent database (Version 2.2) for the different heating technologies and the IPCC (Intergovernmental Panel on Climate Change) greenhouse gas characterization factors (Version 1.02) [68]. For each country and year we determine the energy demand for the seven selected heat carriers and assign the corresponding dataset from the underlying Ecoinvent database (Table 3).

As far as possible for the given data sources, regionalized versions of the Ecoinvent datasets are applied for each country. The electricity mixes used for direct electric heating and GSHPs, and the natural gas compositions burned in gas furnaces are expressed on country levels. For coal stoves and oil boilers, average European datasets are used. Since no further information is available, district heat and wood incinerated in furnaces are approximated with the available specific data for Switzerland. The derived heat demands for the different European countries and the years 2000, 2005, and 2008 are assessed with LCA. With the technology- and country-specific substitution factors, this yields the total life cycle CO_2 equivalent emission factors, γ_{sub}, for modified actual and removed heat mixes (Eq. (4)). These are listed in Table 4 with the dominant heat carriers.

All over data quality is considered good, with the Odyssee database being one of the most popular energy databases in Europe, and Ecoinvent most advanced LCA database. Still, as for example emphasized by Swan and Ugursal [69], the energy flows in the residential sector are not well known in comparison e.g. to the industrial sector. The main reasons for this are the deficiency of knowledge on the individual behavior of occupants, as well as the limited private data accessibility. Therefore, for instance, the heat mix may slightly vary if taken from other sources. For example, the IEA [70] also provides information about the ratios of heat production from different energy sources, but not exclusively for the residential sectors. We minimized potential artifacts from merging different heterogeneous data sources, and uncertainty bounds are included, to reflect uncertainty of calculated values.

Uncertainty also needs to be kept in mind for the underlying LCA data sources. Such databases and calculation procedures commonly have to deal with imprecise and estimated raw data on background

Table 3
Energy carriers and corresponding Ecoinvent v2.2 unit process.

Energy carrier	Ecoinvent unit processes for single family dwellings	Ecoinvent unit processes for multifamily dwellings
Coal	Hard coal briquette, burned in stove 5–15 kW	Hard coal briquette, burned in stove 5–15 kW
Oil	Light fuel oil, burned in boiler 10 kW condensing, non-modulating	Light fuel oil, burned in boiler 100 kW condensing, non-modulating
Gas	Natural gas, burned in boiler condensing modulating <100 kW	Natural gas, burned in boiler condensing modulating >100 kW
District heat	Heat from waste, at municipal waste incineration plant	Heat from waste, at municipal waste incineration plant
Wood	Wood chips, from forest, mixed, burned in furnace 50 kW	Wood chips, from forest, mixed, burned in furnace 300 kW
Electricity	Electricity, low voltage, at grid	Electricity, low voltage, at grid
Ground source heat pump (GSHP)	Heat, borehole heat exchanger, at brine-water heat pump 10 kW	Heat, borehole heat exchanger, at brine-water heat pump 10 kW

Table 4
Emission factors of modified actual heat mix (in 2008, without district heating, GSHPs), of removed heat mix, i.e. only those heatings that declined (2000–2008, [61]), the calculated average (proxy for substituted) heat mix, of low voltage electricity at grid (including electricity imports, [37]), and accordingly by electricity consumed by ground source heat pumps (GSHPs, SPF = 3.5) in European countries. The dominant heat carriers for modified and removed heat mixes are abbreviated by o (oil), c (coal), g (gas), w (wood), and e (electricity).

Country	Modified actual (kg heat CO_2/kJ)	Removed heat (kg CO_2/kJ)	Average (kg CO_2/kJ)	Electricity (kg CO_2/kWh)	Electricity (kg CO_2/kJ)	GSHP, SPF = 3.5 (kg CO_2/kJ)
AUT	729 w,o,g	1250 o,c	990	0.442	1591	455
BEL	967 o,g	1082 o,g	1024	0.366	1318	376
CZE	1007 g,w	1418 c,g	1213	0.923	3323	949
DNK	620 w,g,o	1238 o,g,e	929	0.619	2228	637
ESO	402		402			
FIN	774 w,o,e	1202 o,e	988	0.339	1220	349
FRA	717 g,o,w	912 o,w,c	815	0.108	389	111
DEU	973 g,o	1144 o,g	1058	0.719	2588	740
HUN				0.747	2689	768
IRL	1232	1448 c	1340	0.884	3182	909
ITA	860 g,o	1149 o	1005	0.641	2308	659
NLD	830 g	833 g	831	0.725	2610	746
POL	1105 c,w,g	1141 o	1123	1.188	4277	1222
SVN	647 o,w	756 o,w	701	0.485	1746	499
ESP	970 o,w,g	234 w,c	602	0.592	2131	609
SWE	310 e,w	932 o,e	621	0.105	378	108
CHE	979 o,g	979	979	0.134	482	138
GBR	945 g	1101 g,c	1023	0.683	2459	703
NOR	187 e,w	399 e,o	293	0.046	166	47

processes and with conceptual uncertainty introduced by specific assumptions on the inspected systems' boundaries. When comparing, for instance, the GHG emissions for the residential sector reported by Odyssee and those calculated here by LCA, the more rigorous LCA framework that also accounts for background emissions in the energy production delivers, on average slightly higher values. Since no detailed information on underlying assumptions and all data sources for the Odyssee database are available, further reasons for this discrepancy cannot be determined.

4. Results

The results cover a country based estimation of GHG emission savings by GSHPs using the year 2008 as reference. The uncertainty ranges, as depicted in Fig. 3, stem from the two ways to compute the energy carriers of the substituted heat mix. A major discrepancy between recently removed and currently used energy carriers can be observed for the Scandinavian countries, and the broad uncertainty ranges may reflect substantial changes in residential space heating towards more environmentally friendly technologies. In the following, the ranges are not further discussed and instead the mean value, i.e. the average between removed and modified actual heat mix, is used as proxy for the substituted heat mix (Table 4).

Aside from the 2008 situation, the potential of GSHPs in the future is briefly analyzed. For this, special focus is set on the SPF. We assume a representative European average value of SPF equal to 3.5 for 2008, but technological innovation and advancements are supposed to increase the performance of heat pumps.

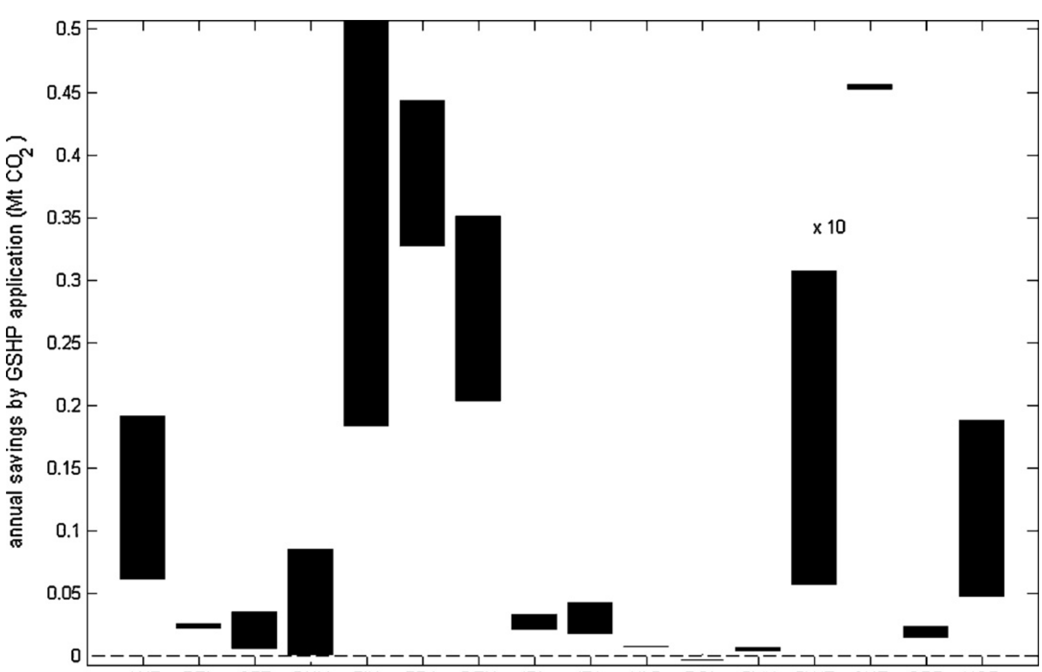

Fig. 3. Ranges of annual GHG savings due to ground source heat pump systems (GSHPs) in the residential sector in 16 European countries for 2008 (no reliable estimates available for Estonia, Spain, and Hungary). Lower bound, modified actual heat mix; upper bound, removed heat mix.

Table 5
Estimated average absolute (t CO_2) and relative GHG emission savings (in percent) by GSHPs in the European residential sector for the years 2000, 2005, and 2008 using a SPF of 3.5.

	Absolute savings (tCO_2)			Relative savings (%)		
Country/year	2000	2005	2008	2000	2005	2008
AUT	53,975	83,803	126,325	0.41	0.75	1.19
BEL		14,746	23,408		0.06	0.11
CZE	1671	7413	20,395	0.01	0.06	0.17
DNK	751	13,797	40,562	0.01	0.25	0.81
ESO						
FIN	22,107	80,523	344,967	0.41	1.50	6.25
FRA	13,959	197,166	384,633	0.02	0.27	0.56
DEU	34,382	110,098	277,034	0.02	0.08	0.20
HUN						
IRL		3238	27,109			
ITA	193	14,554	30,379	0	0.03	0.06
NLD	455	5173	7366	0	0.03	0.04
POL	−695	−2431	−4825	0	−0.01	−0.01
SVN	848	996	5333	0.04	0.07	0.40
ESP			−612			0
SWE	237,053	1,518,043	1,822,482	3.00	25.17	35.85
CHE	135,593	196,869	453,864	1.54	2.09	4.48
GBR	72	1705	19,125	0	0	0.02
NOR	559	50,337	117,379	0.04	3.37	8.69

4.1. Situation in different countries

The discrepancy between 2008 modified actual (729 kg CO_2/kJ) and removed (1250 kg CO_2/kJ) heating mix emission rates (Table 4) shows for **Austria**, similar to Denmark, Sweden and Norway, that the heating markets have substantially changed. In Austria, in particular, oil (67%) and coal fired (23%) systems declined between 2000 and 2008, and the heating market of 2008 is dominated by wood fired systems (33%) and to lesser extent by oil and gas fired systems (Fig. 2). By replacing mainly fossil-based systems, GHG emission savings by GSHPs might be more substantial than can be expected in the future. By average emission factors of substituted heat mix of 990 kg CO_2/kJ we calculate savings of 1.2% in 2008 (126,325 t CO_2, Table 5). This is also spurred by relatively moderate emissions of the electricity mix in this country (0.442 kg CO_2/kWh, Table 2) and a substantial number of GSHPs in operation of nearly 50,000 in 2008 (Table 1).

In **Belgium**, 9500 GSHPs were reported for the year 2008 (Table 1). This number is smaller than that for the neighboring Netherlands, but higher GHG savings can be estimated. Main factors are the higher emission rate from the substituted heat mix (average of 1024 kg CO_2/kJ, Table 4), and even more important, a relatively small emission factor for electricity (0.37 kg CO_2/kWh). The latter is governed by a nearly 50% ratio of nuclear power. The GHG savings calculated for 2008, reach 23,408 t CO_2, which means about 1 per mil savings versus conventional heating technologies (Table 5).

The number of GSHPs in the **Czech Republic** has substantially increased in recent years. In 2008, 9168 GSHPs were reported (Table 1, [58]) and this number is expected to be well above 10,000 in 2011. In contrast to the neighbor Poland, the carbon footprint by electricity from the grid is slightly smaller (0.92 kg CO_2/kWh), and the emissions expected for the substituted heat mix are higher (Table 4). The high value of 1213 kg CO_2/kJ is mainly contributed to the high share of coal-fired boilers, which were replaced during the last decade by alternative energy sources. The contribution of GSHPs to the residential heating sector is relatively small (<1000 TJ in 2008, Table 2), and GSHPs energy has only a share of 0.5%. Thus, due to the high emission rates of the electricity, the CO_2 savings achieved by GSHPs (20,395 t CO_2 per year 2008, Table 5) in comparison to alternative heating systems are rather low (0.17%).

In **Denmark,** the heat mix is dominated by district heating and wood (Fig. 2). Due to a high portion of wood fired installations the emission rate of the modified actual heat mix accordingly is relatively low, at 620 kg CO_2/kJ (Table 4). The removed mix between 2000 and 2008 (1238 kg CO_2/kJ) is dominated (75%) by oil-fired boilers, and thus the Danish heating market has substantially evolved towards more environmentally friendly technologies. By 2008, about the same number of GSHPs as in the UK had been running (11,250). With respect to the average substituted heat mix, GSHPs achieved GHG savings of about 0.81%, or 40,562 t CO_2 (Table 5).

In 2008, 46,412 GSHPs were reported in **Finland**, which supply nearly 10,000 TJ (Tables 1 and 2). The boundary conditions for achieving GHG savings are good. During the last decade, nearly 90% of the removed heating systems are high emission oil fired boilers. This yields an average substituted heat mix with an emission rate of 988 kg CO_2/kJ estimated for 2008 (Table 4). Aside from this, the country-specific electricity mix is dominated by nuclear, coal, gas and hydropower, which results in 0.497 kg CO_2/kWh [37]. By imports of low carbon electricity from Norway and Sweden, the effective electricity emission rate is decreased to 0.339 kg CO_2/kWh (Table 4). This is in favor of operating GSHPs, and the calculated GHG savings of 344,967 t CO_2 add up to 6.25% savings in the residential heating sector (Table 5).

France had more than 120,000 GSHPs in operation in 2008, with substantial growth rates and a number similar to Germany (Table 1). The country-specific GHG emission savings, however, are much higher. This is ruled by the relatively low climate change impacts associated with nuclear power that dominates the electricity market in France. The emission rates are only 0.108 kg CO_2/kWh (Table 4). An average substituted heat mix, with a rate of 815 kg CO_2/kJ (Table 4), yields 384,633 t CO_2 savings by GSHPs for 2008 (Table 5). Still this number means only slightly more than half a percent (0.56%) of the GHG emissions from heating residencies could be avoided.

Italy is more famous for a long history of high-enthalpy geothermics. The number of GSHPs is relatively small and reached only about 12,000 in the year 2008 (Table 1). This is associated with GHG emissions savings of 30,379 t CO_2, which represents relatively low savings of 0.06% (Table 5). The calculated substituted heat mix (1005 kg CO_2/kJ) and electricity (0.64 kg CO_2/kWh) emission rates are close to the European average.

For **Germany**, 148,000 GSHPs were reported in 2008, with nearly 100,000 new installations only in the period between 2005 and 2008 (Table 1). We calculated an average substituted heat mix with 1,058 kg CO_2/kJ, and a relatively high emission rate for the national electricity of 0.719 kg CO_2/kWh (Table 4). This high rate is governed by a high share of coal as the primary energy source (>40%, [37]), which mitigates the potential of saving GHG emissions by GSHPs in this country. On average, it can be calculated that the SPF has to be higher than 2.4 to achieve any emission savings. Based on our assumptions, total savings in 2008 reached 277,034 t CO_2, which imply only 0.2% savings in the residential heating sector (Table 5).

The number of GSHPs has been growing significantly during the last few years in the **Netherlands**. For example, an average rise from 1600 in the year 2005 to 14,600 in 2008 is estimated (Table 1, [31,58]). Despite the popularity, the total CO_2 savings by GSHPs in the year 2008 are small (7366 t CO_2, 0.04%, Table 5). This is triggered by average emissions of residual and substituted heat mix of 831 kg CO_2/kJ, which is dominated by natural gas-fired boilers (Table 4). The moderate average emissions by standard heating technology and the relatively high emissions from electricity from the grid (0.73 kg CO_2/kWh) yield relatively small values for the savings. For the conditions in this country, the SPF of the GSHPs has to be above 3 to achieve any GHG savings at all.

Due to a fraction of more than 80% coal [37], the electricity mix in **Poland** is one of the most carbon intense in Europe. The low voltage electricity in the country (incl. production, grid and transformation) has an average emission rate of 1.36 kg CO_2/kWh, and including all imports and exports reduces to 1.18 kg CO_2/kWh (Table 4). The estimated substituted heat mix is also dominated by fossil-based fuels with a calculated mean emission rate of 1123 kg CO_2/kJ. Accordingly, for the country's average, a SPF of at least 3.8 would be necessary to achieve any GHG emission savings by GSHPs. Representative values of SPF are estimated to be lower in the past, but with improved performance of heat pumps and advancements in electricity production efficiency, GSHP may evolve into an environmentally favorable option in the future. Still, relative benefits in comparison to the average in residential heating are very low. Therefore, case-specific conditions will play the most important role for potential environmental benefits from GSHP operation.

In **Slovenia**, a considerable growth of GSHP installations can be observed between 2005 and 2008. During this reporting period, the number almost increased by a factor of about 10 to 3440 (Table 1). This is accompanied by more savings in GHG emissions that are estimated at 5333 t CO_2 in 2008. This means 0.4% relative GHG emission savings in the residential space heating sector (Table 5). Average emission rates for heating in Slovenia are relatively low (modified actual heat mix: 701 kg CO_2/kJ), especially due to a high share of wood. Replacing these renewables with GSHPs, however, is not desirable due to the additional emissions from heat pump operations.

Sweden is a good example of the major potential of geothermal technologies for the growing European market. In 2008, 320,687 GSHPs were reported (Table 1), which generate more than 52,000 TJ per year. It is difficult to explain this high take-up in Sweden since for example Finland, with similar culture, climate, geology, and infrastructure has only a relatively small number of systems. One explanation to the Swedish success could be that much of the research and testing were undertaken in Sweden. Not only the number of GSHPs is maximal in this country, but also the emission savings with 35.85% in 2008 are the highest (>1.8 Mio t CO_2, Table 5). This is, in particular, promoted by low emission rates of the electricity that stems mainly from nuclear and hydropower (with imports: 0.105 kg CO_2/kWh, Table 4). Further, carbon intense heating systems such as oil fired boilers were substantially reduced, with a calculated rate of removed heatings of 932 kg CO_2/kJ and an estimated substituted heat mix with a rate of 621 kg CO_2/kJ.

In **Switzerland** the number of GSHPs is 61,000 for 2008, which is significant relative to the size of the country (Table 1). They produce about 7403 TJ per year (Table 2). We observe similar conditions as in Finland and Sweden, with a low emission electricity mix dominated by hydro and nuclear power (0.134 kg CO_2/kWh, Table 4). In contrast, the estimated substituted heat mix is at a high rate of 979 kg CO_2/kJ, a value that is amplified by fossil (oil and gas) fuel based boilers (Table 4). Between the years 2000 and 2008, their capacity has not significantly changed and the climate corrected values even indicate a slight increase. Therefore, the removed heat mix here could not be calculated and instead the value of residual heat mix is used. The significant discrepancy between low emission electricity and high emission standard heating are ideal grounds for GSHP application to avoid GHG emissions. We compute savings of 4.48%, or 453,864 t CO_2 for the year 2008 (Table 5).

The **United Kingdom** represents a natural gas dominated market (Fig. 2). However, this is a highly dynamic market as, for instance, in 2006 the UK became a net importer of gas [59]. Lund et al. [57] recognize an "increasing awareness of the use of groundwater for cooling and heating domestic, commercial and public buildings". They also emphasize that the country now understands that GSHPs offer very substantial reductions in carbon emissions compared to fossil-fuelled systems. This fact was incorporated into several official energy programs. Hence, the UK is on the threshold of becoming an emerging market for GSHPs and an increasing number of GSHPs has been observed since 2005, with the 10,000 threshold already reached before 2008 (Table 1). This is still very low considering the final demand of energy of over 1 Mio. TJ for this country and only a capacity of 753 TJ provided by GSHPs (Table 2). At this stage, the calculated savings of GHGs are rather minor (19,125 t CO_2, 0.02%, Table 5). Similar to the Netherlands, average emission rates of substituted heat mix are dominated by natural gas, but during the last decade, in particular, coal-fired heatings were replaced (Table 4). Thus, an average rate of 1023 kg CO_2/kJ was calculated for the substituted heat mix.

The number of GSHPs in **Norway** is not exorbitant, in fact, only 26,000 were reported for 2008. This is only about half of what was reported for Finland (Table 1). Heating practice is mainly based on electricity and wood, and, in particular, oil-fired boilers declined in the past. With the very low emission rates of the hydropower dominated electricity from the grid (>80%, 0.046 kg CO_2/kWh, Table 4), both production of heat and electricity are relatively environmentally friendly. The GSHPs, which provide about 10% of the heat in the residential sector (Table 2), thus achieve calculated emission savings of 8.7% in comparison to alternative, replaced technologies. For 2008, this means 117,379 t CO_2 savings (Table 5).

For **Hungary**, **Ireland**, **Estonia**, and **Spain**, no reliable data on heat mix, electricity emission factors and/or final demand of residential heating energy could be obtained. The first two countries were also in the focus of the EU FP7 GTR-H project that aimed at improving the conditions in countries with poorly developed geothermal direct use by GSHPs. In none of these countries, the reported number of GSHPs surmounted 10,000 in 2008, although the number of 4874 listed for Estonia is remarkable considering its small size (Table 1). Hungary and Ireland, as also demonstrated within the GTR-H project have a certain potential for GSHP development. In these countries, however, rather carbon intense electricity is provided (Table 4), which mitigates potential GHG savings by GSHP operation.

4.2. Potentials for the future

In most countries, GSHP application appears to be at an early stage, which is reflected by often significant growth rates during the last years. Sweden is most developed, with the highest number of household appliances of GSHPs, and this mature market is still growing. Even if it is hardly possible to extrapolate the trends reliably in the future, we can have a look at what would be

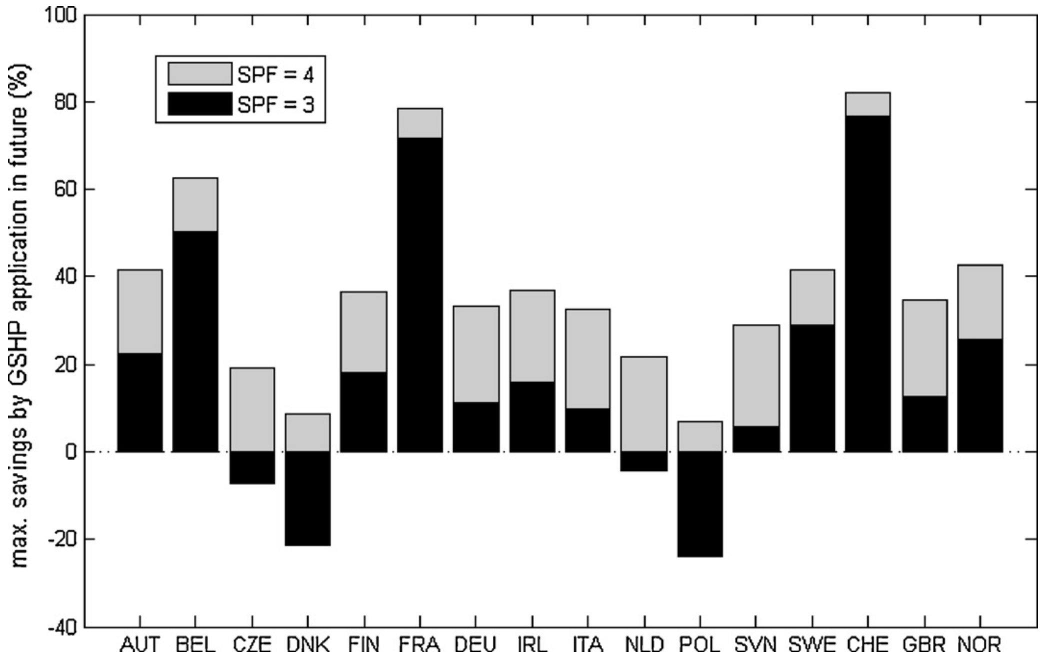

Fig. 4. Maximum GHG savings by GSHPs in European countries by a complete replacement of standard heatings in the residential sector (except district heating; using an SPF of 3 and 4). Calculations are based on current conditions of heat mix, emissions and energy-efficiency as well as current electricity mix (no reliable estimates available for Estonia, Spain, and Hungary).

possible if all markets would be saturated with GSHPs. Such optimistic conditions are not realistic, however are of interest as the best case with maximum potential GHG emission savings. For this calculation, it is assumed that all fossil based fuels, electricity and wood fired boilers would be replaced by GSHPs. Substituted heat mixes are not altered and adopted from Table 4. Aside from this, we suppose that electricity mixes as recorded for the most recent year, 2008, are representative also for the future. This is a very crude assumption that has to be carefully reflected, as feedbacks from the electricity market to the increased electricity hunger from GSHPs have to be expected. Jakob et al. [71] showed that increased electricity demand due to heat pumps could lead to the construction of combined cycle gas power plants in Switzerland. Thus, more accurate future GHG emission results could be obtained, for example, within a consequential LCA framework [72].

Since one main determinant of the environmental performance of GSHPs is the SFP, and variability of representative values exists depending on mainly climate, technology and innovative progress, a range between low (SPF of 3) and high efficiency (SPF of 4) is considered. Fig. 4 shows for all selected countries (except of Estonia, Spain and Hungary), that in fact this SPF range has a large influence on potential GHG savings. This is reflected by the width of the grey bars that visualize the difference in the figure. It is also shown that in countries with very carbon intense electricity production, an SPF of 3 often is not sufficient.

For the Czech Republic, Poland and the Netherlands, even increased GHG emissions would be calculated. This is also the case for Denmark, where the electricity emission rate is not extreme, but in this country, household heatings reveal to be dominated e.g. by wood fired boilers and thus benefits can hardly be achieved from GSHP operation. For these four countries, savings are possible by increased SPF values. However, due to the primary energy consumption by the heat pumps even complete replacement of standard heating technologies with GSHPs would only yield savings of about 20% or less of the current GHG emissions caused by heating. For most other countries, the potential savings lie between 20% (SPF of 3) and 40% (SPF of 4). Countries with electricity mixes dominated by nuclear and hydropower production show higher potential saving rates. Saving rates reach between 60% and 80% for Belgium, France and Switzerland. Sweden reveals to be well developed already, and relative future savings, thus are limited, and range between 10% and 40%.

Summing the maximum savings together, based on the given assumptions at most about 150 Mio t CO_2 emissions (SPF = 3.5) could be saved. This value would be 94 for an SPF of 3 and 191 for SPF equal to 4. The mean value would represent bulk savings of 30% (19–38%) that are possible for the studied countries (based on 2008 conditions). In contrast, the total savings calculated for 2008 was 3.7 Mio t CO_2 (SPF = 3.5), thus reaching savings of only 0.74% in comparison to alternative and substituted residential heating technologies.

5. Conclusions

We presented a comprehensive analysis of the past, current and future role of GSHPs in Europe for saving GHG emissions by replacing alternative space heating technologies in the residential sectors. The cardinal factors are the substituted heat mix, the energy-efficiency of GSHPs as quantified by the SPF, as well as the electricity mix. Accordingly, GSHPs appear attractive if the primary energy for the electricity consumed by the heat pump is renewable, nuclear and/or hydropower. This favors running GSHPs in countries such as Norway, France, Belgium, Sweden, Belgium, Austria and Switzerland. For example, per TJ heating energy provided by GSHPs savings reach up to 47 t CO_2 in Belgium, 49 t CO_2 in France, and even 61 t CO_2 in Switzerland. For the latter, this high value is particularly spurred by the carbon intense substituted heating carriers.

The presented values represent a moment in time, and, in particular, when predictions in the future are drawn, rebound effects on the country-specific electricity mixes have to be considered. Substantially increasing locally or regionally the number of GSHPs means higher electricity consumption, and this is compensated either by cross-border trading of electricity or by building new power plants. Higher numbers of GSHPs, therefore, can lead to a shift in the heat mix. Under such conditions, average European figures appear more robust. For instance, as a mean value for the European countries considered, 36.8 t CO_2 per TJ are saved by GSHP operation. For 2008, total heat provided by GSHPs sums up to more than 100,000 TJ, and hence about 3.7 Mio t CO_2 are saved. This means about 1.4% of the residential space heating is managed by GSHPs in Europe, and about 0.7% GHG emissions are saved in comparison to alternative technologies. Future predictions for Europe indicate that savings of up to about 30% are possible by GSHP operation, a value that could be significantly increased by an improved performance of heat pumps (SPF $\gg$ 3.5). Also current trends towards greener electricity are arguments for expecting higher savings in the future. However, future electricity mix may also be influenced by gradual shutdown of nuclear power plants, which currently provide low carbon electricity in favor of GSHPs.

The presented analysis is based on 2008, the most recent year with complete datasets available. Extrapolated to 2011, we estimate a current number of GSHPs installed of 1.25 million in Europe. By far, most of these are operated for heating private residencies. Thus, even if GSHPs become increasingly attractive in large scale applications, and even if some are utilized for cooling, only minor discrepancies are expected by extending the focus beyond residential heating. Under these assumptions the 1.25 million GSHPs in 2011 are projected to provide about 150,000 TJ heating energy per year, and save annually about 5.5 Mio t CO_2. Still these numbers for 2011 mean only savings of about 1.1% in comparison to standard heating practice.

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