CALCULATING ENERGY PRODUCTION AND SAVING OF GSHP IN TERMS OF LOAD CHARACTERISTICS

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ABSTRACT

A set of generalized formulae for calculating energy production and saving with GSHP both for heating and cooling applications is introduced. Once we have reasonable estimates of thermal output produced by GSHP, we can easily calculate geothermal contribution at source side and energy saving at load side. The most important step for making reliable statistics on energy utilization with GSHP would be the reasonable estimates of capacity factor defined as equivalent full load hours per year according to the load types such as residential houses, commercial and public buildings, greenhouses, and so on. Because the full load hours of building types often vary by a factor of four or more, sample monitoring for more than a year is essential for reasonable estimates of utilization. However, monitoring is not always possible, especially for small installations, so that we also have to use other references such as building standards for the specified load types at each climate zone.

Keywords: geothermal heat pump, Ground Source Heat Pump (GSHP), energy production, energy saving, load factor, equivalent full load hours, seasonal performance factor

1. INTRODUCTION

Geothermal or ground source heat pump (GSHP) became dominant in direct use of geothermal heat covering more than 55% of worldwide heat uses in 2015 (Lund and Boyd, 2016). Major application of GSHP is still for heating individual residential houses especially in northern Europe. Large installations for office buildings and apartments are recently increasing in European countries and north-east Asia including China, Korea and Japan. GSHP installations at public and commercial buildings are not only for heating but also for cooling, and energy utilization in cooling mode is getting bigger and bigger.

Although contribution of GSHP to global thermal energy uses is getting bigger, official statistics (for example, International Energy Agency; IEA) of worldwide energy uses do not consider this type as independent renewable energy sources despite IEA classifies the heat pump (from air, ground, water, and waste sources) as the one of renewable energy sources (IEA, 2014). International Geothermal Association (IGA) collects data for GSHP installations through World Geothermal Congress (WGC) every five years. However, WGC accounts for heating application of GSHP only in geothermal utilization statistics because cooling with GSHP does not extract from the ground but heat the ground. Because cooling with GSHP is getting more important and no other statistics consider this important energy utilization, IEA Geothermal TCP started to devise a new statistical scheme (Song et al., 2015) and they will soon open a new spreadsheet for collecting application data.

In this paper, I introduce a set of generalized formulae for calculating energy production and saving with GSHP for both heating and cooling applications. Generalization is made by introducing concept of net and gross productions. The newly devised spreadsheet for data collection by IEA Geothermal TCP is based on these formulae. I also show a convenient way of estimating energy utilization amount with help of the equivalent full load hours adopting the concept of load characteristics depending on different load types. Discussion is made on how we can estimate equivalent full load hours when monitoring is not performed.

2. ENERGY FLOWS IN HEATING AND COOLING

By nature, a heat pump needs external energy source to make thermal energy flow from the colder side to the warmer side. The most popular type of the external energy to run heat pumps is electricity, so that we consider electric heat pump here. Figure 1 shows a schematic diagram showing energy flows of GSHP system in heating and cooling modes. We can see there are different types of collecting or exchanging heat from ground such as borehole heat exchanger, horizontal collector and ground water well. Note that energy flows along opposite directions in heating and in cooling modes.

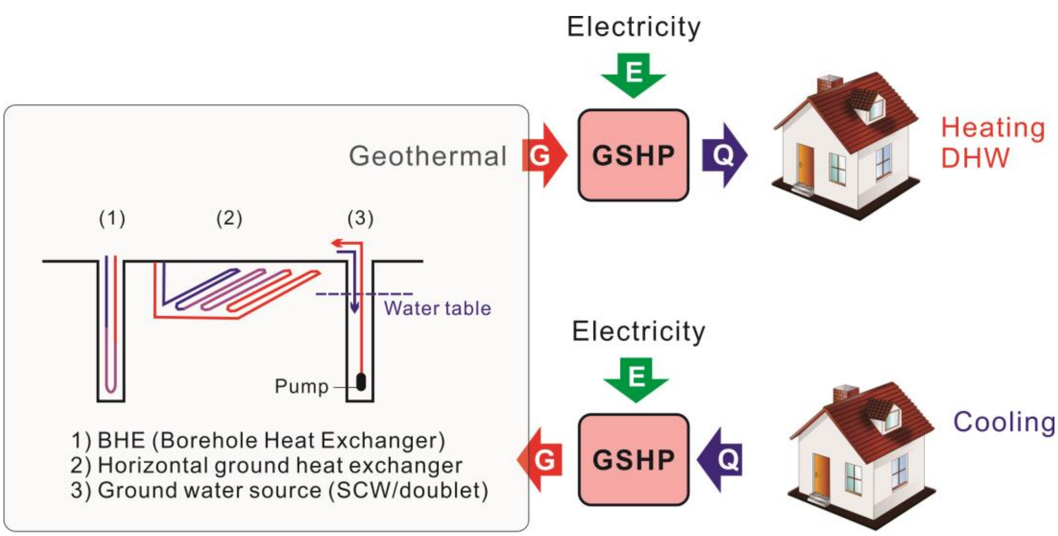

Fig. 1. A schematic diagram showing energy flows of GSHP in heating (upper right) and cooling (lower right) modes.

In heating mode, thermal output or total usable heat energy of GSHP (Q) is the sum of geothermal energy (G) and the electricity (E_{GSHP}) when neglecting energy transformation loss.

$$Q = G + E_{GSHP} \quad (1)$$

$$G = Q - E_{GSHP}$$
$$= Q \times (1 - 1/COP) \quad (2)$$

Here, the coefficient of performance (*COP*), which is the most commonly used dimensionless measure to quantify the performance of a heat pump, is defined as:

$$COP = \text{Thermal Output (kW) / Electricity Input (kW)} = Q / E_{GSHP} \quad (3)$$

In cooling mode of GSHP, on the other hand, energy flow is reversed so that amount of cooled energy plus electricity to run GSHP is to heat the ground as following.

$$G = Q + E_{GSHP} \quad (4)$$

The energy flow in cooling with GSHP, for which supplies heat to the ground instead of extracting from, is the main reason why geothermal community generally does not account for the cooling energy of GSHP in considering geothermal utilization (Lund and Boyd, 2016). This may seem reasonable when considering thermodynamic principle. However, if geothermal community does not consider cooling application of GSHP, then this important quantity will be missed in global renewable energy statistics. Therefore, for the sake of maintaining consistency, we propose to define geothermal (or ground) contribution to cooling mode of GSHP as '*the cooling energy with help of ground*' which is expressed as

$$G_C = Q_C - E_{GSHP} = Q_C \times (1 - 1/COP_c) \quad (5)$$

This new definition for cooling is comparable to equation (2) and can be accepted reasonable because amount of cooling benefit by subtracting electricity portion is '*free of charge*' and from the renewable source. Note that COP_c is for cooling which is usually different from heating *COP*, COP_H, even for the same heat pump unit and also depending on input and output temperatures. In this context, we use subscript '*H*' for heating application and '*C*' for cooling here in after.

3. ENERGY PRODUCTION vs. ENERGY SAVING

Energy production and saving are often used as similar meaning. However, energy production differs from energy saving in whether we define absolute quantity or relative one, that is, energy saving always needs other sources to compare with while production does not. For more in detail, in energy production, we may think of '*net*' and '*gross*' productions depending on whether we include parasitic load or not.

Figure 2 shows a definition of system boundaries for heat pump system adopted in European SEPEMO-Build project (http://sepemo.ehpa.org/). There are four boundaries according to heating/cooling stages involved. We can see boundary 1 for ground or air-source heat pump unit, boundary 2 for including source in-take parts (inlet fan for air-source, or ground circulating pump or groundwater pump for ground-source), boundary 3 for including backup parts, if any, and boundary 4 for including building circulating parts. From the view point of GSHP, we are interested in boundaries 1 and 2 only, because boundaries 3 and 4 are rather related with energy efficiency of building or *heating, ventilation, and air conditioning* (HVAC) system than source part.

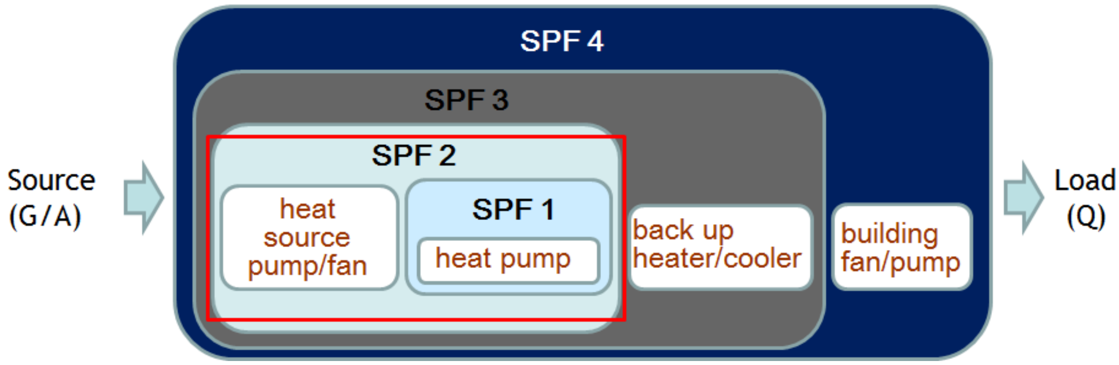

Fig. 2. A definition of system boundaries for heat pump system in European SEPEMO-Build project (modified from Nordman, 2012).

If we compare boundaries in Figure 2 with equations (2) and (5), then *COP*s correspond to boundary 1. When we include parasitic load, that is electricity to run ground circulating pump for closed-loop or groundwater pump for open-loop system, we define $System\ COP = Q / (E_{GSHP} + E_{CP})$, so that *System COP*s is always lower than *COP*s. Note that the Seasonal Performance Factor (*SPF*) in Figure 2 is a general terminology when actual monitoring of performance is made while *COP* is rather used for manufacturer providing ('*nameplate*') value for certain inlet and outlet temperatures.

Summarizing the quantities relevant to geothermal, gross energy products of GSHP for heating and cooling modes are

$$G_H = Q_H - E_{GSHP} = Q_H \times (1 - 1/SPF_{H1}) \quad (6)$$

and

$$G_C = Q_C - E_{GSHP} = Q_C \times (1 - 1/SPF_{C1}), \quad (7)$$

respectively, while net energy product considering parasitic load (the electricity to run circulation pump) are

$$E_{RES,H} = Q_H - E_{GSHP} - E_{CP} = Q_H \times (1 - 1/SPF_{H2}) \quad (8)$$

and

$$E_{RES,C} = Q_C - E_{GSHP} - E_{CP} = Q_C \times (1 - 1/SPF_{C2}). \quad (9)$$

Note that the gross energy product for heating in equation (6) coincides with geothermal utilization used by IGA data collection for WGC as defined in Lund et al. (2011) and Lund and Boyd (2016). On the other hand, the net energy product for heating in equation (8) coincides with the European definition of energy production from renewable sources, EU Directive 2009/28/EC (EU, 2009). Therefore, equations from (6) to (9) can be taken as a generalized definition including cooling application.

Above definitions of gross and net productions can also be considered in the context of energy production and saving from the view point of geothermal energy. The gross productions in equations (6) and (7) are the geothermal energy (heat) we extract from the ground and cooling energy we generate with help of the ground, respectively. On the other hand, the net productions in equations (8) and (9) are free energy utilized for consumer's side, so that these can be considered as energy saving with geothermal energy compared to conventional ones such as fossil fuels. Therefore, we can conclude that the equations (6) and (7) are for geothermal energy production at source side, while equations (8) and (9) are for energy saving by renewable (geothermal) source, or environmental benefit, at load (consumer) side.

4. LOAD CHRACTERISTICS: EQUIVLAENT FULL LOAD HOURS

The energy production and saving expressed in equations from (6) to (9) may be used as a convenient tool for estimating benefits of GSHP in quantitative manners, once we have information on heating and cooling output (Qs) and electricity input to run GSHP (E_{GSHP}) and circulation pump (E_{CP}). Accurate values can only be determined by actual measurement or monitoring. However, in most cases, especially for small installations such as for individual residential houses, monitoring of each system is not made. As a matter of fact, continuous monitoring of all the small installations is almost impossible. Therefore, we have to estimate reasonable amount of energy utilization based on sample monitoring. If sample monitoring data is not available, then next choice would be estimates based on other references such as HVAC data for Qs and COP values from manufacturer.

In the WGC guideline, there are two ways of estimating thermal energy utilization. The first method, which would be an ideal case, is based on actual flow rate measurements (Lund et al., 2011):

$$\text{Thermal energy (TJ/yr)} = \text{flow rate in loop (kg/s)} \times [\text{inlet temp. (°C)} - \text{outlet temp. (°C)}] \times 0.1319, \quad (10)$$

where 0.1319 is equal to 3,600 second/hour × 24 hours/day × 365 days/year × 4.184 (kJ/kg/°C) × 10^{-9}.

Again, when direct monitoring of flow rate and temperature cannot be performed, which is the case for the most of systems, WGC recommends a guideline of estimating thermal energy production as following.

$$\text{Thermal energy (TJ/yr)} = Q_{rated}\ \text{(kJ/hr)} \times [(COP\text{-}1)/COP] \times \text{equivalent full load hours/yr} \times 10^{-9}, \quad (11)$$

where Q_{rated} is the *name plate* value by manufacturer and COP can be substituted by SPF. When we compare equation (11) with equation (6), we need to determine '*equivalent full load hours per year*', or *EFLH*, which is total running time of a unit with full load in hours. Note that *EFLH* should be determined by actual monitoring for at least a year. *EFLH* varies according not only to climate condition of the region but also building types such as residential houses, commercial and/or public buildings, greenhouses, and so on, which can be categorized into different load characteristics.

$$\begin{aligned} Q_H &= Q_{rated,H} \times EFLH_H \\ &= Q_{rated,H} \times \Sigma(L_{f,H} \times hr_H) \end{aligned} \tag{12}$$

$$\begin{aligned} Q_C &= Q_{rated,C} \times EFLH_C \\ &= Q_{rated,C} \times \Sigma(L_{f,C} \times hr_C) \end{aligned} \tag{13}$$

Here Σ stands for summation over 12 months and $L_{f,H}$ and $L_{f,C}$ are the monthly load factors for heating and cooling, respectively. For example, if a unit of 12 kW is running 8 hours per day for heating with full load for 20 days in January, then $Q_{rated,H}$ = 12 kW, $L_{f,H;1}$ = 1.0 and $hr_{H;1} = 8 \times 20 = 160$ for the month. If there are two units of 12 kW each and only one unit is running for the month, then the load factor of the month, $L_{f,H}$ becomes 0.5.

Monthly load factors and running hours vary dramatically depending on load characteristics, so that resultant *EFLH*s can differ by more than a factor of the four. For example, $EFLH_H$ for residential houses in northern Europe reach 2,470 hours according to EU Decision 2013/11/EU (EU, 2013). On the other hand, $EFLH_H$ for an office building in moderate climate (Korea) is as low as 492 hours, while cooling hours, $EFLH_C$ for the same building reach 450 hours, which is comparable to the heating hours (Paek et al., 2015). When we consider tropical region where cooling load is dominant, $EFLH_C$ may reach 1,000 hours or more, while $EFLH_H$ becomes quite small, only for hot water supply, if any.

Above examples tell us that reasonable estimation of *EFLH*s is the most important factor in correct calculation of energy production and saving. *EFLH*s significantly vary according to characteristics of load and continuous monitoring of the system may be the only way to find accurate values. However, because the monitoring of the all the installations, especially small units for residential houses, is almost impossible, we have to use sample monitoring values, if any, or estimates from other references such as building HVAC standards for the specified load types at each climate zone.

5. SUMMARY AND DISCUSSION

I introduced a generalized definition expressed in the forms of energy production and saving for heating and cooling operation with GSHP. Once we have reasonable estimates of thermal output produced by GSHP, we can easily calculate geothermal contribution at source side and energy saving at load side. This definition will be used in the Annual Trend Reports published by IEA Geothermal TCP (http://www.iea-gia.org). Working Group 8 of IEA Geothermal – Direct Use of Geothermal Energy has endeavored to devise new schemes for GSHP statistics for the last five years and offers to share the new spreadsheet for data collection with other geothermal communities including IGA. The newly devised spreadsheet will be presented at the next WGC 2020 in Iceland.

The most important step for making reliable statistics on energy utilization with GSHP would be the reasonable estimates of EFLHs according to the load types such as residential houses, commercial and public buildings, greenhouses, and so on. Because the load characteristics of building types are significantly different from each other, sample monitoring for more than a year is essential for reasonable estimates. However, monitoring is not always possible, especially for small installations, so that we also have to use other references such as building HVAC standards for the specified load types, if any.

Energy saving factors from utilization of renewable energy sources can be in the form of fossil fuel saving or carbon dioxide emission reduction. WGC guideline (Lund et al., 2011; Lund and Boyd, 2016) states fossil fuel saving and CO_2 emission reduction for heating, while CO_2 emission reduction only for cooling. However, we would say that because cooling with GSHP can be defined as energy production with help of ground we can use fossil fuel saving factor (Mongillo, 2005) for cooling application as well. Furthermore for cooling, we can consider electricity saving and CO_2 emission reduction emission comparing to air-source heat pump or air-conditioner, for which we can find some examples in Japan and Korea (Yasukawa, 2018). Because cooling application of GSHP will continuously increase especially for large office buildings and in developing countries of (sub-) tropical region, we expect that contribution of GSHP to fossil fuel saving and CO_2 emission reduction will be seen remarkable by adopting the new statistical scheme devised by IEA Geothermal TCP.

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