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Energy efficiency model for small/medium geothermal heat pump systems

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Abstract. *Heating application efficiency is a crucial point for saving energy and reducing greenhouse gas emissions. Today, EU legal framework conditions clearly define how heating systems should perform, how buildings should be designed in an energy efficient manner and how renewable energy sources should be used. Using heat pumps (HP) as an alternative "Renewable Energy System" could be one solution for increasing efficiency, using less energy, reducing the energy dependency and reducing greenhouse gas emissions. This scientific article will take a closer look at the different efficiency dependencies of such geothermal HP (GHP) systems for domestic buildings (small/medium HP). Manufacturers of HP appliances must document the efficiency, so called COP (Coefficient of Performance) in the EU under certain standards. In technical datasheets of HP appliances, these COP parameters give a clear indication of the performance quality of a HP device. HP efficiency (COP) and the efficiency of a working HP system can vary significantly. For this reason, an annual efficiency statistic named "Seasonal Performance Factor" (SPF) has been defined to get an overall efficiency for comparing HP Systems. With this indicator, conclusions can be made from an installation, economy, environmental, performance and a risk point of view. A technical and economic HP model shows the dependence of energy efficiency problems in HP systems. To reduce the complexity of the HP model, only the important factors for efficiency dependencies are used. Dynamic and static situations with HP´s and their efficiency are considered. With the latest data from field tests of HP Systems and the practical experience over the last 10 years, this information will be compared with one of the latest simulation programs with the help of two practical geothermal HP system calculations. With the result of the gathered empirical data, it allows for a better estimate of the HP system efficiency, their economic costs and benefits and their environmental impact.*

Keywords: geothermal heat pumps (GHP), renewable energy sources (RES), efficiency, technical HP model, economic HP model, seasonal performance factors (SPF).

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Introduction

Finding reliable energy sources and increasing energy efficiency are two of the most important challenges facing humankind. Dependency on energy, environmental harm and climate change are central problems human beings must solve (IPCC, 2014; Böhm, 2010; IEA, 2013; Edenhofer, 2011; Rogall, 2000; Crowley, 2000). Rising energy costs and increasing concern for environmental stewardship over the past 20 years have inspired interest in an old technology first invented in the 1860's (Zogg, 2008). HP is currently used in heating technology using a RES to

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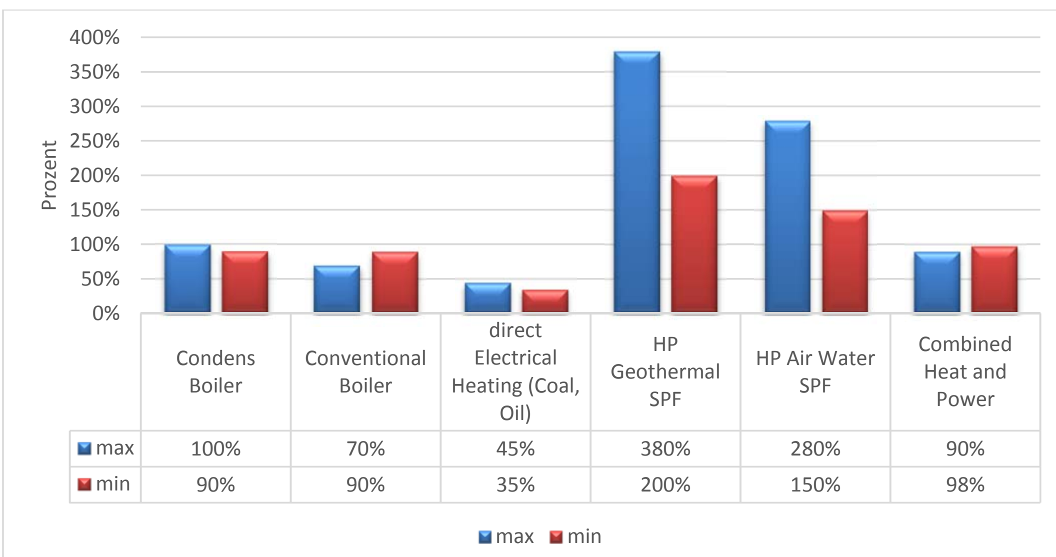
reduce greenhouse gases, energy costs and dependency on fossil energy sources. After the first energy crisis in the 1970's (Yergin, 2008; Inkenberry, 1986; Merril, 2007), HP technologies were developed further. Due to lower energy prices and technical difficulties after the crisis, these technologies made up a small minority of the market until the beginning of 1998. Because of higher energy costs and dependencies on fossil fuels from 1998 until today, HP sales have steadily increased (Nowak, 2013; Bayer, 2012). New ideas and innovation in HP technology increase the efficiency of the different HP devices (Park, 2014, 2013; Jeong, 2014; Wang, 2015; Staiger, 2004, 2005, 2006, 2014; Sanchez, 2014).

More than 40% of the thermal energy demand in the EU (EU 2014, 2010a, 2010b; BMU, 2012) is used for heating. There is a huge potential in saving energy through new energy efficient heating technology. This is one reason that EU directives (EU 2012a, 2012c, 2009, 2013a) clearly define for all member states how buildings should be designed and built, how heating systems should be implemented with RES and how new heating appliances should have increased energy efficiency. In the last 10 years, use of HP technologies has increased over 60% in the EU (Nowak 2013; Rees 2014).

Small heat pump systems are up to 10 kW and medium heat pump systems are up to 25 kW. With these sizes of HP devices, new low energy buildings (comercial and private) with up to 500 m² surfaces and domestic water could be heated. Efficiency of small/medium size GHP corresponds to 200-380% depending of the type of HP and the entire HP system boundaries. This means that for each kW of electrical consumption, 3kW to 4,8 kW of thermal energy are generated. About 75% of the energy that is used in a GHP is renewable, whereas 25% of the energy is generated by other sources (in 99% of the cases this is electricity). If the electricity for the HP is generated from renewables (PV, wind, hydro, biomass etc.) then the HP system is 100% renewable and CO_2-neutral. In comparison to today's heating technologies, Figure 1 shows the average Max/Min efficiencies.

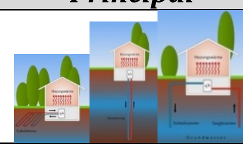
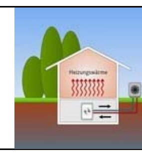


	Condens Boiler	Conventional Boiler	direct Electrical Heating (Coal, Oil)	HP Geothermal SPF	HP Air Water SPF	Combined Heat and Power
max	100%	70%	45%	380%	280%	90%
min	90%	90%	35%	200%	150%	98%

Figure 1: Heating system efficiency comparison
Source: adapted from Langeheiecke (2012), Pehnt (2010), Nowak (2013), Bohne (2014), and Schulz (2013).

There is a variety of HP´s on the market (see Table 1). There are three main types. The first type is a HP which takes energy Q_{renew} out of the soil (GHP) (Königsdorff, 2011; Schröder, 2012). The second type is a combination with other RES such as thermal solar, waste water and others (hybrid systems) (Miria, 2013; Mojic, 2014). Third type is a HP where the Q_{renew} will be taken out of the air (air/water HP) (Königsdorff, 2011). Today's HP technology can be used for heating and cooling (passive and active cooling). Hybrid means "mixed" and combines two energy systems with the aim of achieving ecological and economic sense to satisfy the total heating and cooling demand of a building. The combination possibilities for hybrid heat pumps are varied. The main advantages and disadvantages of HP Types are presented in Table 2.

Table 1. *Different HP types on today's market*

Main type	***HP types details***	***Principal***
- GHP	- *Geothermal HP ground collectors* - *Geothermal HP bore holes* - *Geothermal HP direct evaporation* - *Geothermal HP water/water*	
- Hybrid HP	- *Combination off different RES*	
- AIR HP	- *Air water HP* - *Split HP* - *Air/air HP*	

Source: Authors' own contribution.

Table 2. *Advantages/disadvantages of different HP Types*

Type	Advantage	Disadvantage
GHP ground collectors	✓ Lower investment cost than bore holes ✓ SPF higher than air systems ✓ Constant geothermal temperature ✓ Passive cooling	✓ More space needed outside ✓ SPF lower then bore hole Systems ✓ More complex installation
GHP bore holes	✓ Less space needed outside ✓ SPF higher then ground collector Systems ✓ Constant temperature geothermal ✓ Passive cooling	✓ Higher investment cost then ground collectors holes ✓ Possible state approval ✓ More complex for installation
GHP direct evaporation	✓ SPF higher than ground collector Systems ✓ Constant geothermal temperature	✓ More space needed outside ✓ Complex installation ✓ Refrigerant is used in the ground ✓ Specialist necessary
GHP water/water	✓ Less space needed outside ✓ SPF higher than bore hole systems ✓ Higher geothermal temperature ✓ Quite efficient	✓ Possible state approval ✓ More complex for installation ✓ Dependent on water quality ✓ Risk for constant water flow
HP hybrid	✓ Less space needed outside ✓ SPF higher ✓ Higher geothermal temperature ✓ Less energy usage for HP	✓ Complex for installation ✓ More difficult to control ✓ High investment cost

	✓ Higher efficiency	
Air/water HP	✓ Less complex installation ✓ Less investment cost ✓ Less space needed	✓ Lower SPF ✓ Possible difficulties with very low air temperature
Split system (evaporator outside)	✓ More efficient ✓ Less difficulties in very cold conditions	✓ Investment cost higher than air/Water ✓ Specialist necessary
Air/air	✓ Cooling ✓ No water system	✓ Only special power sizes ✓ More space necessary ✓ Lower SPF ✓ Complex installation

Source: Authors' own contribution.

HP manufacturers, HP sales companies and HP installers use efficiency as the most important criteria in the sales and marketing process. The EU energy label will be the most important selling point for heat pumps in the future (BWP, 2015; EHPA, 2013; Rasmussen, 2011; EU, 2013b).

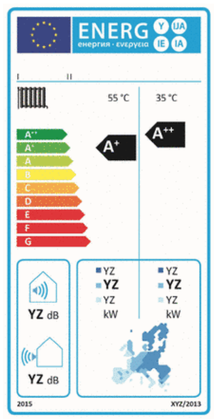


Figure 2: New energy label for HP devices

Source: EU (2013b)

Theoretical energy efficiency for technical and economic HP models

The energy efficiency for a technical HP model can be explained using the Carnot cycle process (Cube, 1997; Baehr and Kabelac, 2006; Miara, 2013; Reisner, 2013; Tiator, 2014; Tonert, 2013). In a Carnot Cycle Process, the energy from a RES (Q_{renew}) is transferred through a heat exchanger (evaporator-eva) to a special medium (*refrigerant like R407, R134*). This refrigerant has a special property which evaporates with very low temperature (-5°C - +10°C) depending on the pressure. That means low temperature from a renewable source from air, water, geothermal in a temperature range from -20°C up to 20°C can be transferred to the refrigerant. The low pressure on the output of the evaporator is increased through a compressor (Comp.- *today mostly scroll compressors*). For these there is a need of electrical energy (Q_{elec}). This pressure increase will also increase the temperature level of the refrigerants. The high temperature level will be released over a heat exchanger to the condenser (Cond). The refrigerant will condense and send the higher temperature to a sink (heating system) (Q_{out}). On the output of the condenser, the refrigerant still has high pressure. Through an expansion valve the pressure will be released to low pressure and the Carnot Cycle start under the same conditions from the beginning. The operating principals of the heat pump cycle are: *Evaporation, Compression, Condensation and Expansion.*

The Max efficiency of a Carnot Cycle Process can be derived from the Carnot efficiency:

$$\varepsilon_{HP\ limit} = \frac{T_2}{T_2 - T_1} \quad (T\ absolute\ Temperature) \quad [1] \qquad \rightarrow \text{Max limit}$$

T_2 = Output Temperature, T_1= Input Temperature

The physics behind this cycle will be found in the thermodynamic fundamentals. The technical explanation of a HP is shown in Figure 3.

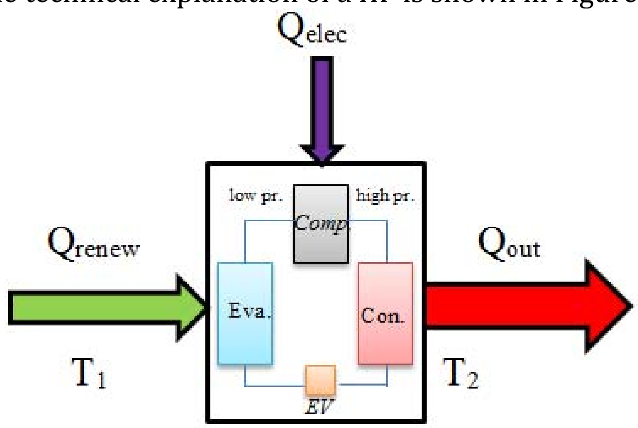


Figure 3: *Technical HP*

Source: Staiger's own contribution.

The performance (*Coefficient of Performance (COP))* of a real HP device is calculated as: delivered output energy divided by the input energy to run the HP device.

$$\varepsilon_{HP} = \frac{\dot{Q}_{out}}{Q_{Elec}} \quad [2]$$

The energy efficiency for the economic HP model is based on the flow of the different energy direction of a HP. The amount of energy is dependent upon input and output factors which determine the performance of a HP device over a period of time.

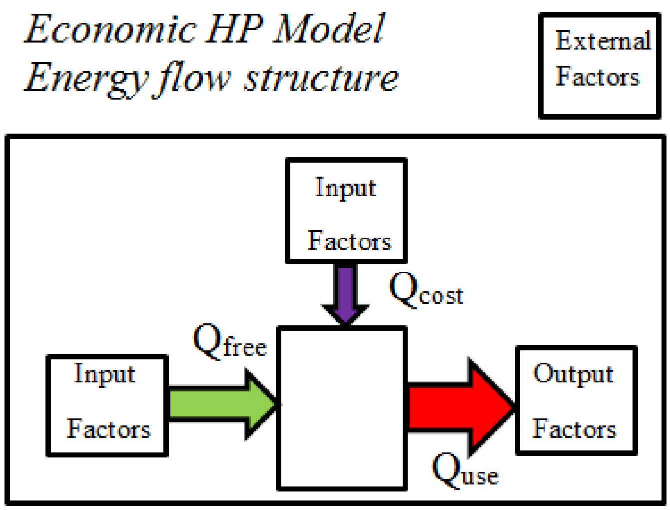


Figure 4: Economic HP energy flow a dynamic energy view

Source: Authors' own contribution.

The efficiency based on energy power ratio which determine internal and external dependencies and giving the basis for calculating cost and environmental aspects in a static view of a HP device.

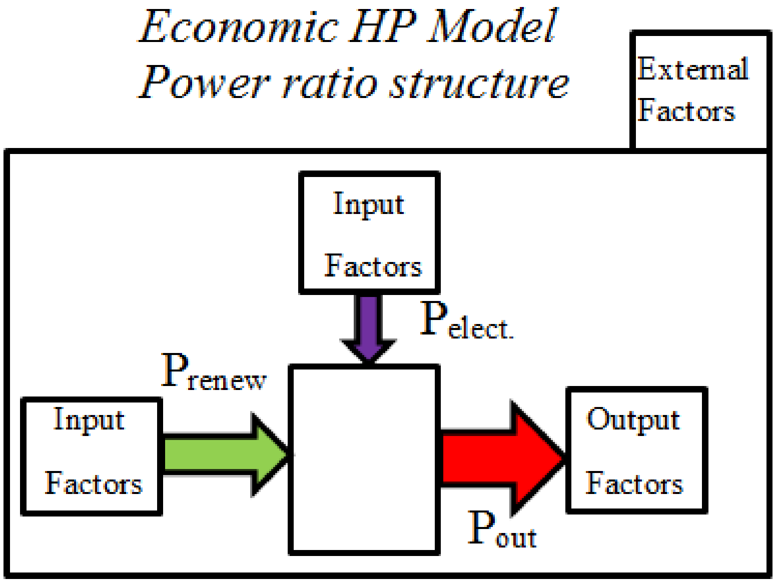


Figure 5: Economic HP model power ratio static view
Source: Authors' own contribution.

The economic HP model has to take into account the variation of the parameters which influence the energy efficiency. The economic model for this article will use both static and dynamic flows on input, output and external factors as well as the possible boundaries (B1-B4) (Norman, 2012; EU, 2009, 2012b, 2013) of a complete working HP System.

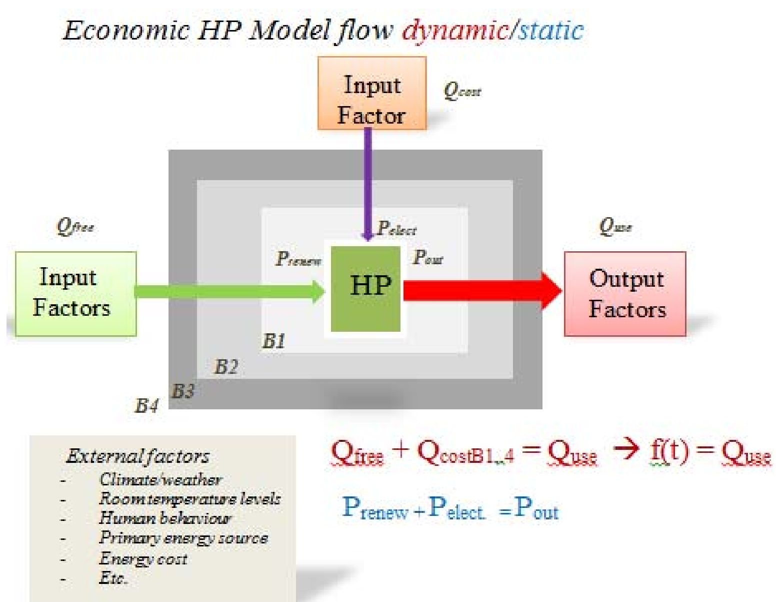


Figure 6: Economic HP Model static/dynamic
Source: Authors' own contribution.

The main factors that influence the efficiency of HP System are input, output and external factors. Input factors are: the renewable energy source (horizontal, vertical, air, direct evaporation, split, solar), the type of HP, the fossil energy source (driving source) and the auxiliary energy usage (pumps, fans, electrical heat exchanger, emergence heater etc.). Output factors are: the heating systems (low temperature system, under floor, wall heating, and radiators), the domestic water (puffer, indirect heated, domestic water tank) and the process of heat and cooling. External factors are: climate conditions, operation hours, room temperature levels, heating demand versus heating power, human behaviour, thermal loses through wrong insulation habits on pipes and puffer tanks, oversizing/undersizing HP, primary energy source (fossil, RES), design layout (Tanţău et al., 2014), greenhouse gas emissions and calculation procedures. These factors will be used in the different boundaries B1-B4 for a HP System (see Figure 7).

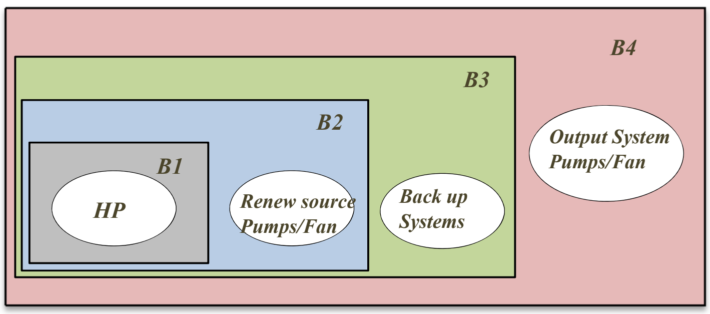


Figure 7: Economic HP Model static/dynamic boundaries

Source: Authors' own contribution.

The auxiliary appliances which are calculated in the Q_{cost} are defined in different boundaries in the calculation procedure of the SPF for HP Systems (B1-B4).

In order to compare efficiencies for HP Systems, there are different views and scientific definitions:

a) An efficiency figure which is defined from the department of energy, from the EU commission. Example: minimum efficiency of a HP System > 3.5 (Kohler, 2008), or > 2.0 (UK, 2014), > 2.5 (EU, 2013);
b) Break-even point for efficiency, environmental, energy cost or investment figures depending on various factors,
c) Comparison between different heating systems.

From a static view, the performance (efficiency) of a geothermal HP described from the Energy Output P_{out} and the amount of electricity Energy $P_{elec.}$ to operate the HP (see Figure 6).

Coefficient of Performance

$$\varepsilon_{HP} = \frac{\dot{P_{out}}}{P_{Elec}} \quad [3]$$

$\dot{P}_{OUT}$ is the sum of P_{Elec} and $\dot{P}_{Renew}$

In the data sheets for HPs, there are multiple ε_{HP} defined under different working conditions. Table 3 shows the working conditions of a GHP (SI 14TU) and the depentencies on COPs under different input and output temperatures. With this information, HPs are comparable for the end user and as a marketing instrument for HP manufactuerers. Due to the incentitives given by goverments (BAFA, 2015), COP figures are documented for each HP Type and model. For small and medium HP devices the COP figure are similar.

Table 3. Working Conditions *Input/output depentancies COP on a GHP*

Input	*Output*	*COP HP*	*Change in % +-*
0°C	35°C	4.5	0%
0°C	45°C	3,8	-15 %
0°C	55°C	2,8	-38 %
10°C	35°C	6.2	+ 38%
-5°C	35C°	3,6	-20%
-5°C	45C°	3,1	-32%
-5°C	55C°	2,2	-52%

Source: DIMPLEX (2015).

As an example, if the flow temperature would be increased from 35°C to 40°C, the efficiency of the HP would drop around 14%. This means 14% higher energy costs and higher CO_2 emissions. The WPZ Test Institute has tested more than 100 different HP models since 2002. In the technical data sheets of the different HP manufactures, the efficiency factors are described (WPZ 2014a, 2014b).

Through technology innovation, HP efficiency improved significantly in the last 12 years (see Fig. 8). In the last three years, there have been no significant improvements for air/water HP efficiency.

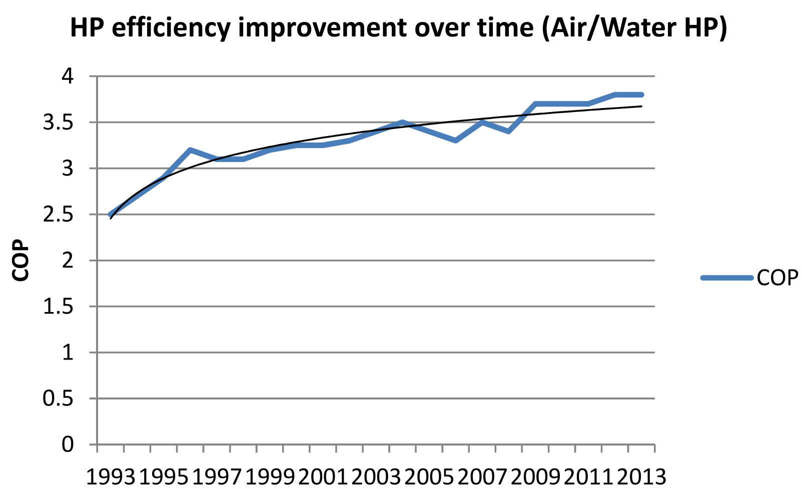


Figure 8: *HP efficiency improvement over Time WPZ*

Source: WPZ (2014a).

From a dynamic view of a HP System, the performance must be analysed over a period of operation. The overall efficiency of a working HP system is called the Seasonal Performance Factor (SPF). The amount of input energy for driving the HP and auxiliary appliances for the complete heating system (Compressor and other necessary energy required under different boundaries) is represented by Q_{cost} and the delivered Output Energy by Q_{use} . For this reason, the seasonal performance efficiency must be taken for the real efficiency calculations of a HP system.

$$SPF = \frac{\dot{Q}_{use}}{Q_{cost}} \quad [4]$$

T

$$SPF = \frac{\sum Q_{use}}{\sum Q_{cost}} \; or \; SPF = \frac{\int_0^T \dot{Q}_{use} dt}{\int_0^T Q_{cost} dt} \quad [5]$$

A *practical approach* for an estimation of the SPF if the operation hour of the HP is known (running time for Compressors and auxiliary appliances): HP size P_{out} or HP Power divided by the *average electrical power per period* of the HP**.** The average electrical power $P_{elect.average}$ over a period of time could be calculated:

$$P_{elect.average} = \frac{\sum Q_{cost\,(periode)}}{operation\ hour\ HP(periode)} \quad [6]$$

Another calculation of the SPF for HP Systems is described in the VDI 4650 Part. These foundations are used in the different simulation software packet. The SPF (β_{HP}) is dependent upon β_h (heating) and β_{dw} (domestic water) with different correction factors (see [12-14]).

Energy cost calculation

To calculate the amount of energy a HP uses over a periode of time:

$$Q_{cost} = P_{elect} \cdot op.hour \quad [7]$$

Energy cost is the amount of energy used for driving a HP System multplied by the energy price per unit.

$$Energy_{cost} = Q_{cost} \cdot Energy_{price} \quad [8]$$

Energy cost comparison and investment calculation

To perform an investment comparison, there is a comparison between the amount of energy for the HP and the amount of energy for the alternative energy source. With the SPF, the amount of energy of the alternative system can be calculated.

Alternative Energy cost:

$$Q_{outalter.} = \frac{SPF * \sum Q_{cost}}{\varepsilon_{alter.}} \quad [9]$$

$$Energycost_{alter} = Q_{outalter.}[kWh] * \; Energy_{price}[\frac{€}{kWh}] \quad [10]$$

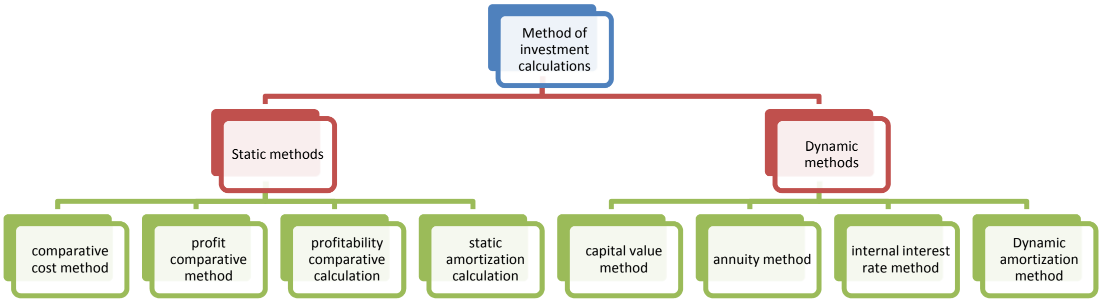
Savings and investment calculation

To compare the energy cost for HP and alternative energy systems, the savings per period is calculated:

$$Savings_{alter} = Energycost_{alter.} - \; Energy_{costHP} \quad [11]$$

With the information of the savings potential, an investment calculation can be done over a period of time, with the help of static and dynamical calculation methods (see Figure 9).

Another method could be a live time cost analysis for HPs and the complete system in comparison with alternative heating systems (Ness, 2007; Coennenberg, 2008, p. 583; Ala-Risku and Kopri, 2008; Rebitzer, 2003).



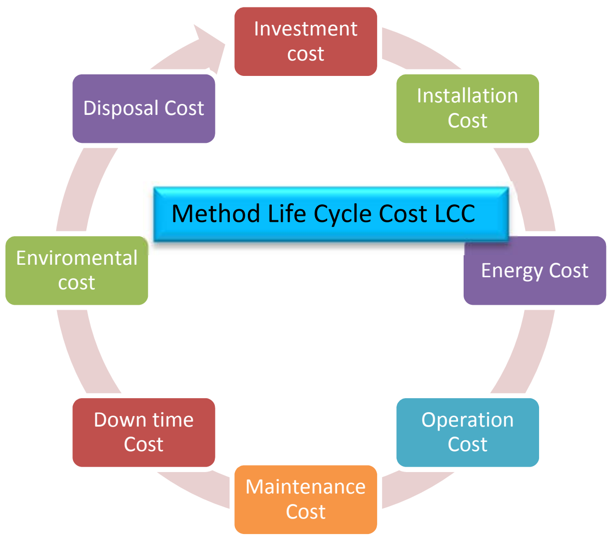


Figure 10: Life cycle cost method

Source: Staiger (2014b).

Research methodology

The research methodology is based on the technical and economic models of HP that have been explained in this article. The models are used to reduce the complexity and to simulate the main key factors of the real, practical HP system. Field test reports over the last 10 years and practical experience with HP systems will be analysed and compared with a simulation software program for HP systems. For this research, efficiency will be defined as the *physical thermal energy output* divided by the *energy amount to run a HP System*. The hypothesis that small/medium GHP Systems up to 25 kW thermal energy output are very efficient heating systems will be critically analyzed. The article will inquire into the real (practical working) GHP efficiency and dependency issues. Additionally, it will strive to increase understanding of the technology and how to overcome possible difficulties. For this research we also use the WPZ database in Buchs, Switzerland, to get a static overview about COP values.

For the investigation and hypothesis approach of energy efficiency on GHP and Air/Water HP, there are 9 scientific field test reports from 2006-2013 in Switzerland, Germany and the UK examined and figures from our own HP Systems in Germany installed the last 10-15 years. The nine scientific field test reports are in the public domain: UK_Trust (2013), Lahr (2013), Bafa (2014), EU (2014), Staiger (2015), ISE (2013,2014), RHPP (2014), FAWA (2008), EON (2005).

Table 4. *ISE Min/MAX SPF Test 1*

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	3,0	-24 %	2,3	-24%
Average	3,9	0 %	3,0	0 %
Max	5,1	30 %	3,5	16%

Source: Authors' own research results.

Table 5. *ISE Min/MAX SPF Test 2*

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	3,5	-20 %	2,5	-22 %
Average	4,3	0 %	3,2	0 %
Max	5,4	+25 %	4,3	34 %

Source: Authors' own research results.

Table 6. UK Trust Phase 1

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	1,55	-33 %	1,2	-35 %
Average	2,31	0 %	1,83	0 %
Max	3,47	50 %	2,2	20 %

Source: UK_Trust (2013).

Table 7. UK Trust Phase 2

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	1,6	-45 %	2,0	-22 %
Average	2,82	0 %	2,45	0 %
Max	3,8	34 %	3,6	46 %

Source: UK_Trust (2013).

Table 8. RHPP grant scheme measurement

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	1,55	-48 %	1,2	-55 %
Average	3,01	0 %	2,71	0 %
Max	4,5	50 %	4	47 %

Source: RHPP (2014).

Table 9. FAWA CH field test

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	2,3	-35 %	1,7	-37 %
Average	3,5	0 %	2,7	0 %
Max	5,5	42 %	4,3	60 %

Source: FAWA (2008).

Table 10. EON field test

	SPF_{B4} GHP	% average
Min	2,8	-20 %
Average	3,5	0 %
Max	4,2	20 %

Source: EON (2005).

Table 11. Agenda Lahr Phase 1

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	2,0	-40 %	1,9	-27 %
Average	3,3	0 %	2,6	0 %
Max	4,4	33 %	3,2	23 %

Source: Lahr (2013).

Table 12. Agenda Lahr Phase 2

	SPF_{B4} GHP	% average	SPF_{B4} Air HP	% average
Min	2,8	-22 %	2	-29 %
Average	3,8	0	2,8	0 %
Max	5,2	20 %	3,4	22 %

Source: Lahr (2013).

Table 13. *Staiger*

	SPF_{B4} GHP	% average
Min	3,0	-17 %
Average	3,6	0
Max	4,5	25 %

Source: Staiger (2014).

From the various field test studies, we have carried out an analysis on the maximum and minimum SPF. The results demonstrated that the efficiency difference between the maximum and minimum SPF lies between 40 % and 90% from the average SPF figure. This result has a clear impact on running cost, payback time calculations, investment calculation and greenhouse gas emissions for a HP System. The main reason for this huge variation of performance is not the technical COP values of the HP itself. The values are comparable to the different HP manufacturers and are clearly defined in the Standards and Labels [HP labels, EN 14511-2]. It must be noted that each field test has a different amount of tested systems as a base. The data is all primary data.

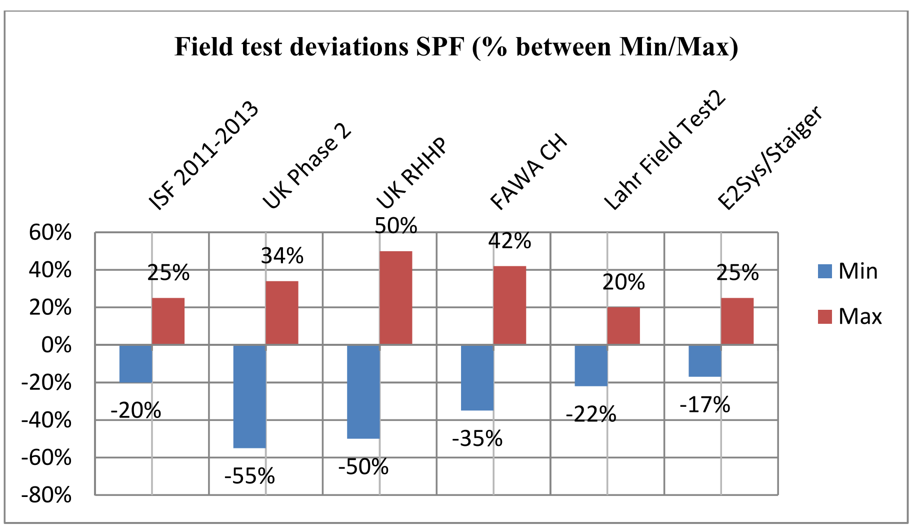


Figure 11: Field Test Deviations GHP Systems

Source: ISE (2013), UK_Trust (2013), Lahr (2013), Staiger (2015), ISE (2014), Merik (2013), Rees (2014), RHPP (2014), Rees (2014), FAWA (2008), EON(2005), Lahr (2011), Lahr (2013).

For the German, Austrian and Swiss markets there are five simulation programs available (DK, Integral, WP OPT/4.7, Polysun HP Software 7.1, Wärmepumpe ETU 2.05, Geot SOL 2.0). Other special simulations packets with building simulations are available. For this article the ETU Package is used. For an exact efficiency calculation of a HP system, there are a variety of parameters which also increase accuracy on the simulation output and data entry effort. The most influential data that is taken into account in this research for the calculation of the overall HP system are:

- type of heat source
  - bore holes, horizontal absorber, water, brain, air or combinations
- absorber surface and length, number and depth of the boreholes, geological conditions (thermal conductivity, heat capacity, density), moisture content of the soil
- type of heat sink (heating distribution system)
  - low temperature (under floor, wall heating)
  - radiator system
- domestic hot water treatment
  - type of puffer and hot water tanks (direct, indirect)
  - average hot water demand per day
- basic data of the HP device
  - COP, electrical demand, thermal power and cooling power dependent from heat source and hot water output temperature
  - Temperature difference between evaporator and condenser
- Building data
  - Heat load and heat demand
  - Solar and internal gains
  - Desired room temperature
- Climate factors
- Energy supplier
  - Tariff
  - High and low tariff times
  - Electricity cost.

The VDI 4650 Part 1 provides the annual coefficient of heat pump systems, as a necessary initial piece of data for the calculation of efficiency, expected costs, heating of primary energy consumption and CO2 emissions. When comparing annual coefficients, it is vital to pay close attention to the same system boundaries. If not, the discrepancies of calculated SPF could have extreme variations.

The calculation and simulation procedure is the measured performance according to standards (DIN EN 14511) measured on test performance figures of the HP by correcting the factors on the influence taken into account by:

- different conditions during measuring and operating the heating system
- design heat source temperatures
- proportion of water heating and portion of the electrical auxiliary heating power supply
- standard external temperature
- heating limit temperature on hot water

Simulation calculation of SPF for space heating is:

$$\beta_h = \frac{\varepsilon_n \cdot F_\vartheta \cdot F_{\Delta\vartheta}}{F_P} \quad [12]$$

ε_n *test bench measurement under* $B0/W35$

$F_\vartheta, F_{\Delta\vartheta}, F_P \rightarrow$ *correction factors under defined Temperature Situation see table VDI*

Simulation calculation of SPF for domestic water:

$$\beta_{dw} = \frac{\varepsilon_n \cdot F_\vartheta \cdot F_{\Delta\vartheta}}{F_P} \quad [13]$$

ε_n *test bench measurement under* $B0/W35$

Simulation calculation of total SPF for the whole system:

$$\beta_{HP} = \frac{1}{0{,}82 \cdot \frac{\alpha}{\beta_h} + 0{,}18 \cdot \frac{\alpha}{\beta_{dw}} + 1 - \alpha} \qquad \alpha = 1: \ monovalent\ operation \quad [14]$$

The framework used in this research for the simulation of SPF for HP Systems, with the software package from ETU Software [ETU 2015 are:

- Heating demand determination: the heating energy demand based on building information (building size, fabrics, building use and climatic conditions)
- Calculation of the technical configuration of the local HP System installation
- Integration of several different possible heat pumps (with various input sources)
- Primary and secondary boiler
- Arbitrary and editable user profiles for the nominal value of the heating and hot water
- Calculation and consideration of the electricity by using photovoltaic power generation to meet demand of the HP System
- Simulation according to climate and building data, user profiles, etc.
- Interpretation of air / water HP, water / water HP and brine / water HP according to the climatic conditions
- Determining the annual coefficient according to VDI 4650 and simulation of the SPF
- usage profile of the customer.

Research analysis and results

The results of this research are based on simulation results obtained by using the software package for simulation ETU/Hottgenroth (a software manufacturer in Cologne) which are compared with the practical evaluation and analyses of the GHP systems. Table 15 shows the different results of practical and simulation SPF for small/medium GHP systems. Two extreme HP systems (Family Ernst and Family Kaplan) are used for the analysis. These systems were installed 2006 and 2008 near Lake Constance close to the Austrian-Swiss border. The HP sizes are medium sized devices with 14kW and 17kW thermal output and a COP under standard conditions (B0/W35) from around 4.5. The calculation procedure is defined through VDI 4650 Part 1.

Table 14. Comparison SPF practical ver. theoretical simulation

Project	SPF_{pract}	Simulation. SPF_{theo}	Deviation %
Klotter	3.5	4.1	-18 %
Kaplan	***4.5***	***4.2***	***+7 %***
Ernst	***3.0***	***4.2***	***-35 %***
Beckmann	3.4	4.1	-21 %

Kiene	3.8	4.3	-13 %
Mathies	4.0	4.1	-2 %
Matteis	3.6	4.2	-17 %

Source: Authors' own research results.

The SPF is a dynamic view with all possible external factors. The simulation program shows the same effect on the SPF like in the field test results. The variations of theoretical and practical factors are similar like those on the installed HP systems. Too many variables make it difficult to accurately compare existing HP Systems. Table 16 shows the simulation result. This result is compared with the practical measured SPF. Out of the SPF, the economics parameter of energy cost and savings are calculated.

Table 15. Simulation results

Description	Simulation 1 "Ernst"	Simulation 2 "Kaplan"
Building Type k**Wh/m²a**	*< 50*	*< 50*
Building size m²	*300m²*	*140m²*
Amount of People	*5*	*3*
$SPF_{theo.}$ GHP System *Simulation*	*4.2*	*4.2*
$SPF_{pract.}$ GHP System *Actual System*	*3.0*	*4.5*
$Q_{costpract}$ kWh/a	*12.500kWh/a*	*2.400*
$Q_{costtheo}$ kWh/a	*8.900kWh/a*	*2.600*
HP Energy $Cost_{pract}$ (0,20 €/kWh)	*2.500€*	*480€*
HP Energy $Cost_{theo}$ (0,20 €/kWh)	*1.780€*	*520€*
$Q_{oilpract}$ kWh/a efficiency oil 0.85	*44.100kWh/a*	*12.700 kWh/a*
$Q_{oiltheo}$ kWh/a efficiency oil 0.85	*44.000kWh/a*	*12.800 kWh/a*
Oil Energy $Cost_{pract}$ (0,8 €/l oil)	*3.528€*	*1.016€*
Oil Energy $Cost_{theo}$ (0,8 €/l oil)	*3.520€*	*1.024€*
Energy saving/a Oil ver HP pract.	*1.028€*	*536€*
Energy saving/a Oil ver HP theo.	*1.740€*	*504€*

Source: Authors' own research results.

In the first simulation, *"Ernst"* shows a high energy demand for operating the GHP. There are four reasons for the bad performance (SPF) of the GHP System.

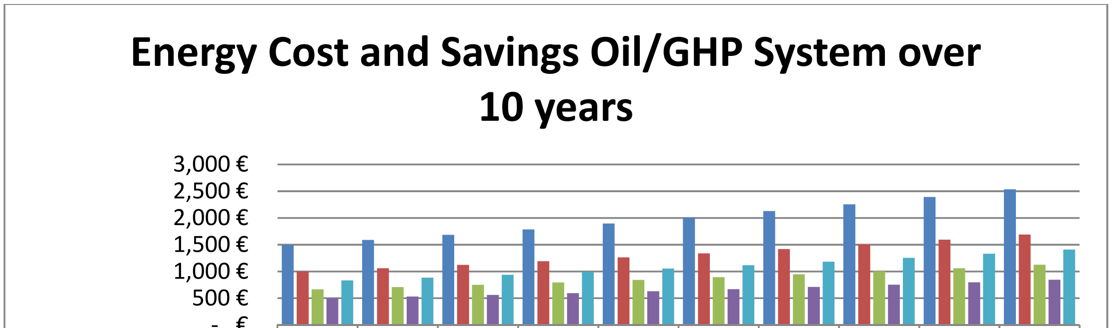
a) The temperature level in the building. One person is over 90 years old and lives in a third of the building. The room temperature adjustment is 24°C. The consequences are higher output temperature (> 35°C) of the HP with less performance (see Table 3);
b) The temperature level in the other part of the building is more than average to room calculation;
c) The operation hour of the system is ca. 18h/day. Theoretically, a heating system runs for 1.640 hours per year. In this case the system runs more the 2.700h per/a giving a lower SPF;
d) Through the high energy demand of the building, the renewable energy side (geothermal system) cools down too much and the geothermal temperature lays in winter time under – 4°C input temperature. Because of the temperature levels in the geothermal system the performance (SPF) drops significantly (see also Table 3 working condition of HP).

In the design and calculation process of that installation seven years ago, this extreme usage profile of the customer has not been included and discussed with the customer in the planning process.

The second simulation, *"Kaplan"* shows that the energy demand of the GHP system is quite low. There are three reasons for this performance:

a) The renewable energy side of the geothermal system. The geothermal pipes are lying beside a small river with constant temperature input of 8-12°C (see also Tab.3, working condition of HP);
b) The room temperature control is adjusted to the demand for the people. This means the running time of the system is less than 1.000 h/a increasing the SPF;
c) The building fabrics were better designed than calculated. Less energy spending and higher performance.

The following figures (12 – 15) show the economic dependency, consequences and bandwidth of the efficiency variation from the field test result for working GHP systems. Figure 12 shows the savings over a period of time for an oil/GHP system with different SPF from Min 3.0 and Max 4.5 (50%). The calculation is based on the compound interest calculation. The 6 % energy price increasing is based on prices from the last 20 years. Oil price 0,8 €/l, electricity cost 0,20 €/kWh. Energy demand building is considered 15.000 kWh/a.



	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10
oil (energy cost)	1,500	1,590	1,685	1,787	1,894	2,007	2,128	2,255	2,391	2,534
HP SPF 3.0 (e. cost)	1,000	1,060	1,124	1,191	1,262	1,338	1,419	1,504	1,594	1,689
HP SPF 4.5 (e. cost)	666 €	706 €	748 €	793 €	841 €	891 €	945 €	1,001	1,062	1,125
Savings HP SPF 3.0	500 €	530 €	562 €	596 €	631 €	669 €	709 €	752 €	797 €	845 €
Savings HP SPF 4.5	834 €	884 €	937 €	993 €	1,053	1,116	1,183	1,254	1,329	1,409

oil (energy cost) HP SPF 3.0 (e. cost) HP SPF 4.5 (e. cost) Savings HP SPF 3.0 Savings HP SPF 4.5

Figure 12: Energy cost and savings oil ver GHP with different SPF and 6 %, energy price increasing/a

Source: Authors' own research results.

Figure 13 shows the total savings over a time period from 10 years for an oil/GHP system with different SPF from min 3.0 and max 4.5 (50%).

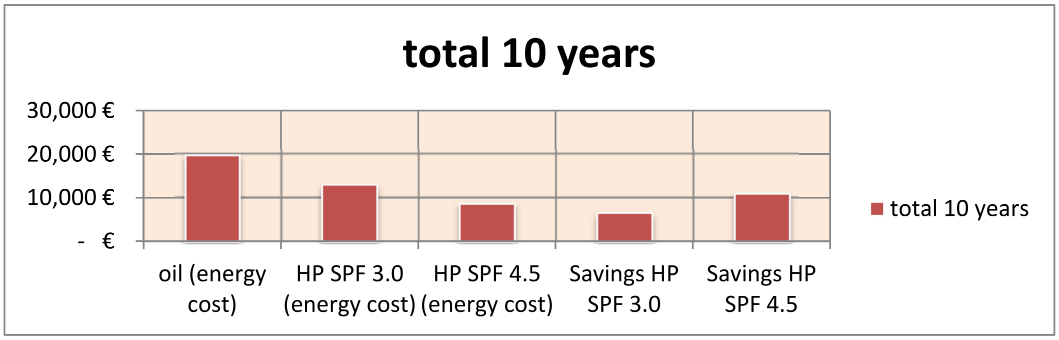


Figure 13: Total energy cost and savings over 10 years oil vs. GHP with different SPF and 6%, Energy price increasing/a

Source: Authors' own research results.

Figure 14 shows the investment calculation of a GHP and oil system. The calculation is based on the data from Figure 13.

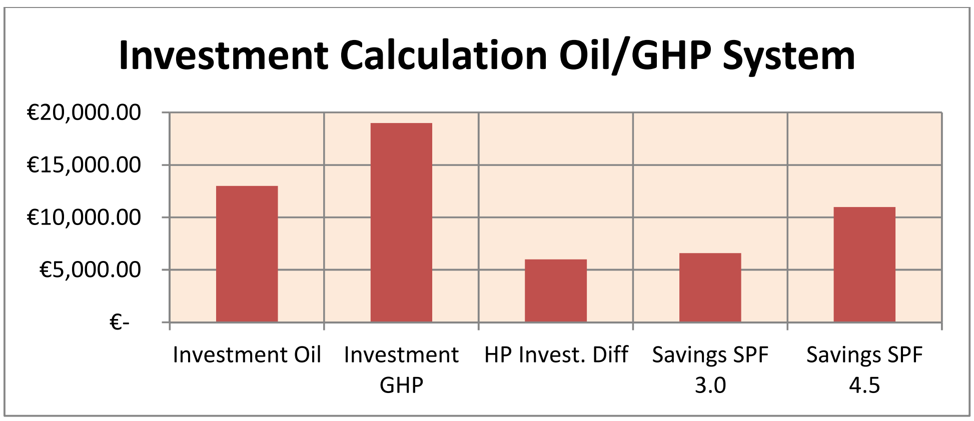


Figure 14: Investment calculation GHP/ Oil System with different SPF

Source: Authors' own research results.

Figure 15 shows the payback time of the investment of a GHP and Oil System. The calculation is based on the data from figure 14. A live time of a GHP is > 15 years. After 15 years the savings is nearly the amount of a new GHP if investment cost stays on the same level.

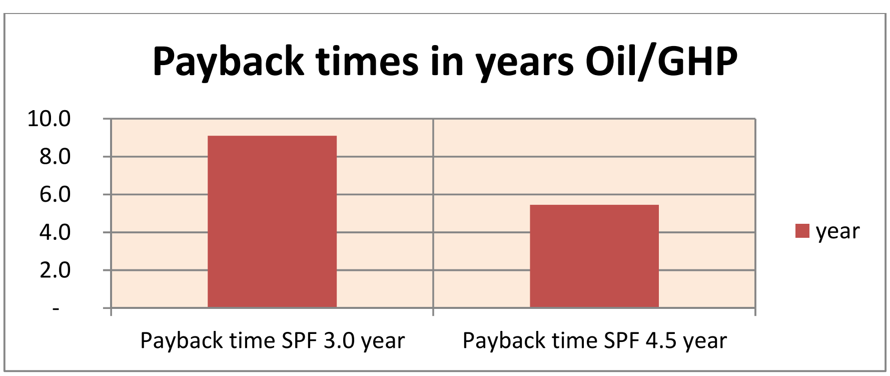


Figure 15: Payback time oil/GHP for different SPF

Source: Authors' own research results.

Conclusions

The efficiency of GHP and air/water HP systems is dependent on a variation of different factors of influence. These factors must be clearly defined and communicated with the different stakeholders involved in a HP system implementation process. Stakeholders can be HP suppliers, refrigeration systems installers, electricians, heating installers, architects, planners, energy consultants, builders, future owners of the system and financial services partners. The *interdisciplinary* view for installing HP systems is the *most crucial point*. Different technology combined in a complex heating system is the main difficult part. Theory and practice can vary greatly (see simulation and field tests). The variation of these influential factors requires competent people on the building side, even before construction has started. The research shows that efficiency of HP System varies greatly, depending on input, output and external factors like.

The economic viability of GHP System is defined by the SPF, as shown in the analysis of the field test and simulation result. The energy saving potential over a longer period of time could make this heating technology uneconomical in comparison to other fossil driven systems if the SPF is too low. Environmental aspects like reducing greenhouse gases and reduction of energy dependency from fossil fuel would be another benefit.

With a correct *planning* and *design* of HP systems, an *interdisciplinary* view to such system, *good training*, a good *understanding* of the *different technology involved* and *communication* with the people involved, the risk of fail installing a high efficient HP system can be reduced and economic dependencies minimized. Higher SPF can also be achieved with hybrid systems. These systems are using different RES together in a HP System. A hybrid system is more complex in comparison to a normal GHP System. There are more special demands on the planning and design of the system, as well as their installation, programming and control. This can lead to further opportunities for error and reduction of efficiency. Using a hybrid HP system, the Max/Min levels of the SPF are similar to the field test reports. The difference lies in a higher efficiency level.

Small/medium GHP Systems are some of the most efficient heating systems today. They reduce the energy bill, greenhouse gas emissions and the energy dependencies from fossil energy sources. There is no difference in efficiency (SPF) between small and medium GHP systems to the field test results. If all stakeholders in the installation process work together in a team with a clear view using the positive aspects of the factors influencing the performance of a GHP system, the economic success will be secured.

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