MONITORNG AND EVALUATION OF RENEWABLE HEATING AND COOLING IN A MULTI-PURPOSE BUILDING

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Abstract

In order to demonstrate the potential of technical building equipment based on renewable energies in daily industrial operation as well as to generate planning information, the *CENTRE OF EXCELLENCE FOR RENEWABLE ENERGY RESEARCH* at *Ingolstadt University of Applied Sciences* monitored an innovative multifunctional building. Thermal energy for heating of the building is provided by two groundwater-coupled heat pumps. They feed the thermo-active structure of the building as well as the surface heating installations. Cooling is also driven by groundwater. In this case, the heat is also dissipated by the building´s thermo-active structure and surface heating installations. A very special feature of this building is its heating/cooling façade that combines the glazing function with heating and cooling through its piping-like structure.

During the monitoring, all energy flows in the building itself, the weather data, as well as the room conditions in selected sections of the building, were measured. Considering the different climatic conditions, the performance of the heat pumps and the installed heating/cooling systems, especially the effect of the active façade were evaluated. The function of the installed heating systems, especially the active façade, was demonstrated and the performance of the system could be improved significantly. However, a number of drawbacks with regard to operation and controls had to be overcome and recommendations for action were made.

1. Introduction

Office buildings of the past can be characterised by an architecture solely oriented at its purpose. The control of the indoor climate was generally restricted to the opening of the windows. There were no further requirements concerning acclimatisation. Energy consumption, respectively the cost of energy was of little importance then. The situation of today´s office buildings is described by increasing demands concerning architecture, the requirement of high flexibility with regard to utilisation, increasing external heating/cooling loads due to a growing proportion of glass in the façades, increasing internal cooling loads due to more and more technical office equipment and finally by increasing (justifiable) demand for thermal comfort.

To fulfil all these requirements, more and more technical building equipment for heating, ventilation, air-conditioning and lighting is necessary which consumes more and more energy. Low energy consumption, therefore, can only be reached by the combination of appropriate architecture, building physics and technical building equipment based on renewable energies.

In order to demonstrate the potential of technical building equipment based on renewable energies in daily industrial operation and to generate planning information, the *CENTRE OF EXCELLENCE FOR RENEWABLE ENERGY RESEARCH* at *Ingolstadt University of Applied Sciences* monitored an innovative multifunctional building in Ingolstadt in the south of Germany for 3 years. The project was funded by the *Bavarian State Ministry of the Environment and Public Health* and was supported by the building owner.

2. Description of the Building

The monitored office and production building (Figure 1) was built in 2005 and has a gross floor area of 3,700 m². The ground floor is used for production purposes, the first three upper floors are used for offices, and the top floor provides living space [1].

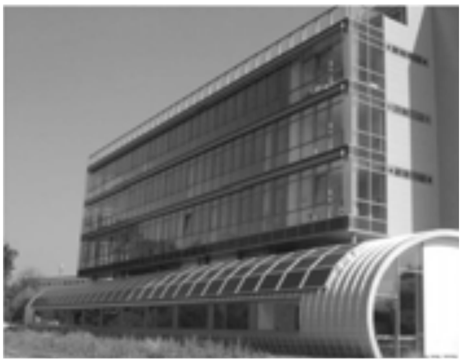

Fig. 1. Western Façade of the Monitored Building.

2.1 Heat Generation and Refrigeration Supply

Thermal energy for heating of the building is provided by two monovalently driven heat pumps (HP) with an electrical connected power of 16 kW_{el} and 8 kW_{el}, able to generate an overall heating power of approx. 100 kW_{th}. The heat pumps are supplied with groundwater from a hoisting well with a depth of 7 m. Due to soilings and the corrosiveness of groundwater, a brine circulation between the groundwater hoisting, respectively the injection well, and the heat pumps is installed. Next to the space heating system, the heat pump plant supplies an enamelling line with heat.

For controlling the room temperature during cooling, the groundwater is directly used as heat sink. This means that the heat is discharged from the building into the injection well. As well as the heating circulation, the cooling circulation is hydraulically decoupled from the groundwater. Hence, cold water is available with a flow temperature of about 16 °C without electricity-driven refrigeration, so that primary energy is only required for circulating and distributing of the cold water. Groundwater is also used for year-round cooling of the computer server room.

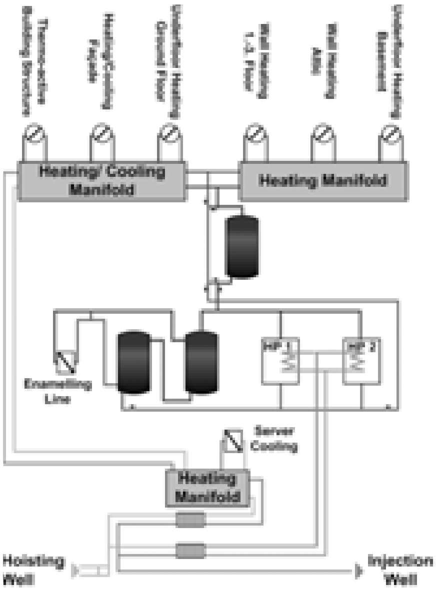

Fig. 2. Hydraulic Scheme of the Heating/Cooling System.

The basic hydraulic scheme of the monitored heating/cooling system is shown in Figure 2.

2.2 Heating and Cooling Systems

The air-conditioning is based on surface systems. Heating the building's basement (B) and ground floor (GF) takes place by an underfloor heating. In the ground floor, the underfloor heating is also used for cooling. From the 1st up to the 3rd floor, the heating and cooling base load is provided by a thermo-active building structure (TABS). In the rooms on the east side and in the attic of the building, wall heating modules cover the heating peak loads.

A very special feature of this building is its heating/cooling façade on its west side, which combines the glazing function with heating and cooling. Purpose of this building´s heating /cooling façade is to cover the heating/cooling peaks in the rooms on the west side of the building. Its piping-like water flow structure makes it possible that the façade itself can be used as an active heating, respectively cooling surface. In this way, the negative aspects of glazed façades - uncomfortably cold while cold ambient temperatures and uncomfortably warm while high sun radiation through the façade - especially in the near of the façade, can be minimised.

3. In-situ Monitoring

The target of the monitoring was to demonstrate the performance of the installed heating/cooling technology and to gather relevant field-testing knowledge. For the scientific analysis of the building, extensive measurement equipment (76 measuring points) was installed to survey all inputs and outputs of energy in the system.

Considering the different climatic conditions, the performance of the heat pump plant, the removed heat from the groundwater, the supplied heat and the consumed electrical energy were surveyed. Apart from that, all heat consumers (TABS, underfloor heating, wall heating and the heating/cooling façade) were monitored. Furthermore, the air temperature and air humidity were measured in four different sections in the first floor of the building in order to evaluate the behaviour of the installed heating/cooling system with regard to the achieved comfort levels. An on-site meteorological station supplied all necessary weather data.

Basically, the analysis and the evaluation of the system were reached by the following measurement categories:

- Flow rate, return and flow temperature for the calculation of the heat consumption,
- ambient temperature, air humidity as well as the solar radiation,
- interior air conditions (humidity and temperature),
- electrical power consumption.

4. Monitoring Results

4.1 Heat Balance

The proportion of the total heating consumption of the different energy consumers showed that most of the heating energy was released into the building by the TABS (approx. 40 %) followed by the underfloor heating of the ground floor (approx. 35 %). The share of the heating/cooling façade and the wall heating on the eastern side of the building was 15 %, respectively 5 %. The underfloor heating of the basement and the wall heating at the attic covered the remaining 8 %. The high percentage of the TABS is positive, since the low flow temperature of the TABS is advantageous for an energy-efficient operation of the heat-pump plant.

In case of cooling, the TABS absorbed approx. 60 % of the thermal loads. Approx. 25 % was effected through the heating/cooling façade, 5 % through the underfloor heating of the ground floor. The cooling of the computer server room represented approx. 10 % of the cooling load.

Summarising, the heat balance showed that the heating and cooling base load was generated by the TABS. As intended, peak loads were realised through the heating/cooling façade at the west side, respectively through the wall heating modules at the east side of the building.

4.2 Level of Comfort Achieved

The degree of comfort depends among others on the air temperature and air humidity [2]. To evaluate the achieved level of comfort in the rooms of the monitored building, these parameters were measured in four different sections of the building.

The array of comfort of these four positions showed that the climate in the monitored rooms while heating was generally comfortable, even at very cold ambient conditions. In general, during the heating period the room temperature could even be 1...3 °C lower without a deterioration of comfort. This, in turn, would lead to a more efficient heat pump operation, provided that a consequent heating control strategy is realised. During the cooling period, at the east side of the building the installed cooling systems ensured that the room climate was highly comfortable (Fig. 3), whereas on the west side the conditions were quite often uncomfortably warm due to the high solar radiation through the glazed façade (Fig. 4). The measured humidity, however, did not negatively influence the level of comfort, neither during heating nor cooling.

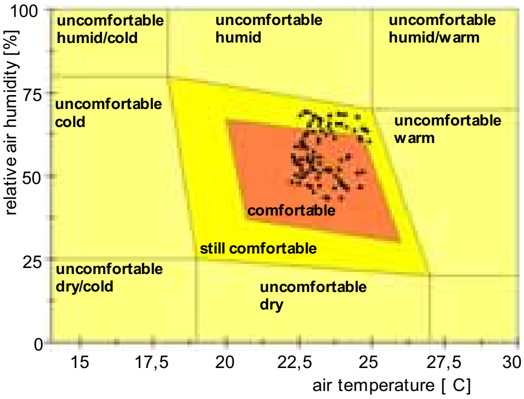

Fig. 3. Array of Comfort at the East Side

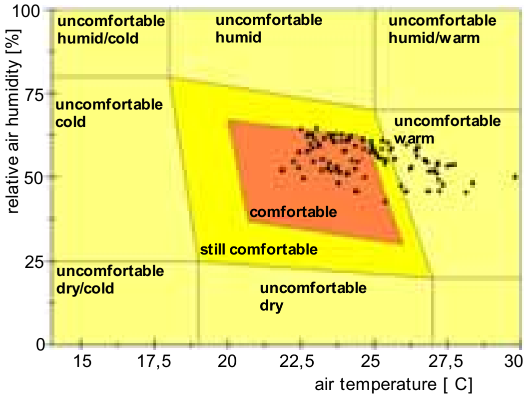

Fig.4. Array of Comfort at the West Side, near the Heating/Cooling Façade

4.3 Performance of the Heating/Cooling Façade

In the case of heating, the heating/cooling façade (Fig. 5) ensured a satisfying level of comfort in the façade area. Related to the theoretically effected space, the installed wall heating modules, however, transmitted more heat into the building as the façade.

The heat balance showed that the façade covered a considerable part of the building's cooling load (cf. 4.1). However, the façade was not able to fully compensate the heat input from the solar radiation, so that the room temperature was often too high (cf. Fig. 4). Especially, an improved supervisory co-ordination of the buildings cooling with the blind control could increase the level of comfort significantly.

Fig. 5. Inside View of the Heating/Cooling Façade

4.4 Performance of the Heat Pump Plant

Over the entire monitoring period, the performance factor (PF) of the heat-pump plant was only 2.84. Thus, the PF was far behind the expectations. This could be attributed to the following causes:

- The groundwater temperature as the decisive influence of the heat source on the heat pump efficiency was with 3 °C far below the expected (design) level of minimal 9 °C during the heating period.
- The control of the two heat pumps with their two compressor stages each, connected in cascades, originally was not energetically optimised.
- The flow temperatures of several heating circuits as the decisive influence of the heat sink on the heat pump efficiency were with up to 50 °C unreasonably high and led to heat pump flow temperatures up to 60 °C.

During the winter months, the groundwater supply temperature droped to 3 °C. With that, the temperature was far below the design temperature of 9 °C. Under these conditions the high PFs (generally expected up to 4.5 [3]) of groundwater-driven heat pumps cannot be achieved. The measured low groundwater temperatures could be traced back to the low depth of the groundwater of between 1.5...2.5 m at the location of the building.

During the measurements, a permanent synchronous clocking of both heat pumps was found. A detailed investigation of the heat pump system showed that the heat pumps were operated with congruent heating curves, adjusted ex-work. Thus, a cascade-like switching of the individual aggregates with their respective compressor stages was prevented. It has to be stated, that this operation mode is reasonable neither from a technically nor from an energetically point of view. Therefore, the heating curves of the two heat pumps were adjusted, so that a cascade-like switching of the individual aggregates with their respective compressor stages was possible. With this optimisation measure, the PF could be improved by approximately 50 %, which is illustrated in Fig. 6 for exemplary operational periods, proving the considerable optimisation potential of the monitored system.

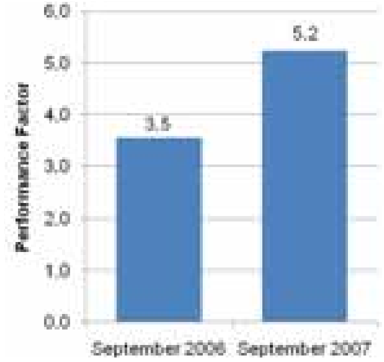

Fig. 6. PF before and after Optimisation

4.5 Influence of Control Settings on the Heat Pump Plant Efficiency

In the course of the monitoring, non-documented (and especially non-co-ordinated) manual user interventions induced changes of the optimised, meaning co-ordinated, control parameters. This led, on the one hand, to a significant reduction of the heat pump plant´s efficiency and, on the other hand, to a deterioration of the intended functionality of the system.

For example, as shown in Fig. 7, in the middle of November 2007 a significant change of the PF was noticed. Fig. 8 illustrates that the heating curves, hence the flow temperatures, were raised by more than 10 °C (upper graph). The return temperature of both

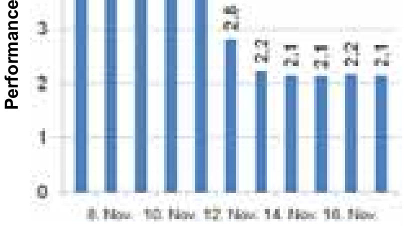

Fig. 7. Daily PF before and after User Intervention (2007).

heat pumps was obviously higher than the ambient temperature dependent hysteresis band. Further, the cascade-like switching of the heat pumps was suspended (lower graph).

As shown in Fig. 9, the flow temperatures of the heat consumers changed simultaneously with the heat pump flow temperatures. This points to a user intervention also in the central building control system. At an ambient temperature during the shown period of about 0...6 °, the measured heat consumer flow temperatures especially that of the wall heating 1.-3. floor with up to 45 °C were obviously too high for an efficient heat pump operation.

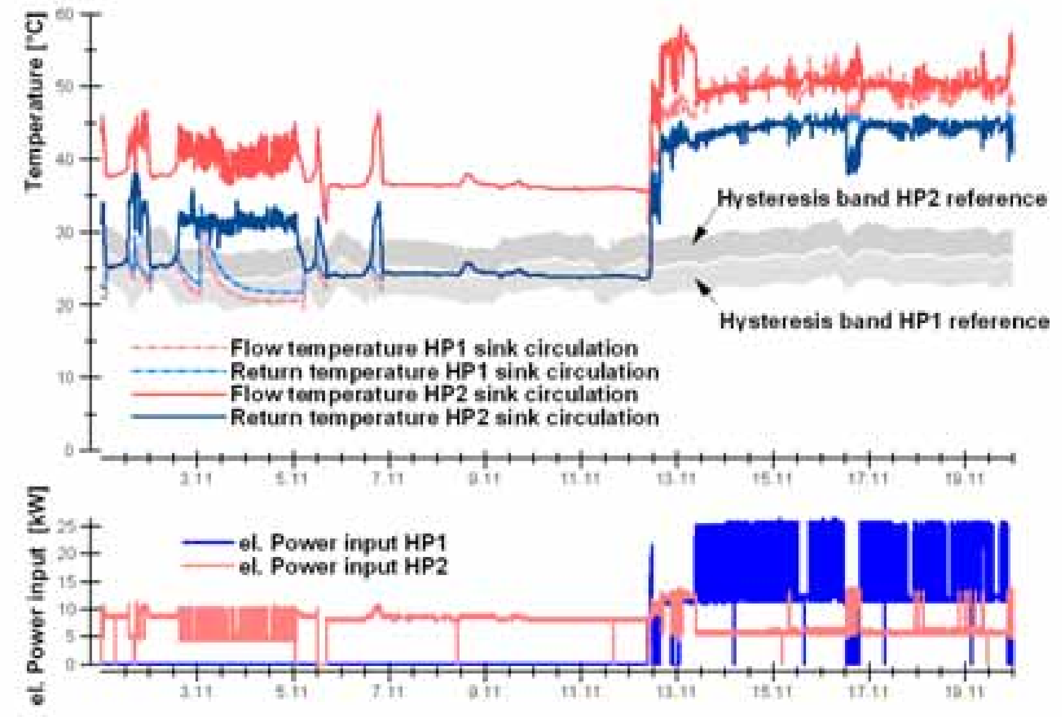

Fig. 8. Effect of an User Intervention in the Heat Pump Control.

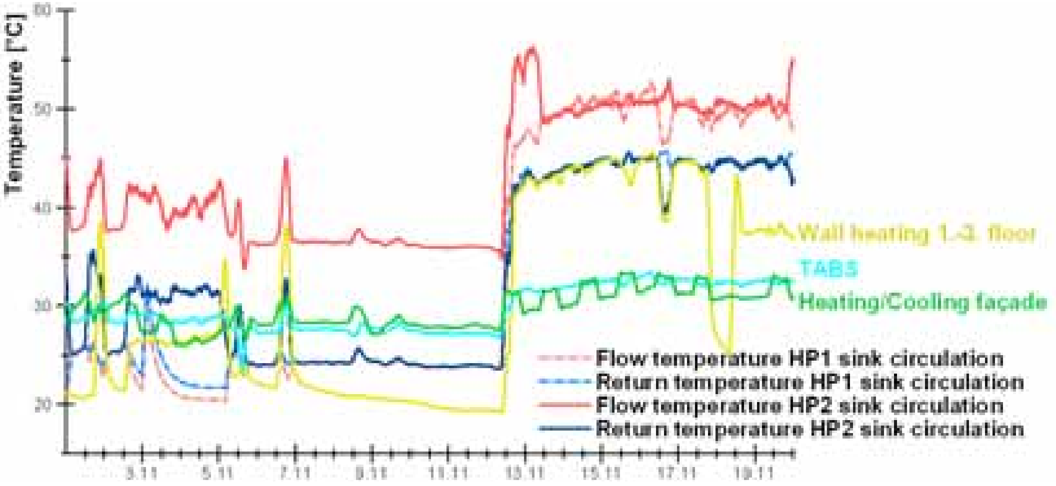

Fig. 9. Heat Consumer Flow Temperatures before and after an User Intervention
in the Central Building Control System.

4.6 Comparison to Conventional Heat Generation

In comparison to conventional heat generation based on oil or gas, the monitored system in principle has a distinct CO_2 emission advantage. However, this advantage highly depends on the efficiency and with that on the control of the heat pumps. During the entire monitoring period, compared to an oil central heating approx. 25 % of the CO_2 emissions could be saved, while compared to a natural gas central heating only approx. 9 % of the CO_2 emissions could be saved. Assuming a realistic heat pump PF of 4.0 (+ 41 % as compared with the actual state), the saving of CO_2 emissions could have been 43 % (oil heating) respectively 31 % (natural gas heating) as shown in Fig. 10.

Regarding the energy costs, approx. 9 % compared to conventional oil heating and only approx. 5 % compared to conventional natural gas heating could be saved over the entire monitoring period. If a PF of 4.0 had been continuously achieved, the energy costs of the monitored system could have been 30 % respectively 27 % lower than energy costs of conventional oil respectively gas heating (Fig. 11).

Assuming that a heat-pump PF of 4.8 will be achieved, as it was proven in comparable buildings [4], considerable CO_2 emission (51 % / 40 %) and energy cost (40 % / 37 %) savings are feasible with the system. This illustrates the significant, undoubtedly existing potential of such systems.

However, the monitoring results confirm that non-optimised overall supervisory control strategies of HVAC concepts with high regenerative proportions can lead to low and even negative emission savings in comparison to conventional systems.

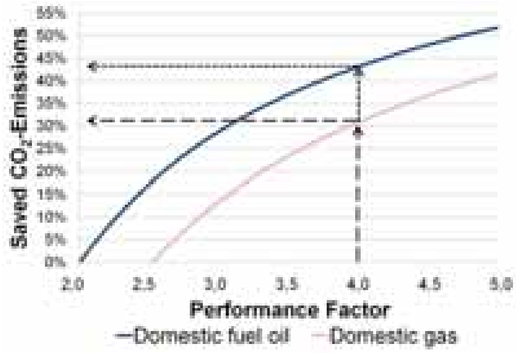

Fig. 9. Saved CO_2 Emissions depending on the PF.

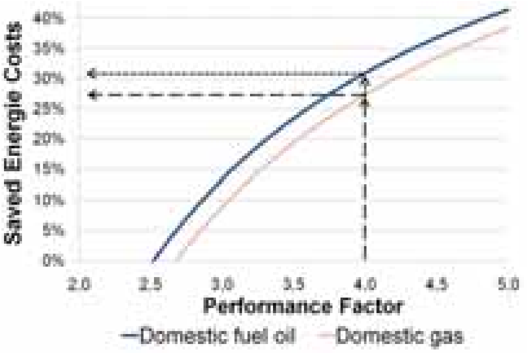

Fig. 10. Saved Energy Costs depending on the PF.

5. Conclusions and Recommendations

Problems, on the one hand, on component level and, on the other hand, with the co-ordination of the system components were identified during the three-year monitoring of a promising building. Especially during the implementation and first operation phase numerous problems were identified. However, by the scientific analysis the removal or improvement of these could be initiated. As already claimed in similar projects [5], the diverse experiences confirm the necessity of a detailed implementation and commissioning phase as well as an adjustment of such complex systems. The operational problems shown, meaning the needless increased energy consumption and the associated increased CO_2 emissions, most probably would have been missed and unremedied without an extensive scientific analysis. This strongly supports the need of an appropriate operational monitoring and management adequate for the (often complex) system. The operational monitoring should include the implementation of an appropriate self-monitoring strategy for the system components and especially for the overall system.

Finally, user interventions, for example in the control of components and in the system co-ordination, which reduce the energy efficiency without an appropriate feedback regarding the effects of the respective action, were detected. In order to avoid these negative experiences with innovative building concepts in the future, the recommendations for action described in Table 1 regarding planning, implementation and adjustment phase as well as operational management may be considered.

Table 1. Recommendations for Action.

Phase	**Recommendations**
Planning	■ At first, the fundamental concept of energy supply must be checked for plausibility and feasibility. Further, this concept should be resolutely pursued. ■ The technical base concept must not be too complex. ■ The overall control of the system has to be determined, already during the system planning. ■ The planning phase should consider that the theoretical and physical performance of heat pumps is hardly achieved during operation; hence, economic objectives should be adapted to that. ■ In the planning of heat pump plants, the availability and the temperature level of the heat source must be thoroughly investigated for each location. ■ In the planning, the integration of an automated, controller based monitoring system should be provided.
Implementation/ Adjustment	■ Before implementation, a complete handover of the inventory documents and operating instructions should take place. ■ An intensive training of the system operators should be carried out. ■ The system planner must be involved also in the adjustment of the system.
Operational Management	■ During operation, a self-monitoring of the system must be included. ■ Trends in energy efficiency should be shown in an annual energy report. The results should be compared with the results of preceding years. ■ As an integral part, energy efficiency should be added to the maintenance plan.

6. References

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