REDUCTION OF ENVIRONMENTAL IMPACTS OF HEAT PUMP USAGE WITH SPECIAL REGARD ON SYSTEMS WITH BOREHOLE HEAT EXCHANGERS

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Abstract
Ground coupled heat pump systems are suitable for extracting subsurface thermal energy with low environmental impact especially regarding CO_2 emission. The efficiency of such systems strongly depends on the temperature of the ambient heat (thus underground substrate). This temperature usually changes unfavourably during operation and efficiency becomes lower than the nominal value. Appropriate installation and operation cause lower temperature drop, thus higher efficiency. Consequently, it means lower electricity demand, therefore lower specific CO_2 emission, more CO_2 saving and lower operation costs. Quantitative analysis with 21 heat extraction models presented in the paper points out that the differences could be significant (up to 30 %), in addition using bivalent mode the environmental impact of the installation or/and operation can be reduced as well, especially using biomass firing as auxiliary heating.

Keywords: heat pump, seasonal performance factor, carbon-dioxid emission, borehole heat exchanger, bivalent system

1. Introduction

Heat pump systems using underground heat of shallow reservoirs seem to be the most dynamically developing sector of geothermal energy utilization (Lund et al., 2010). In contrast with most geothermal energy utilization types, heat pump system does not require good geothermal conditions, their installation and operation can be executed almost anywhere. Numbers of these systems show exponential growth in many countries where encouraging factors such as proper national income, environmental awareness and availability of technological and economical tools exist. Closed loop geothermal systems have no firm technological requirements in the aspect of installation, less favourable geological conditions may imply larger underground heat exchanger surface and increase payback time of investment.

The great advantage of geothermal energy compared to some renewable energy sources appears to be that their accessibility is not influenced by meteorological conditions, whereas similarly to biomass utilization, overproduction may have significant effects on it resulting in the failure of reservoir's initial potential. Contrary to public opinion, geothermal energy extraction may have disadvantageous environmental impacts, which can be amplified by under or oversizing and negligent construction. However, using heat pump systems means carbon saving in comparison with the conventional heating types (Jenkins et al., 2009; Blum et al., 2010), especially in countries with low carbon intensity in electricity.

The aim of this paper is to present some aspects of installation possibilities of ground source heat pumps (GSHP) and to highlight the general possibilities of reducing environmental impacts of GSHP. Although operation of different types of heat pump results in different environmental impacts certainly (Buday et al., 2014c), the main possibilities of reducing these impacts were possible to be detected in the case of borehole heat exchangers.

2. Basic concepts of shallow geothermal energy utilization

Energetical considerations

Heat pump applications transform low temperature ambient energy to high temperature thermal energy by using external energy (Ochsner, 2007; Omer, 2008). The external energy is usually electricity or natural gas based on the construction of the heat pump, however, innovations for heat pump systems which can use renewable energy resources exist. In heating mode the efficiency of the heat pump is defined by the nominated ratio of the delivered heat energy and the external energy (COP, coefficient of performance). This ratio is determined by given circumstances during the operation, since in long term the average ratio is used as SPF (seasonal performance factor).

$$COP=Q_n/P_n \quad (1)$$
$$SPF=E_d/E_c \quad (2)$$

where: COP – coefficient of performance in nominal circumstances [–]; SPF – seasonal performance factor [–]; Q_n – delivered heat in nominal circumstances [W]; P_n – external (e.g. electrical) power to the heat pump in nominal circumstances [W]; E_d – delivered energy in a studied period [J]; E_c – external (e.g. electrical) energy in a studied period [J].

In more detailed calculations these values can be given by using the primary energy demand of the external energy, or may contain the energy demand of the whole system.

One of the main benefits of GSHP systems is that cooling can also be operated by them. The heat subtracted from the building is imparted to the underground space. If there is no intensive groundwater movement, energy is stored near the underground heat exchanger, thus it reduces the cooling effect in winter, which increases the efficiency of the system.

Classification of heat pump systems based on the heat source

One of the most important classifications of heat pumps is based on the heat source in heat mode. The heat can stem from air, surface water, ground water or the whole ground (Ochsner, 2007; Omer, 2008). In this paper the environmental impacts of only the ground source systems (Fig. 1.) are discussed.

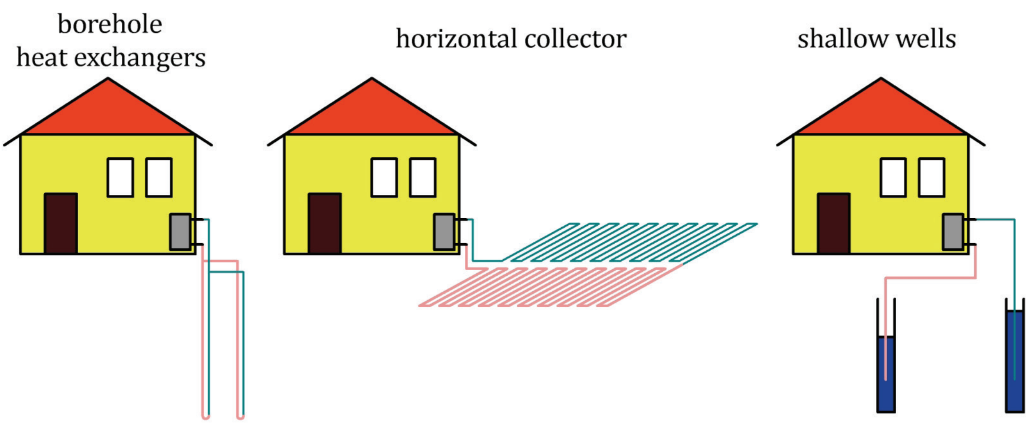

Fig. 1. Generic setting of the three main types of ground coupled loop of ground source heat pump systems

In open groundwater is produced from the reservoir by shallow (<15 m) supply well(s) and after the usage the water is re-injected into the same reservoir by re-injection well(s). The re-injected water should not reach the supply wells. The temperature of the reservoir is constant; its value is about 10 °C. The economically extractable yield of water is limited by thickness, extension and hydraulic conductivity of the targeted reservoir. Deep groundwater level is unfavoured in water extraction, while shallow level is unfavoured in re-injection and can cause inundation. The appropriate reservoirs are located near greater rivers, but occurrence of such areas is usually limited.

The energy content of the solid parts of underground space can be extracted by closed systems. In such systems heat is conducted to the surface of the underground heat exchanger, from which fluid carries the heat to the heat pump. The heat exchanger can be installed in boreholes (usually not deeper than 100 m) or in shallow depths (horizontal collector, trench collector, energy piles).

Classification of heat pump systems based on the external and auxiliary energy source

In monovalent systems the entire heat demand is supplied with the heat pump. If some degree of the heat demand is supplied in a different way (e.g. using auxiliary heat source), the system is so called bivalent. Installing these modes could be prosperous in several cases such as when investors try to shorten the payback period or when limited resources are available. Well-planned complex systems generate less environmental impact, above and beyond the economic benefits, and can be designed regarding to the geological-geographical-meteorological character of the investment's location. Besides the thermal properties of the building the calculation of the heat demand is based on the temperature value of the coldest days. In monovalent mode the capacity of the heat pump is designed for the maximum temperature difference (between the indoor temperature and the design outdoor temperature). Consequently, there are only a few days in the year when the system runs with its full capacity. In the bivalent mode heat pump systems are completed with auxiliary heating systems such as natural gas or electric boiler. Below a certain set temperature (bivalent point) the heat demand is partially or fully served by the auxiliary heating (Fig. 2.). This mode is used after renovation or with air source systems and can serve higher temperature than a monovalent mode (Ochsner, 2007).

3. Most important environmental impacts of the primary loop of GSHP utilizations

Open loop systems

The environmental impacts of drilling

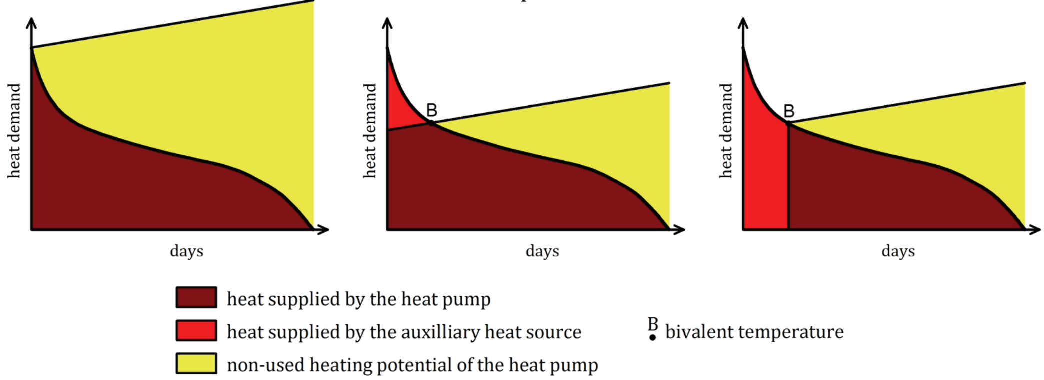

Fig. 2. Heat supply in different heat pump mode

and configuring of an open loop system are moderate. During operation the flow velocity and direction of groundwater may change permanently which causes sinking near the wells and immoderate shallow groundwater level near the re-injection wells (Buday et al., 2014b). Both problems lead to building damages. Damage events of operations such as contamination of the injected water or changes in transmissivity of the reservoir are rare, and as a result, surroundings of the well may become contaminated. If mechanical damage of the well does not occur, the contamination could be terminated by well-known techniques through the wells (e.g. pump and treat). Wells can be closed temporarily or finally, and the casing can be removed if necessary.

Closed loop systems

In the case of borehole heat exchangers the drilling technique is similar to that used in well drilling, but the total length is longer and by optimal installation there is no hydraulic connection between the inner part of the borehole and the surroundings. Unfortunately, it is common that casing is not installed in the borehole but only the grout (cement, clay). The main problem could be the penetration of the aquiclude layers, thus vertical connection could evolve between the aquifers and vertical movement of contamination is possible. Supplying 10 kW with a typical heat pump unit with SPF value of 4 with borehole heat exchanger(s) besides average geological capability requires 150 m total length of borehole(s) (based on VDI 4640, Ochsner, 2007). Drilling has lower space demand thus relief has only a minor effect on installation. Deep boreholes can impinge on the water source protection areas. Since the drinking water wells are usually located inside or close to the settlements, thus water source protection areas cover some parts of the settlement. It means that the prohibition of drilling due to water source protection and the demand for drilling to produce heat without significant environmental impacts appear in the same location (Buday, 2012; Buday et al., 2014b). In this case protection of the water source has higher importance.

To install horizontal heat exchangers significant landscaping is necessary. Considering a typical heat pump unit of 10 kW with SPF value of 4 and average geological capability (mixed clay and sand layers) the size of the horizontal loop is around 375 m^2, and a few metres deep hole should be dug (based on VDI 4640, Ochsner 2007). The permanent effect of installation is lower if the disturbed area is built in after the fitting. In addition after the installation disharmonic sinking or compaction concerning the horizontally heterogeneous sediments can cause cracking and leakage of the circulated fluid. Changes in land-use are also a limiting factor, since disturbing the layers above the loops or plantation in the area can also cause damages. Consequently, the influenced area should be used as lawn, meadow, covered area, etc.

During usage of heat pump systems the most important environmental impact is overcooling. This could happen when the heat pump demands higher amount of energy than the steady state conditions can conduct to the heat exchanger. The soil could be frozen deeper, the moisture can condensate to the pipes which may worsen the heat transfer. Decreasing temperature of the return fluid results in lower SPF and increasing operation costs. If the rate of heat supply by horizontal heat conduction or solar irradiation is not sufficient to cover demand fully until the next heating season the cooling of the system is certain (Rybach – Eugster, 2002). Some systems can cool buildings in the summer period, when heat may be transferred to the underground, which assists recovery (Buday, 2010). The ratio of the heating and cooling demand depends on the climate and the building thus the initiation of thermal energy storage is the designer’s responsibility.

The most important problem which can occur in a closed loop system is that if the pipes are damaged the heat carrier fluid is released into the reservoirs. Usually the heat carrier fluid is an organic refrigerant which could be dangerous especially when it reaches the drinking water reservoir (Heinonen et al., 1996). In this case the malfunctioning pipe should be closed, however, the retrieval of contamination is not possible with the system. The pipes of borehole heat exchangers and some types of shallow systems cannot be removed during the final closing.

4. Methods to determine the environmental impacts of heat pumps

Life cycle analysis suggests that the main environmental impact regarding the heat pump systems connect to the external energy (Saner et al., 2010; Bayer et al., 2012; Greening – Azapagic, 2012), which is usually electricity. Therefore the environmental impacts of the system can be derived from the environmental impacts of the electricity generation (energy structure, concentrated emission, low efficiency of electricity generation, energy losses). This is not the duty of the end-user, since it is normally out of their competency, although these effects could be decreased if the energy demand of the building from heat pump becomes lower or the SPF value of the heat pump is high. The environmental impacts are rather low in heat pump systems in which the external and/or auxiliary energy is supplied by renewable energy sources.

The CO_2 emission related to the heating was determined as the product of the external energy and the specific value of 316 g CO_2/kWh of Hungarian electricity generation (IEA, 2013). In some cases the CO_2 emission related to different sources is also calculated with the following specific parameters: natural gas firing has 35 MJ/m^3 low heating value, 1.775 kg CO_2/m^3 specific emission and 90 % efficiency, thus the overall specific emission is 203 g CO_2/kWh; wood firing has 17 MJ/kg low heating value, 1.466 kg CO_2/kg specific emission (Paládi et al., 2014) and 90 % efficiency, thus the overall specific emission is 345 g CO_2/kWh. Moreover wood firing is considered as a carbon neutral process, however presented calculations do not contain the CO_2 emissions connected to the plantation, fertilization, cutting and transportation.

Value of external energy can be determined by Eq. 2. if the SPF value is known. SPF value of the system could be estimated from the actual COP values of the heat pump or calculated from the probable temperature of the evaporator (Ochsner, 2007; Stiebel Eltron, 2012), using analytical or numerical calculations. In the calculations the COP function of the WPF 10 E type brine-water heat pump is used (Buday et al., 2014c based on data of Stiebel Eltron 2012):

$$COP_{act}=0.1171\cdot T_e+3.2381 \qquad (3)$$

where: COP_{act} – actual coefficient of performance [–]; Te – temperature of the evaporator [°C].

In this paper the evaporator temperature was determined by numerical models (Buday – Török, 2012) during different heat extraction schemes, different borehole installations and

Table 1. Main physical properties of the materials used in the models

	specific heat capacity J/(kgK)	bulk density kg/m^3	specific volumetric heat capacity kJ/(Km^3)	heat conductivity W/(Km)
soil	1500	1300	1950	1.8
concrete (grouting)	880	2200	1936	2.1
steel (casing)	469	7850	3682	50.0
heat carrier fluid	3680	960	3532	0.5

Table 2. Description of the models

model no.	description	operation scheme	HP delivered power per length (W/m)	length (m)	HP delivered energy (kWh)
models with constant heat demand					
0.0	base; λ=1.8 W/(Km)	continuous	20	500	43200
0.1	λ=2.1 W/(Km)	continuous	20	500	43200
0.2	λ=1.5 W/(Km)	continuous	20	500	43200
0.3	constant COP	continuous	20	500	43200
1.1	higher power, constant heat No.1	16 hour per day	30	500	43200
1.2	higher power, constant heat No.2	12 hour per day	40	500	43200
1.3	higher power, constant heat No.3	8 hour per day	60	500	43200
1.4	higher power, constant heat No.4	6 hour per day	80	500	43200
2.1	higher power&heat_1	continuous	30	334	43200
2.2	higher power&heat_2	continuous	40	250	43200
3.0	casing+grout_0	continuous	20	500	43200
3.1	casing+grout_1	continuous	20	500	43200
3.2	casing+grout_2	continuous	20	500	43200
3.3	casing+grout_x1	continuous	20	500	43200
3.4	casing+grout_x2	continuous	20	500	43200
models with real heat demand					
9.0	real heat demand	variable	40	250	20856.02
9.1	real heat demand	continuous	variable (design: 40)	250	20856.02
9.2	real heat demand	continuous	variable (design: 80)	125	20856.02
9.5	bivalent alternate, real heat demand	variable	40	250	8378.17
9.6	bivalent alternate, real heat demand	variable	20	250	8378.17
9.7	bivalent parallel, real heat demand	variable	40	250	19418.17
9.8	bivalent parallel, real heat demand	variable	20	250	19418.17
9.9	bivalent parallel, real heat demand	variable	40	125	19418.17

different geological conditions in cylindrical symmetry (Table 1. and 2.). The models calculated the average borehole temperature value which was used as the temperature of the evaporator as estimation.

The heat extraction was continuous or daily periodic during 180 days (heating season), the delivered energy was 43.2 MWh in each theoretical model (Table 2.). In most cases the delivered power per borehole length was 20 W/m, in addition, in some cases this parameter was higher. The ambient heat power per length demand was determined by the actual COP value. Models 0.x mean continuous operation with different thermal conductivity values, while in Model 0.3 constant COP value was used which was the same with the SPF value of Model 0.0. Models 1.x contained periodic heat extraction schemes, one extraction and one regeneration term each day. Models 2.1 and 2.2 used higher delivered power and shorter borehole length. Casing and grouting was built in models 3.x. In Models 3.0, 3.1, 3.2 the casing had 200 mm inner diameter and 25 mm wall thickness, the thermal conductivity of the soil was the same as Models 0.0, 0.1, 0.2 respectively, while in Models 3.3 and 3.4 the inner diameter of the casing were 400 mm and 600 mm respectively, the wall thickness and thermal conductivity of the soil were similar to the values of Model 3.0.

Models 9.x described real heat demand based on modelled air temperature detailed by Buday et al. (2014c), the system designed 40 W/m delivered power per borehole length value, heat pump of 10 kW, 20 °C inner temperature and -15 °C design outdoor temperature for winter. The base temperature derived from the temperature distribution and the length of the heating season was 10 °C. In models 9.1 and 9.2 heat extraction was continuous, the power was decreased for supplying the daily energy demand. This is not realistic, since the power of the heat pump is constant in most heat pump types, in addition, the actual length of heat exchanger is also constant thus daily operation time

Table 3. Main acquired parameters of the theoretical models

model no.	maximum temperature drop (°C)	SPF	extracted (ambient) energy (MWh)	external (electrical) energy (MWh)	CO_2 emission (kg/y)	relative CO_2 emission per kWh to the base case (-)
base (0.0)	9.13	3.52	30.94	12.26	3874.72	1.00
0.1	8.31	3.61	31.24	11.96	3780.45	0.98
0.2	10.21	3.41	30.52	12.68	4008.18	1.03
0.3	9.19	3.52	30.94	12.26	3873.34	1.00
1.1	11.39	3.33	30.24	12.96	4096.04	1.06
1.2	13.34	3.14	29.46	13.74	4342.28	1.12
1.3	16.50	2.82	27.91	15.29	4832.77	1.25
1.4	18.90	2.57	26.40	16.80	5307.34	1.37
2.1	12.88	3.10	29.26	13.94	4400.22	1.14
2.2	16.01	2.74	27.45	15.75	4975.59	1.28
3.0	8.65	3.58	31.13	12.07	3813.79	0.98
3.1	8.18	3.63	31.29	11.91	3764.57	0.97
3.2	9.29	3.52	30.92	12.28	3881.47	1.00
3.3	8.61	3.58	31.15	12.05	3807.97	0.98
3.4	8.56	3.59	31.17	12.03	3802.68	0.98

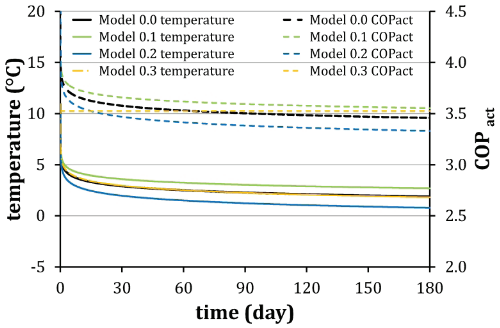

Fig. 3. Actual COP and temperature changes as a function of elapsed time in the case of different thermal conductivity values

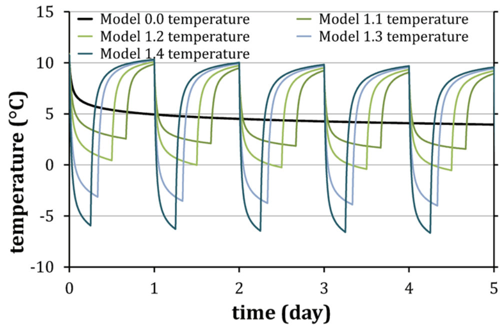

Fig. 4. Temperature changes as a function of elapsed time in the case of different heat extraction duration and specific power

varies during the heating season (Model 9.0). In bivalent models (9.5, 9.6, 9.7, 9.8, 9.9) the bivalent temperature was 2.5 °C, the power was constant and the length of daily operation time was reduced (Table 2.).

5. Results

Installation practice for better operation and lower grade environmental effects in monovalent mode

Thermal conductivity is an essential parameter in the operation of heat pump systems, however, its value is not constant neither spatially along the underground heat exchanger, nor temporally, thus in the practice average thermal conductivity is determined. In the case of borehole heat exchangers the geological units could be significantly different from each other therefore the average thermal conductivity strongly depends on the length of the unit, i.e. the maximum depth. In Models 0.0, 0.1, 0.2 the significant (16.6 %) increase or decrease of thermal conductivity causes only 3–4 % decrease and increase respectively in external energy demand and emission (Table 3.), however, the temperature drop is significantly favourable in the case of higher thermal conductivity. (Based on Model 0.3, using constant COP_{act} in the calculations causes similar temperature drop values as the base model, thus modelling with constant heat extraction could be acceptable approximation (e.g. in Buday et al., 2014a).

Constant heat demand can be supplied with shorter but more intensive heat extraction periods as well. More intensive heat extraction means higher temperature drop (Fig. 4.), lower SPF, however, not necessarily more expensive operation. If there is differential tariff in the current supply and off-peak periods last for only a few hours but off-peak electricity is significantly cheaper, the higher energy demand could be cheaper as well. The main problem about these systems is the possibility of extreme overcooling. Heat extraction with the same duration but higher power cause higher cooling and lower SPF (Model 2.1 and 2.2, Fig. 5.), thus if the total length of the boreholes is reduced due to the higher power per length value, the efficiency of the system becomes lower.

Using casing and grouting (Model 3.x) has moderate positive effects, since the temperature drop is lower and SPF is similar (Table 3.). It seems that both the casing and the grouting have positive effects depending on the radius of the casing and grouting, but together these effects become independent from the radius (Model 3.0, 3.3, 3.4). Besides these effects casing and grouting provide mechanical stability of the system, in addition limit the horizontal groundwater flow around the borehole and vertical groundwater movement along the borehole, thus their utilization is recommended especially if

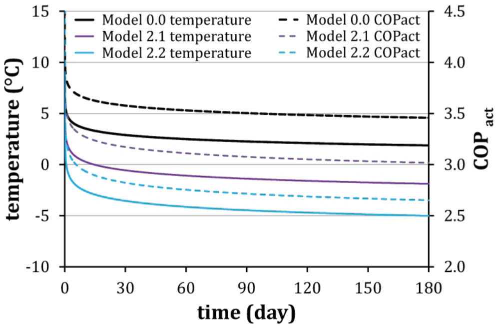

Fig. 5. Actual COP and temperature changes as a function of elapsed time in the case of different specific power values

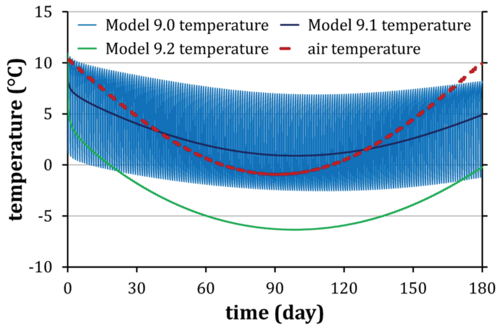

Fig. 6. Temperature changes as a function of elapsed time in the monovalent real heat demand models

Table 4. Main acquired parameters of the models with real heat demand

model no.	maximum temperature drop (°C)	SPF	extracted (ambient) energy (MWh)	external (electrical) energy (MWh)	auxiliary energy (MWh)	CO_2 emission (kg/y)	relative CO_2 emission per kWh of HP to the 9.0 (-)
9.0	13.53	3.14	14.22	6.64	0.00	2100.02	1.00
9.1	10.11	3.51	14.91	5.94	0.00	1877.65	0.89
9.2	17.35	2.73	13.21	7.65	0.00	2417.60	1.15
9.5	12.47	3.30	5.84	2.54	12.48	803.67	0.95
9.6	8.11	3.70	6.11	2.27	12.48	716.47	0.85
9.7	13.17	3.18	13.31	6.11	1.44	1931.44	0.99
9.8	8.94	3.56	13.97	5.45	1.44	1723.04	0.88
9.9	15.76	2.80	12.48	6.94	1.44	2192.42	1.12

thermal energy storage is planned.

Considering real heat demand and appropriate designing the daily average extracted power per length value is significantly lower during the whole year than the design value excluding the coldest days, when the heat pump operates continuously. Since single heat pumps usually cannot be suitable for different power, thus the daily operation time varies to supply the heat demand, consequently during most of the operation days the temperature can be partly regenerated, resulting in periodic temperature changes (Model 9.0, Fig. 6., Table 4.). However, this regeneration cannot provide so favourable conditions as a continuous heat extraction with controlled power (Model 9.1 and 9.2), where the SPF and relative CO_2 emission values are similar to the constant heat extraction models (Model 0.0 and Model 2.2 respectively).

Environmental benefits of bivalent systems

In the bivalent systems the CO_2 emission is usually higher than in the case of monovalent systems, since the specific CO_2 emission of the HP systems is favourable than values of auxiliary sources (Fig. 7.). Nevertheless, the installation causes fewer disturbances, as the surface of the heat exchanger could be smaller (shorter total length of borehole heat exchangers or smaller area of horizontal collector). In the case of similar configurations the temperature drop is lower

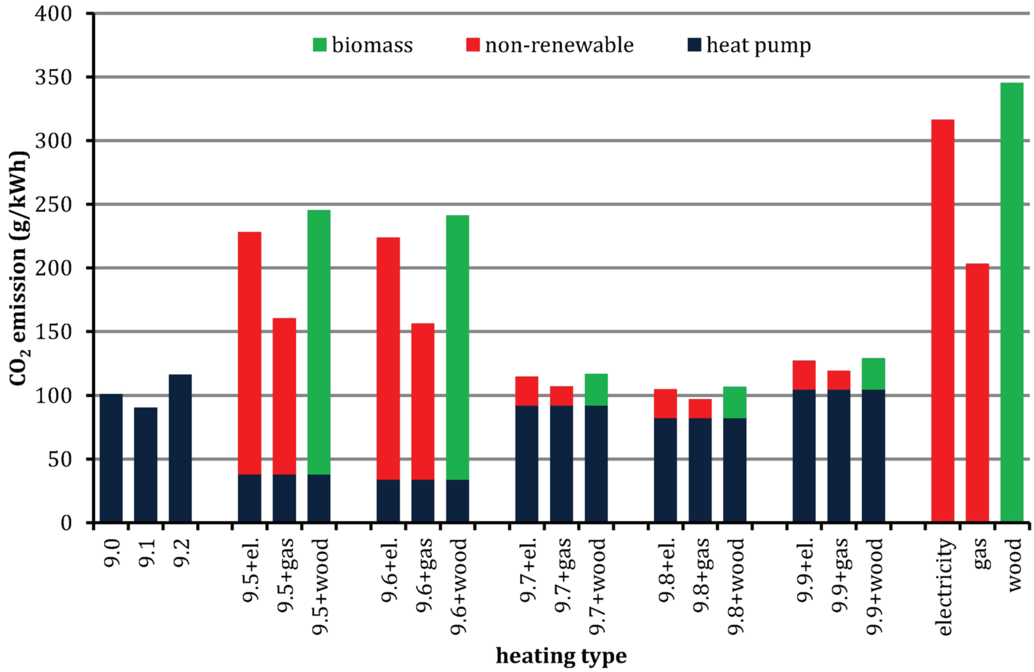

Fig. 7. Specific CO_2 emission of the different monovalent (9.0-9.2) and bivalent (9.5-9.8) heating modes and the proportion of the CO_2 emission related to different heat sources

and SPF is higher, since the value of full load hours is lower (Models 9.5 and 9.7). In Models 9.6 and 9.8 the specific heat extraction rate is reduced and the calculated parameters show cheaper and more environment-friendly operation, while in the case of Model 9.9 the heat extraction rate is similar and the heat exchanger area is reduced. In this way the installation is cheaper and more environment-friendly, although the operation has worse conditions.

If the temperature does not reach 0 °C surely, pure water can also be used as heat carrier fluid, which is the most environment-friendly solution. In these cases the environmental impacts are less harmful since lower amount of electricity is used.

6. Conclusions

The environmental impacts of heat pump systems can be decreased by appropriate view of the designers, the decreased heat demand of the buildings and the enhanced geological knowledge. Design has significant effects on both the installation and operation costs. Although the installation of complex systems is more expensive, the operational costs of bivalent systems could be cheaper. In most locations the closed loop system is preferred based on the geological availability, where the overcooling and the contamination of drinking water reservoirs can cause problems.

Most heat pump systems generate CO_2 emission via using electricity. Emission depends on the SPF type of heat pump, and the specific emissions of external and auxiliary energy as well. SPF value could be held higher as temperature of the evaporator is as high as possible which can be obtained if the specific heat extraction value is lower than the design value (overdesigned primary loop with higher installation costs).

Environmental impact would be sufficiently low when heat pump can use renewables. Auxiliary energy can be covered by other renewable sources, mainly by solar energy or biomass. However, when a larger amount of auxiliary energy would be required, solar heat is usually limited. Based on the data, the most appropriate system could be a bivalent parallel system in which the auxiliary heating related to wood (lopping) firing or using other renewable. Solid biofuels, such as wood and pellet, can be easily stored, and if the dosage is automatic the convenience of the owner is similar to that in the case of a monovalent system. Firing biomass has lower CO_2 emission than the average CO_2 emission of power plant systems using fossil fuels, in addition this carbon was fixed recently in geological aspect. In rural areas prosperous biomass potential exists, which can be involved in bivalent systems economically. The most important limiting factor of their rapid spreading is that the cost of this system is quite high compared to the stock of the inhabitants, as a result usually natural gas or biomass is chosen as the sole heat supplier.

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7. References

Bayer, P. – Saner, D. – Bolay, S. – Rybach, L. – Blum, Ph. (2012): Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. Renewable and Sustainable Energy Reviews. 16 (2): pp. 1256-1267.

Blum, Ph. – Campillo, G. – Münch, W. – Kölbel, Th. (2010): CO_2 savings of ground source heat pump systems – A regional analysis. Renewable Energy. 35 (1): pp. 122-127.

Buday, T. (2010): Effects of operating heat pump systems on the underground temperature based on a case study in Debrecen. In: Kalmár F. – Csomós Gy. – Csáki I. (Eds.): 16th „Building Services, Mechanical and Building Industry Days" GEOREN International Conference, 14-15 October 2010, Debrecen, Hungary. pp. 107-114.

Buday T. (2012): A felszín alatti hőt hasznosító hőszivattyús rendszerek primeroldali kiépítésének korlátozó tényezői alföldi kisvárosokban, Létavértes példáján (Limiting factors in the primarily loop installation of ground source heat pump systems in small towns of the Great Plain, based on the case study of Létavértes, Hungary). In: Fazekas I. – Szabó V. (Eds): A környezettudatos települések felé. Meridián Alapítvány. Debrecen. pp. 45-51.

Buday, T. – Török, I. (2012): Possibilities and problems in the modelling of operating borehole heat exchanger (BHE) systems based on field studies. In: Proceedings of 18th Building Services, Mechanical and Building Industry days, International Conference, EUG-12-02, 8

Buday T. – Fazekas I. – Szabó Gy. – Paládi M. – Szabó Sz. – Szabó G. – Kerényi A. (2014a): A talajhőt primeroldali forrásként használó hőszivattyús rendszerek környezeti hatásainak csökkentési lehetőségei (Possible reduction ways of environmental impacts of ground coupled heat pump). In: Szabó V. – Fazekas I. (Eds.): Környezettudatos energiatermelés és -felhasználás III. MTA DAB Megújuló Energetikai Munkabizottsága. Debrecen, pp. 57-63.

Buday, T. – Fazekas, I. – Szabó, Gy. – Paládi, M. – Szabó, Sz. – Szabó, G. – Kerényi, A. (2014b): Environmental Effect of Ground Source Heat Pump Systems on the Shallow Groundwater Resources. poster, 41st IAH International Congress „Groundwater: Challenges and Strategies", Marrakesh, 15–19 September 2014

Buday, T. – Szabó, Gy. – Fazekas, I. – Paládi, M. – Szabó, Sz. – Szabó, G. – Kerényi, A. (2014c): Annual pattern of the coefficient of performance considering several heat pump types and its environmental consequences. Interational Review of Applied Sciences and Engineering. 5 (2): pp. 173-179.

Greening, B. – Azapagic, A. (2012): Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. Energy. 39 (1): pp. 205-217.

Heinonen, E.W. – Tapscott, R.E. – Wildin, M.W. – Beall, A.N. (1996): Assessment of anti-freeze solutions for ground-source heat pump systems. New Mexico Engineering Research Institute NMERI 96/15/32580, 156 p.

IEA (2013): CO_2 emissions from fuel combustion, highlights. IEA, Paris, France, 110 p.

Jenkins, D. P. – Tucker, R. – Rawlings, R. (2009): Modelling the carbon-saving performance of domestic ground-source heat pumps. Energy and Buildings 41 (6): pp. 587-595.

Lund J.W. – Freeston D.H. – Boyd T.L. (2010): Direct Utilization of Geothermal Energy 2010 Worldwide review. Proceedings World Geothermal Congress, Bali, Indonesia, 25–29 April 2010. 23 p.

Ochsner, K. (2007): Geothermal Heat Pumps. A Guide for Planning and Installing. Earthscan, London. 146 p.

Omer, A. M. (2008): Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews. 12 (2): pp. 344-371.

Paládi M. – Szabó Sz. – Megyeriné Runyó A. – Kerényi A. (2014): Firewood consumption and CO_2 emission of detached houses in rural environment, NE-Hungary. Carpathian Journal of Earth and Environmental Sciences, 9 (1): pp. 199-208.

Rybach, L. – Eugster, W.J. (2002): Sustainability aspects of geothermal heat pumps. Proceedings 27th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford California, pp. 50-64.

Saner, D. – Juraske, R. – Kübert, M. – Blum, Ph. – Hellweg, S. – Bayer, P. (2010): Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems. Renewable and Sustainable Energy Reviews. 14 (7): pp. 1798-1813.

Stiebel Eltron (2012): Technical guide. Heat pumps. Stiebel Eltron. 347 p.