CROSS COMPARISON BY MEANS OF LONG-TERM MEASUREMENTS: ENERGY AND EFFICIENCY ANALYSIS OF HEAT PUMP SYSTEMS IN NON-RESIDENTIAL BUILDINGS

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Abstract: This paper presents a cross-comparison of 16 ground-coupled heat pump systems installed in different non-residential buildings, based on high-quality measurement data collected with high temporal resolution (typically 60 seconds) over several years of operation. The heat pumps have thermal powers ranging from 7 to 291 kW_{therm}, six of them can also provide active cooling (reversible operation). They are integrated into various hydraulic concepts including different ways of free cooling and waste heat recovery.The heat pump systems of the analyzed buildings reach seasonal performance factors (heat pump with compressor and primary pump) between 2.9 and 6.1 kWh_{therm}/kWh_{el} in heating mode, 3.5 to 42.1 kWh_{therm}/kWh_{el} when using free cooling via a heat exchanger and 2.1 to 5.0 kWh_{therm}/kWh_{el} in active cooling. Crucial design factors are the auxiliary energy demand of the primary pump as well as the supply temperature for the distribution systems. Good efficiencies can be reached when using heat pumps systems which include free cooling, waste-heat-recovery and distribution systems which permit supply temperatures near room temperature (16 to 20 °C in cooling mode, 28 to 33 °C in heating mode).

Key Words: Heat Pumps; Monitoring; Nonresidential; Efficiency Analysis

1 INTRODUCTION

While geothermal heat pumps in residential buildings (single/double family houses and multi-family residencies) have reached a high stage of development and, for applications in new buildings, the market penetration is already large and it is currently developing, the situation for heat pump applications in non-residential buildings is different: they only represent a small share in currently sold heat pumps [1]. If knowledge and confidence in these systems grows, their adoption could be increased in the future and they could represent an optimum answer for many non-residential heating and cooling demand applications.

2 BUILDINGS AND ENERGY CONCEPTS

The analyzed buildings are nonresidential buildings located in Germany. Floor areas are between 1,000 and 17,400 square meters. All heat pumps systems are used for heating and all include the possibility of free cooling. Six buildings also use active cooling (reversible heat pumps) and six buildings benefit of waste heat, coming from e.g. a server room. The heat pumps have nominal heating powers from 7 to 291 kW. Three buildings are equipped with ground Water Systems (W.), 15 buildings use Ground-Coupled systems (G.). 13 buildings are equipped with electrical heat pumps, and three buildings have thermal heat pumps (T.), two of them gas-driven. Those key facts are listed in Table 1.

Table 1: Key facts of the analyzed buildings and their energy concepts.

	W01	W02	W03	G01	G02	G03	G04	G05	G06	G07	G08	G09	G10	G11	G12	T01	T02	T03
Occupancy	School	Pro-duction	Office												School	Mu-seum	School	Sports hall
Total conditioned area in m^2	10700	4600	1600	2100	5000	100	1000	4100	4900	900	17400	3300	2000	1800	1700	3200	4440	1600
HP nominal heat. power in kW	2x135	54	75	57	-	-	33	122	2x112	3x7	291	75	68	64	40	54	75	37
Heat source/sink	Ground Water			Borehole heat exchanger					Energy Piles	Earth Coll.	Borehole heat exchanger							
Heating																Th. HP	Gas-HP	Gas-HP
Direct cooling																		
Active Cooling																		
Waste heat use																		
Storage Heating ($l/kW_{HP,nom}$)	11	0	11	16	0	0	121*	23	7	24	4*	13	29	23	0 / 13	150*	20	65*
Storage Cooling ($l/kW_{HP,nom}$)			15					26	17			15		17		74*		
Multiple heat/ cold generators																		

* shared storage

2 METHODOLOGY

This study is based on high-quality measurement data collected by universities and research institutes during long-time monitoring campaigns, mainly as part of the research program “Energy Optimized Buildings (EnOB)”, funded by the German Federal Ministry for Economic Affairs and Energy(namely: EnOB:Monitor, LowEX:Monitor and ModQs [2]). In each building, extensive monitoring-systems have been recording detailed performance data of the heat pump systems: system temperatures, volume flows, supplied heating and cooling energy, electrical consumption of the heat pump, auxiliary energy demand of the pumps, operating times and operation modes of the heat pumps have been monitored with a typical time resolution of 60 seconds.

The various hydraulic layouts and the differences in the exact positioning of the monitoring sensors of each building were taken into account at the first step of the data processing, before all heat pump systems were analyzed in a standardized way: Four balance boundaries were defined as in Figure 1, and the electric consumption and thermal energies were divided according to the three operating modes heating, active cooling and free cooling. If multiple operating modes occur at the same time (e.g. free cooling for the server and heating of the building), the electrical energies are divided according to the ratio of the thermal energies supplied for each operation mode.

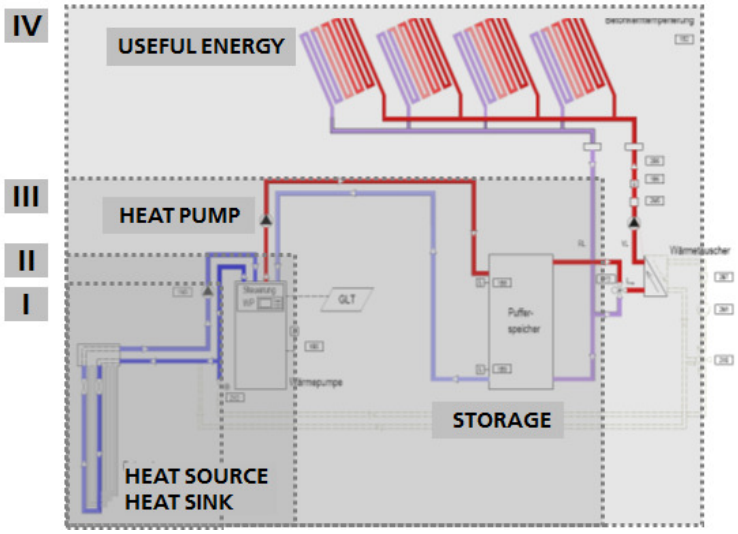


Figure 1: Definition of balance boundaries

3 ENERGETIC ANALYSIS

3.1 Boundary I: Heat Source/Sink and Primary Pump

In boundary I (only heat source/sink and primary pump), the systems reach seasonal performance factors (SPF) between 3.5 and 42.1 kWh_{therm}/kWh_{el} in free cooling mode and 2.9 to 61.7 kWh_{therm}/kWh_{el} in heating mode, see Figure 2 and Figure 3. Reasons for low efficiencies are pumps running constantly, unmatched volume flows of the individual boreholes, unfavorable hydraulic layouts and oversized pumps (up to 230 W_{el}/kW_{therm}). High efficiencies in boundary I can be reached with well-planned hydraulics and correctly dimensioned high-efficiency pumps (Buildings G09 – G12 in Figure 2).

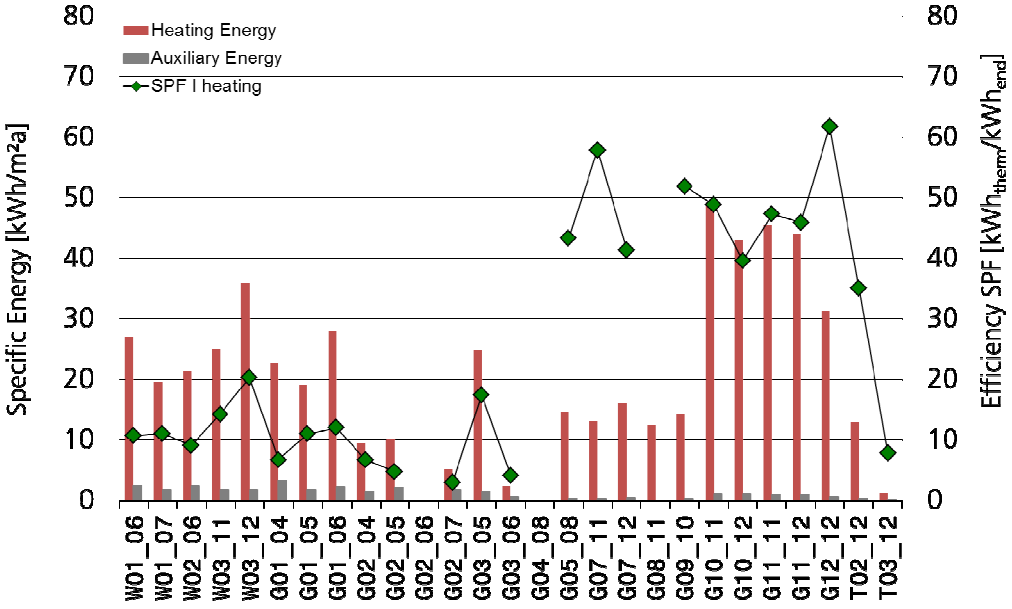


Figure 2: Specific Energies and Seasonal Performance Factors (SPF) for boundary I (only heat source and primary pump), heating. Abbrevations: ground water (W), ground (G), thermal (T). The number after the building name represents the operation year.

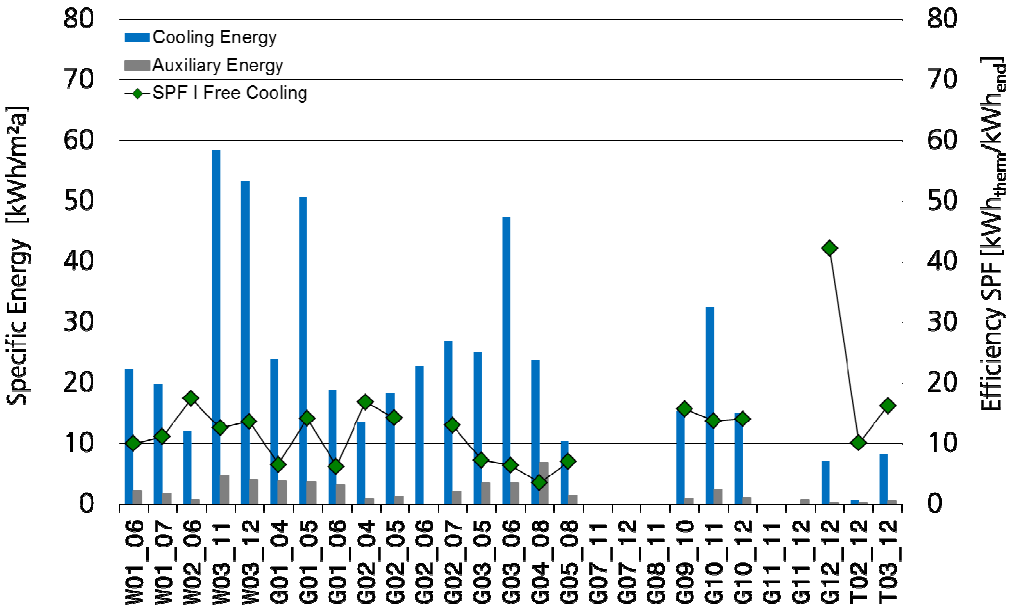


Figure 3: Specific Energies and Seasonal Performance Factors (SPF) for Boundary I I (only heat sink and primary pump), free cooling. Abbrevations: ground water (W), ground (G), thermal (T). The number after the building name represents the operation year. For the buildings G07, G08 and G11 no monitoring data is available for the free cooling system.

3.2 Boundary HP: Heat Pump without Primary Pump

The heat pumps themselves (without accounting the primary pump) reach seasonal performance factors between 3.2 and 6.7 kWh_{therm}/kWh_{el} for electrical heat pumps and 1.1 – 1.3 kWh_{therm}/kWh_{el} for gas driven heatpumps (green diamonds in Figure 4). The significant differences in efficiency of the individual systems are mainly due to the different temperature differences between primary and secondary side, which are dictated on the secondary side by the type of distribution systems and by the hydraulic layout. The use and optimized operation of low-temperature distribution systems leads to a high energy efficiency of the heat pump of 4.8 – 6.7 kWh_{therm}/kWh_{el} (Figure 4: Buildings G01, G05, G09). In contrast, for example at the building G10 the heat storage both supplies the concrete core conditioning (temperature requirement from 27 to 30 °C) and the air register (temperature requirement 40 – 45 °C). Consequently, the heat pump only reached an SPF of 4.0 kWh_{therm}/kWh_{el}. In Building G12, the different distribution systems are separated hydraulically with respect to their temperature levels, i.e. the concrete core conditioning is connected by switching valves directly to the heat pump, and the air register to the heat storage. This system achieved a SPF of 5.2 kWh_{therm}/kWh_{el}.

3.3 Boundary II: Heat Pump with Primary Pump

The seasonal performance factor of heat pump system and primary pump (boundary II) reaches from 2.9 to 6.1 kWh_{therm}/kWh_{el} for electrical heat pumps and 0.9 – 1.3 kWh_{therm}/kWh_{end} for gas driven heatpumps (blue diamonds in Figure 4). In active cooling mode, the analyzed systems reach efficiencies of 2.1 to 5.0 kWh_{therm}/kWh_{el}.The electrical demand of the primary pump accounts for 6 to 25 percent of the total electrical demand in balance boundary II, heating mode. Thus, depending on the system, it has a significant impact on the overall efficiency. The operation of high-efficiency systems requires a good and careful planning of the hydraulic and thermal design and of the heat sources. Misconceptions in the planning (e.g. undisturbed soil temperature, extraction capacity for geothermal probes, possible delivery rates for groundwater) and sizing errors lead to insufficient heating / cooling capacities and low energy efficiency, which can hardly be

compensated or corrected during system operation. For example, in the buildings W03, G05 and G09, the entire system (heat pump, borehole exchangers, storage and pumps) is a complete package in which the individual components are already well matched by the manufacturer. The thus achieved quality assurance in planning, design and installation allows a significant increase in efficiency to 3.8 kWh_{therm}/kWh_{el} (groundwater) and 5.1 to 6.1 kWh_{therm}/kWh_{el} (soil). In addition, this complete system also allows for a dual operation mode, in which the heat pump can provide heating and cooling energy simultaneously. For primary energy analysis, the cumulative energy consumption (CEC) was used, as this factor includes the whole upstream conversion chain, including for example also the energy needed to construct the power plants. This analysis shows that the electric heat pumps (1.3 to 2.8 kWh_{therm}/kWh_{prim}) even at today's electricity mix in Germany are significantly more efficient than gas heat pumps (0.9 to 1.1 kWh_{therm}/kWh_{prim}) (CEC: Electricity 2.19, Natural Gas 1.12 kWh_{prim} / kWh_{end} [3]).

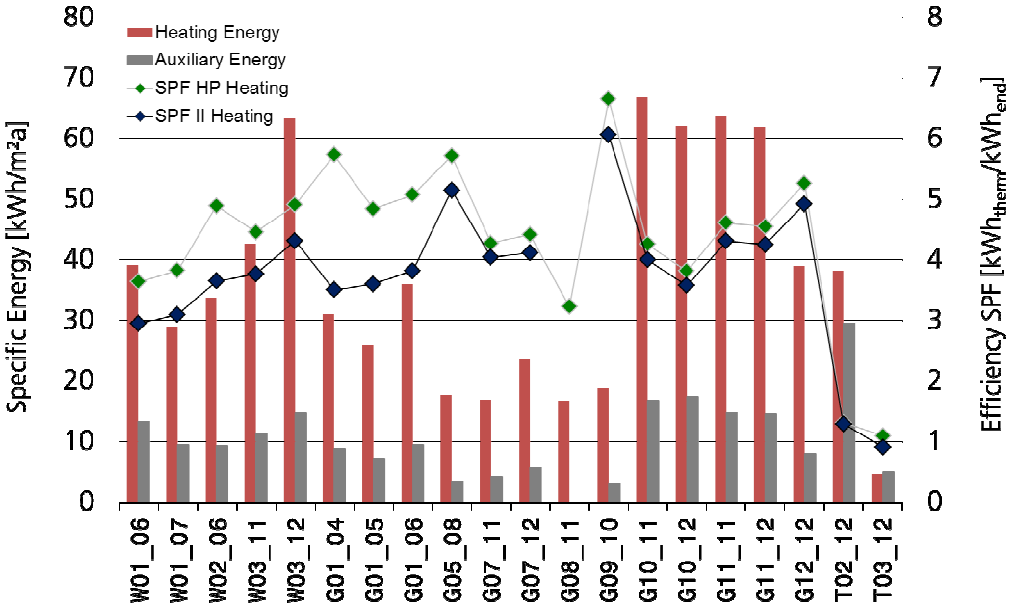


Figure 4: Specific Energies for boundary II, Heating Mode. Seasonal Performance Factors (SPF) are displayed for only heat pump (boundary HP, green markers), and for heat pump including primary pump (boundary II, blue markers. Abbrevations: ground water (W), ground (G), thermal (T). The number after the building name represents the operation year.

4 CONCLUSION AND OUTLOOK

The heat pump systems of 16 nonresidential buildings have been analyzed regarding specific Energies and Efficiencies using long-term monitoring data with high temporal resolution. Their seasonal performance factors vary between 2.9 and 6.1 kWh_{therm}/kWh_{el} (heating mode, heat pump with compressor and primary pump). This shows the efficiency potential of ground-coupled heat pumps, but also that they are very sensitive to incorrect planning and/or operation. So, to realize the full potential of heat pump systems, several aspects have to be taken into account: Single components (e.g. pipe diameters) have to be dimensioned correctly, target values for the maximum installed power of pumps have to be set during planning phase and distribution systems which permit supply temperatures near room temperature (16 to 20 °C in cooling mode, 28 to 33 °C in heating mode) have to be installed. Further areas of the detailed cross-section analysis of ground coupled heat pumps in nonresidential buildings will be published in the near future.

5 FUNDING

This study was performed within the projects LowEx:Monitor (BMWi 0327466B), EnOB:Monitor (BMWi 0,327,431 C) and “Netzreaktive Gebäude” (BMWi 03ET1111A), which were funded by the Federal Ministry of Economic Affairs and Energy (BMWi) following a decision of the German Parliament. Special thanks also go to the Project Management Organisation Jülich for the support of the projects. The authors thank the various evaluation teams and research institutions for providing and processing of the monitoring data and the building owners for the opportunity to examine their buildings.

6 REFERENCES

[1] P. Bayer et al. (2012) “Greenhouse gas emission savings of ground source heat pump systems in Europe: A Review.” In: Renewable and Sustainable Energy Reviews Volume 16, Issue 2, February 2012, pp. 1256-1267.

[2] Project Websites: www.enob.info, http://lowexmonitor.ise.fraunhofer.de/ and www.modqs.de

[3] Fritsche UR, Greß H-W (2013) “Der nicht erneuerbare kumulierte Energieverbrauch des deutschen Strommix im Jahr 2012.” www.iinas.org.