EBC
Energy in Buildings and Communities Programme

HEAT PUMP SYSTEMS

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GENERAL RELEVANCE

Heat Pumps are a widely used technology for heat and cold supply in buildings enabling the use of environmental energy by the thermodynamic anticlockwise Carnot cycle. As environmental energy usually act ambient air, waste air near-surface geothermal energy, ground or sea water and solar thermal heat. In addition heat pumps are used to utilize waste heat, low temperature heat from deep geothermal or within cold district heating networks. The majority of heat pumps are of the type electric driven compression and as such a heating and cooling technology which is coupling the sectors electricity and heat. In combination with PV and or wind and battery storage a high degree of energy autonomy can be achieved and a grid supportive operation delivered.

RELEVANCE IN BUILDING COMPETITIONS & LIVING LABS

Looking at the technology used for heat and cold supply in the recent SD competitions since the early 2000s heat pumps was the must. All homes are “all electric”. On one hand this is a simplification for the teams and increases fairness, on the other hand, further technological options are. As long as small homes are in the focus, the limitation to heat pumps is reasonable, but for apartment buildings and urban situations, other options like district heating or cooling add to the heat pump scenario.
The energy performances of heat pump systems are highly depending on their system integration due to their temperature dependent performance. Thus in building competitions and living labs the focus should be less on the performance of the heat pump itself but on optimal system integration.
The performance (SPF and COP) of the heat pumps was not monitored in competitions up to now, but has partly been addressed in living labs of the participating universities following the competition. Within the competition, the monitoring was limited to the power metering of the total HVAC circuit, but not more detailed and no heat output was monitored.

PARAMETERS

The energy performance of a heat pump system is substantially determined by the temperature level of the heat source and the heat sink, thus temperatures have a considerable impact on the efficiency. There are a diverse range of factors that influence the operating temperatures, whereby it is not just the field of application of the heat pump that plays an important role but also the planning, installation, commissioning and operating phases. The field of application of a heat pump is limited to a certain extent by the availability of environmental energy and their temperature level, which has an impact as well on the chosen heat pump technology. In addition there are boundary conditions and limits in terms of the required sink temperatures: Example given there are relevant differences between the requirements in existing, non-refurbished buildings with radiators and in new buildings. In new buildings with floor heating, the heating operation differs considerably from the operation for domestic hot water heating. In multi-family buildings with a higher share of domestic hot water and higher requirements on pure water this is even more evident. Through their choice and size of heating system, design engineers determine the required heating circuit temperatures within the framework provided by the heating requirements and the spatial conditions.

Heat and Cold Delivery

Common Systems for heat and cold delivery are air intakes, recirculation and floor heating respective slab cooling systems. For heat delivery radiators are widespread as well. With air intakes and radiators delivery temperatures are generally higher than in floor heating, thus the latter is preferable. The higher time shift in floor heating systems has to be taken into account in the control.

Domestic Hot Water

Due to water quality a defined way to avoid unwanted contamination has to be defined – especially in larger systems with multiple distributed taps. The common and save solution is to keep system pure water temperatures over 60°C, which is critical regarding the energy performance of heat pumps. Innovative concepts like a combination of ultrafiltration and automatic tapping to avoid stagnancy allow the operation of the DHW System at lower temperatures and are thus favourable regard the performance [Kistemann2015].

Environmental sources

As environmental sources air and ground source heat pumps are the most common ones. Air source heat pumps are due to their stronger seasonal variation of the source temperature less performant but less expensive. Beside these two main technologies ground or sea water could be used as source, as well as waste heat e.g. heat exchanger in the sewage duct. Solar thermal collectors could act as source as well, a promising solution are combined PV and thermal collectors, especially those which could collect energy from the ambient air in times with no or low irradiation.

Installation

Careful installation, professional commissioning and controlled operation help to maintain the planned operating temperatures and adapt to any deviating requirements in practice. For example, a non-adjusted heating curve could mean that the system is operated with heating circuit temperatures that are higher than required. An unfavourable positioning of the storage temperature sensors can cause the storage tanks to be incorrectly charged, particularly with combined storage tanks: the heat pump then generates more energy at the high domestic hot water temperature level than is required. Not completely closing 3-way vents and missing check valves can cause undesired discharging of the domestic hot water storage tank. In addition to aspects that influence the operating temperature, the auxiliary energy for control also has to be taken into account.

Performance indicators

The key performance indicators of a heat pump system are the following:

(i) The coefficient of performance (COP) of a heat pump is a characteristic of the heat pump itself and is determined in the steady state, i.e. under constant operating conditions. It indicates the ratio of the heating capacity to the electrical power consumption electrical power of the heat pump.

(ii) The seasonal performance factor (SPF) describes the ratio of the provided thermal energy to the consumed electrical energy over a longer period of time (e.g. one year).

Coefficient of performance (COP)

The anticlockwise Carnot cycle provides an ideal reference cycle for comparing heat pump processes. With the Carnot cycle, the efficiency is only dependent on the upper temperature T_U and the lower temperature T_L between which the cycle runs. Even if the coefficient of performance for a heat pump is considerably lower, its temperature dependence is still largely comparable with the reference cycle. The respective evaporation and condensation temperatures are therefore decisive for the efficiency of heat pumps as can be seen in the following equation: $\mathrm{COP} = \frac{\dot{Q}_H}{W} = \eta \times \mathrm{COP}_{\mathrm{Carnot}} = \eta \times \frac{T_U}{T_U - T_L}$ T in K. The coefficient of performance COP is a characteristic of the quality of the Carnot cycle and is determined on test rigs with defined boundary conditions. For example, the B0/W35 operating point in accordance with EN 14511 is used as the rated standard operating point for brine-water heat pumps. This describes the operation with a brine temperature of 0 °C/-3 °C (input / output) and a heating circuit temperature of 35 °C/30 °C (output / input). When calculating the coefficient of performance in accordance with the standards, not only is the electrical power consumed by the compressor taken into account but also the electrical power consumed by the source pump and heating circuit pump in order to overcome internal pressure losses. Since the coefficient of performance considerably depends on the operating conditions, in particular the temperatures, it should only ever be specified and considered in relation to the operation conditions. In EN 14825 the SCOP (Seasonal COP) is defined, which gives an average COP under given conditions using a bin method.

Seasonal Performance Factor SPF

A general form to describe the SPF is the following: $SPF = \frac{\int_{t1}^{t2} \dot{Q}_H \, dt}{\int_{t1}^{t2} P_{el} \, dt}$. The parameters influencing the seasonal performance factor of heat pumps are the timespan (usually a year or a month) and the chosen system boundaries. Fig. 1 depicts four possible system boundaries for a heat pump system:

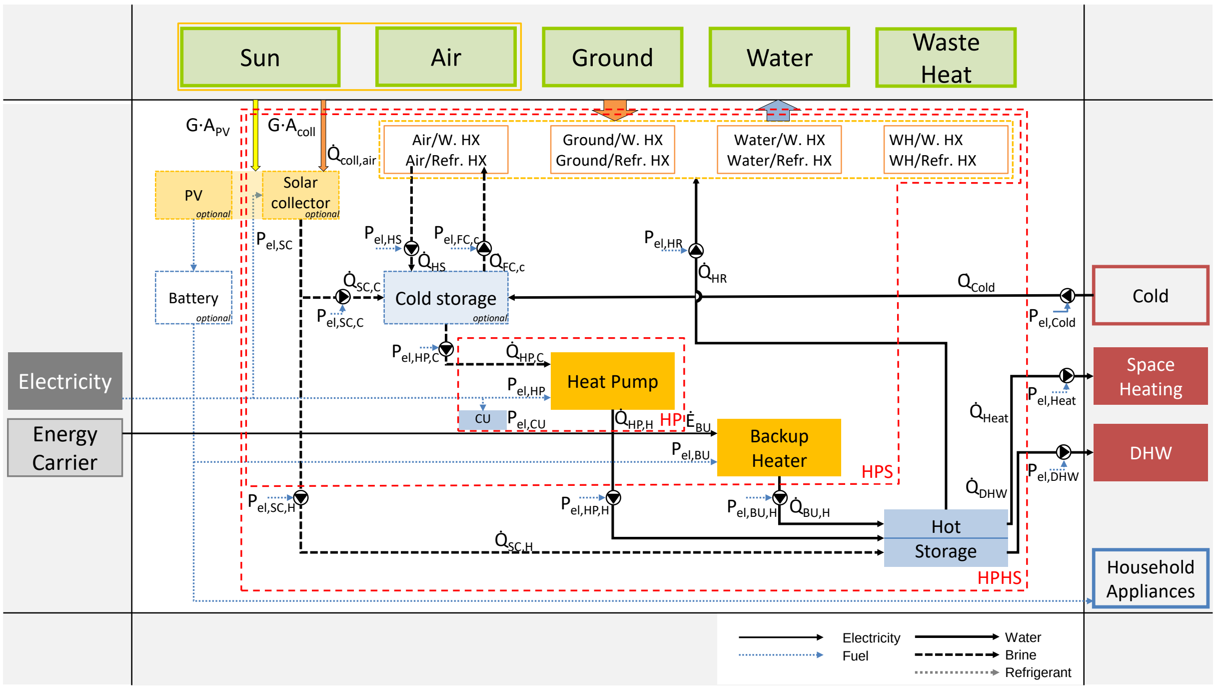

Figure 1: System boundary of a Heat Pump based heating system. In the upper part the environmental heat sources and sinks at site are shown, on the left side energy delivered to the site and on the right the net energy delivered to the building.

The "narrowest" system boundary (HP) only includes the energy required by the heat pump unit (compressor, internal control system and, if required, an oil sump heating system for the compressor). If the heat source circuit's ventilator, brine or well pump is also included in the balancing scope with supplementary electrical heating when installed this is described as a heat pump system (HPS). When balancing both the HP and the HPS, the thermal energy is determined directly behind the heat pump and/or the electrical back-up heater. When considering the efficiency of the entire heat pump heating system (HPHS), only the effective energy – i.e. behind the storage systems – is taken into account. In this case the charge pumps are also incorporated into the calculation as loads.

The following example shows graphically the temperature dependence of a heat pump with a COP of $3{,}8_{A2/W35}$ in a multi-family house (see figure 2). In case 1, a high performance new building the share of domestic hot water is 40% and a DHW temperature of 45°C, in combination with floor heating, the SPF_{HP} is 40%*3,7+60%*5,4 = 4,7. In the second example (case 2), a partly retrofitted building with radiators and a share of DHW of 25% the SPF_{HP} is 25%*2,3+75%*3,6 = 3,3. Comparing these two examples shows a difference of 30% in the SPF suing the same heat pump and underlines the effect of the chosen system temperatures.

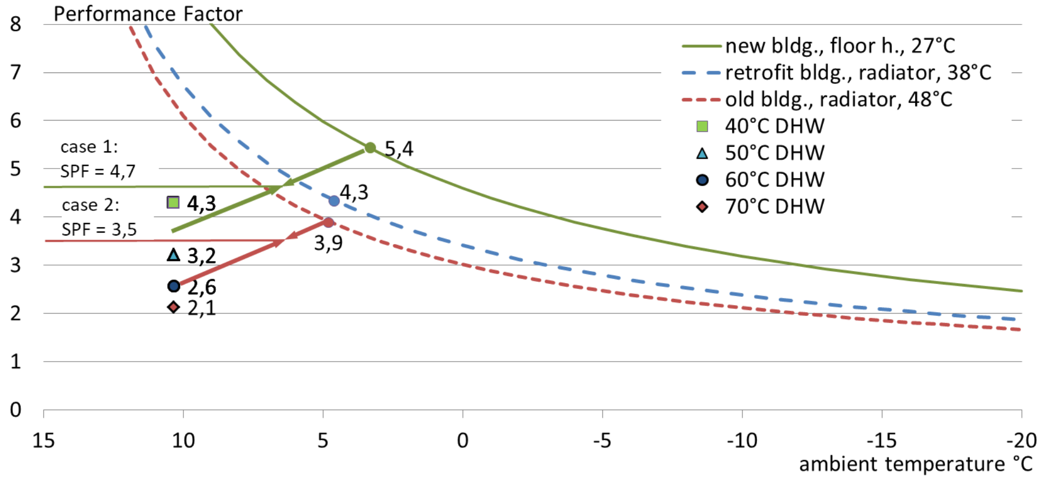

Figure 2: Performance factor of an air source heat pump depending on the ambient temperature. The markers show the annual average and thus the seasonal SPFHP. The SPF for the domestic hot water is related to the average ambient temperature of the whole year, for the heating related to the building dependent average ambient temperature in the heating season.

ASSESSMENT OF HEAT PUMPS

The coefficients of performance of heat pumps enable different heat pumps from various manufacturers to be compared with one another - under the assumption that the coefficients of performance have been determined under the same boundary conditions. Likewise, a comparison of the results from different field tests or simulation is only possible to a limited extent if they have not used precisely the same balance boundaries and analysis methods. In addition to the issue as to where the system boundaries were defined, there are also other aspects that are relevant. For example, when calculating the seasonal performance factor it is a difference whether unused heating energy is taken into account that was produced in summer as a result of the system or as a result of faulty operation. It is also only possible to compare the same balancing periods with one another (e.g. one year).

In classifying the seasonal performance factor information, not only do the balance boundaries and the balance periods need to be specified but also the type of heating source, the application area (e.g. building standard, heating systems, ratio of the heating requirement to the domestic hot water requirement) and the operating temperatures. Quite often only the supply temperatures are specified as operating temperatures in the heating circuit. However, these are not the only ones that are decisive for the condensation temperature. The return temperature also has an impact.

Performance calculation and Simulation

For calculation of the SCOP the EN 14825 give a detailed method to assess the calculation of the annual performance based on a classification method. To calculate a heat pump based heating systems in a more detailed way, there are manifold open source and commercial tools available with different degrees of detail. Heat pump models are available as part of large simulation packages like Energy Plus, ESP-r or Modelica, the latter gives the opportunity to extend your own models and compute even the thermo-hydraulic effects of specific refrigeration circuits, e.g..

Monitoring

As can be derived from the large variety of different boundaries and possible SPF values, there are many ways to monitor a HP system, ranging from very simple to rather complicated and detailed. Therefore, depending on the aim of the measurements also the complexity of the monitoring equipment and resulting from this also its costs can vary a lot. The easiest way to monitor a HP system would be to measure only the amount of produced useful heat for domestic hot water and space heating on the one hand, and the total electric energy consumption of the overall system on the other hand. By measuring these two values the performance factor SPF_{HP} or SPF_{HPHS+} (which includes additionally the electricity for the heating distribution pump) can already be determined in order to have a first hint for comparison of the systems' performances.

However, much more information can be derived from a more detailed measurement strategy. Depending on the main goal or interest of the investigation, different questions may be addressed. The performance factor SPF_{HPS} e.g. is very useful for the comparison of a SHP system with conventional heating systems as e.g. gas boilers as it does not consider storage losses. For any performance figure to be evaluated all energy flows have to be measured that cross the boundary corresponding to the respective performance figure's definition.

For model-based evaluation of complete systems, i.e. by means of simulation, or for the validation of numerical component models a more complex and highly differentiated monitoring strategy is required. Many heat flows and electricity consumers are to be covered and determined separately in order to have a detailed picture of the overall energy flows. As input for the validation of simulation models, also a relatively high frequency of data logging time steps is crucial e.g. collected data as mean values in a time frame between every one to five minutes.

Post Processing of Results from Simulation & Monitoring

The post processing of data could be seen as a two-step approach, first filtering and aggregation of data and second the visual representation of them. For comparison of different systems key performance indicators should be presented in a highly aggregated form. They are usually the mentioned performance indicator SPF with defined boundaries, the delivered heat and the electricity for compression, back-up heater and source pumps. For comparison as well the average temperatures on the condenser and evaporator side should be shown, see example from the German field test "WPsmart im Bestand" [Guenther2018].

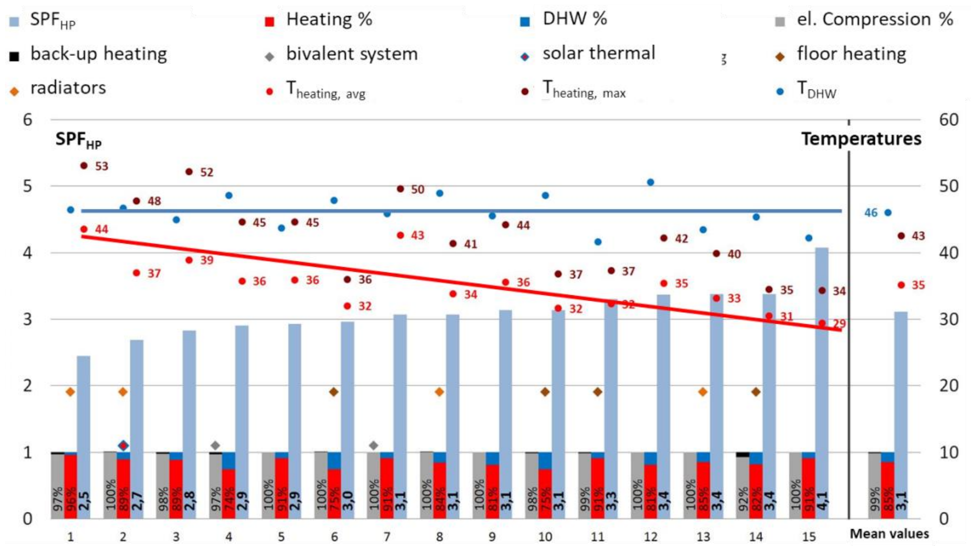

Figure 3: Comparison of the Seasonal Performance Factor SPFHP of 15 systems ordered by the performance. The dependency on the system temperatures can be seen clearly. source: [Guenther2018]

As second example for a graphical representation of results a temperature analysis during the seasons of the in- and outlet temperatures of a ground source and their dependence on the ambient temperature is shown in figure 4.

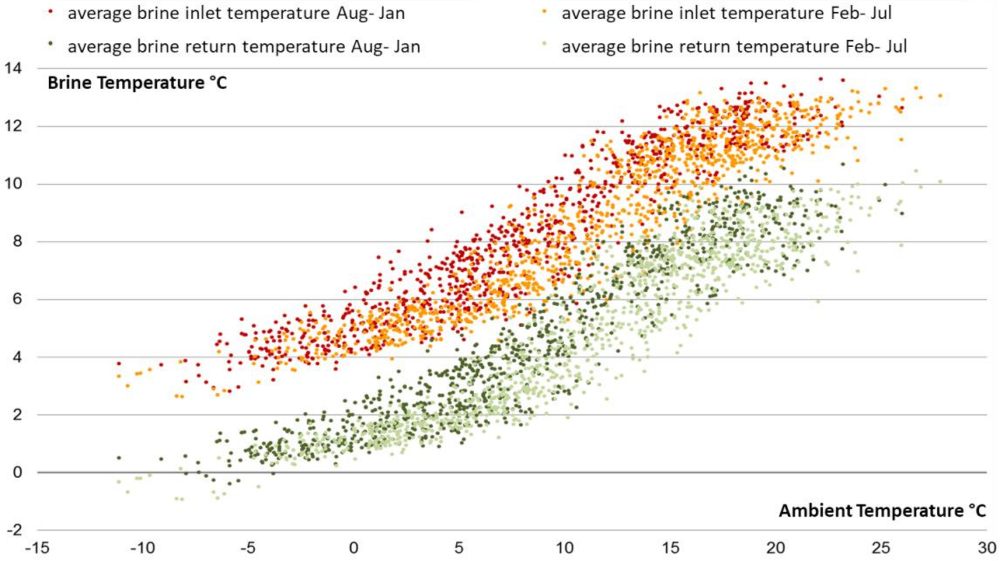

Figure 4: Inlet and outlet brine temperature of a ground source heat pump borehole heat exchanger. Using different colors the seasonal time shift in the temperatures can be indicated (temperatures in the period August to January are higher due to the regeneration of ground in spring and summer), source: [Miara2014]

FURTHER READING

[Loose 2015] A. Loose, S. Herkel et al. "Monitoring" in J.C. Hadorn (ed.) Solar and Heat Pump Systems for Residential Buildings August 2015, ISBN: 978-3-433-03040-0 IEA SHC Task 44/HPP Annex38

[IEASHCT44] IEA SHC Task 44 – Solar Heat Pumps, http://task44.iea-shc.org/publications

[IEAHPTA50] IEA HPT Annex 50 Heat Pumps in Multi-Family Buildings for Space Heating and DHW https://heatpumpingtechnologies.org/annex50/best-practices/

[Guenther2018] Günther et. al.; Feldtests bestätigen Potenzial von Wärmepumpen; HLH Bd. 69 (2018) Nr. 3 - März

[Miara2014] Miara et. al.; WP Monitor - Feldmessung von Wärmepumpenanlagen; Abschlussbericht; Freiburg; Juli 2014

[BINE2013] Wapler et al. "Electrically Driven Heat Pumps", BINE INFO 2013, http://www.bine.info/fileadmin/content/Publikationen/Themen-Infos/I_2013/themen_0113_engl_Internetx.pdf

[Kistemann2015] Völker S, Kistemann T Field testing hot water temperature reduction as an energy-saving measure – does theLegionellapresence change in a clinic's plumbing system?, Environmental Technology 36(16): 2138-2147, 2015