Monitoring results of innovative energy-efficient buildings in Austria

Beermann M¹, Sauper E²

¹ JOANNEUM RESEARCH Forschungsgesellschaft mbH, Waagner-Biro-Strasse 100, 8020 Graz, Austria
² Eckhard Sauper Mess-, Regel- und Steuerungstechnik, Wolfgang Pauli Straße 4, 9020 Klagenfurt, Austria

martin.beermann@joanneum.at

Abstract. The objective of this paper is to present real-world energy monitoring and sustainability assessment results of innovative energy-efficient service buildings in Austria. In the investigated buildings, the energy flows for the supply and distribution of heating, hot water and cooling energy, the object-related electricity consumption and, if available, energy generation with PV and solar thermal systems were recorded during a period of at least twelve months. The room parameters temperature and relative humidity, and in some cases the CO₂ content were also monitored. The use behavior was described based on the users of the building as well as on the operation and parametrization of mostly fully automated energy facilities. The buildings were classified in a sustainability assessment according to the Austrian Total Quality Building (TQB-) system. The buildings investigated are three office buildings, a research laboratory building, a supermarket, a hotel, a nursing home, a culture and event center and a student dormitory. The main findings presented in this paper include energy efficiency potentials identified in the automated operation of the energy facilities in the investigated service buildings. Recommendations also relate to challenges of energy monitoring itself.

1. Introduction

In Austria numerous innovative, energy-efficient buildings have been built in recent years and existing buildings renovated. Such buildings are characterized by requirements as lowest energy use, use of onsite renewable energy sources or waste heat, use of ecological building materials, ensuring adequate room comfort parameters and all this at life cycle costs comparable to conventional building concepts.

The realization of such buildings, in particular larger service buildings, includes the planning and operation of sometimes complex technical systems for heating, cooling and ventilation (HVAC). Although the planning process of complex building systems is increasingly supported by digital working methods aiming to integrate the design of buildings and their conditioning concept, the real world performance of energy efficient buildings also depends on the parametrization of mostly automated HVAC systems in larger service buildings, and on actual user behavior which can significantly deviate from standard user profiles applied in the planning phase.

Previous investigations of planned and real energy consumption of several demonstration buildings in Austria [1], [2], [3] have resulted in deviations to a varying extent. The objective of this paper is to present additional nine service buildings in Austria and to make the potential of innovative building
concepts and technologies visible, but also point to possible areas of concern. The monitoring and
assessment results shall serve future building projects to realize the optimization potential with regard
to energetic, ecological and social aspects.

The following table 1 and figure 1 present an overview of the investigated service buildings and the
main technical elements of the HVAC systems.

| Use category | PV | Solar-thermal | Heat pump | Free Cooling | Active cooling | District heating | Steam humidifier | Component activation |
|--------------|----|---------------|-----------|--------------|---------------|------------------|-------------------|----------------------|
| Office building 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Office building 2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Office building 3 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Laboratory building | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Nursing home | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Market | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Hotel | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Event center | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Student dormitory | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Figure 1: Locations of the investigated service buildings

2. Methods
In all buildings, the generation and distribution of heating and cooling energy and hot water, the
electricity demand of the HVAC system and its subsystems (e.g. heat pump, ventilation) and of other
electricity consumers such as lighting were measured by using heat flow and electricity meters. The monitoring period was at least 12 months, thus covering all seasonal climatic differences, all values were recorded as 15 minute-mean values. Data management and visualization was supported by a web- and server-based professional hard- and software solution with universal interfaces to any energy and flow meters. The measurement data were evaluated in plausibility tests, specific attention was paid to the heat measurement data. Heat energy data are based on the measurement of the heat medium volume flow and the difference of flow and return flow temperatures. The measurement of small temperature differences of a few degrees, e.g. at heat pumps, is very sensitive to measurement errors of a few tenths of degrees within the class inaccuracy of the meter, which already have a major impact on the measured heat energy. Systematic errors therefore need to be corrected with appropriate factors.

Based on the measurement data, energy indicators were calculated: heating energy consumption (ambient temperature adjusted by heating degree days), warm water consumption, cooling energy consumption and final energy consumption, which is the energy supplied to the building to cover the demand of the HVAC system and of general consumers as lighting (free energy supplied by environment as solar energy, PV electricity or geothermal energy is per definition not considered as final energy).

The comfort parameters temperature, relative humidity, and in some cases the CO₂ content were measured in at least 3 rooms per building with different exposures to solar radiation. The use behavior
was evaluated based on the use category of the building as well as on the operation and parametrization of mostly fully automated energy facilities.

All buildings were assessed with the Austrian sustainability rating system Total Quality Building (TQB). This rating system is based on five equally weighted criteria groups: location and facilities, economy and technical quality, energy and supply, health and comfort, resource efficiency. Criteria assessment was based on information provided by the building operators and, where available, on monitoring data. Two ecological indicators as part of TQB are explicitly presented in the results table 2 below: the life-cycle based OI3-indicator, combining global warming potential, acidification potential and non-renewable primary energy demand of the materials used in the building (system boundary BG1), and the disposal indicator EI, weighting the volume of building materials by its utilization potential after end-of-life. Detailed information on the TQB-method is provided in [4].

3. Results

Results are presented below in table 2 for the energy indicators, the comfort parameters, the TQB scores and ecological indicators. Due to the different use categories of the buildings, a comparison of results is only feasible for the three office buildings. For the other buildings the results are commented individually.

Table 2: Results of monitoring

| Gross floor area [m²] | Office building 1 | Office building 2 | Office building 3 | Laboratory building | Nursing home | Supermarket | Hotel | Cultural and event center | Student dormitory |
|-----------------------|------------------|------------------|------------------|--------------------|-------------|-------------|-------|--------------------------|------------------|
|                       | 13.051           | 5.353           | 4.878           | 9.18               | 3.727       | 1.236       | 1.449 | 1.538                    | 1.456            |
| Surface volume ratio [1/m²] | 0.29         | 0.42            | 0.81            | 0.41               | n.a.        | 0.52        | 0.32  | 0.36                     | 0.46             |
| U-mean value [W/m²K] | 0.33            | 0.38            | 0.24            | 0.21               | 0.38        | 0.19        | 0.23  | 0.23                     | 0.21             |
| Heating energy consumption [kWh/m²a] | 17           | 44.2            | 25.2            | 163.3              | 47.3        | 32.7        | 30.7  | 12.4                     | 30.1             |
| Warm water consumption [kWh/m²a] | 1.3           | 3.3             | 0               | 0                  | 27.1        | 2.0         | 33.1  | 0.6                      | 21.3             |
| Cooling energy consumption [kWh/m²a] | 12.9          | 20.1            | 9.2             | 102.1              | 0           | 0           | 0     | 5.3                      | 5.3              |
| Final energy consumption HVAC [kWh/m²a] | 21.4          | 44.1            | 19.7            | 370.5              | 95.9        | 28.8        | 58.6  | n.a.                     | 25.6             |
| Mean room temperature (ambient T<15°C / >15°C) [°C] | 22.8/23.9 | 24.1/24.8       | 23.5/24          | 23.1/22.8          | 23.9/25.9   | 20.8/21.3   | 21.3  | n.a.                     | 21.7/24.1        |
| Mean relative humidity (ambient T<15°C / >15°C) [%] | 46.8/55.7 | 29.9/49.4       | 34.4/51.3        | 42.2/44.8          | 33.9/45.6   | n.a.        | 31.9  | n.a.                     | 32.9/47.5        |
| OI3-Indicator (BG1) | 800-900         | 700-800         | 800-900         | 800-900            | 800-900     | 900-1000    | 800-900 | 800-900                   | 700-800          |
| EI (V1, 2012) | 52               | 176             | 309             | 117                | 62          | 211         | 61    | 244                      | 101              |

3.1. Office buildings

The three office buildings 1, 2 and 3 (OB 1, 2 and 3) have similar HVAC concepts, but completely different building shells. All three buildings supply heating energy demand by heat pumps, in OB1 using waste heat from neighboring water turbine generators, in OB2 and OB3 using groundwater, in OB3 in combination with district heating. Cooling energy is supplied by free cooling, at OB1 with water from the neighboring reservoir and in the other two buildings OB1 and OB2 with groundwater. Heating and cooling energy is distributed in OB1 by floor heating and cooling ceilings and in OB2 and OB3 by concrete-activated ceilings. The building shell of OB1 is a wood-concrete hybrid construction, and in OB2 and OB3 massive concrete construction. OB3 also has a unique stamped concrete façade. This is reflected in the average building U-value, which is particularly low for OB3 with 0.24 W/m²K compared to OB1 and OB2 with 0.33 and 0.38 W/m²K. OB1 in turn is a very compact building with an A/V value of 0.29 m² compared to 0.42 for OB2 and 0.81 m³ for OB3.

Ambient temperature-adjusted heating energy consumption is 17 kWh/m²a for OB1, 25 kWh/m³a for OB3 and 44 kWh/m³a for OB2. In addition to the building shell characteristics U-value and compactness, solar radiation as well as the average room temperature in the heating season have an influence on heating energy consumption. Impact by solar radiation is higher in OB1 and OB2 due to large windows (east and west oriented). OB3 has smaller windows as well as the additional storage mass of the stamped concrete façade, which reduces the transmission losses of the building shell. The average room temperature during the heating season is lowest with 22.8 °C in OB1, 23.5 °C in OB3 and 24.1 °C in OB2.
Cooling energy consumption at OB1 is 12.9 kWh/m²a, at OB2 20.1 kWh/m²a and at OB3 9.2 kWh/m²a. The average room temperature in the summer in OB1 and OB3 is on average 24 °C, in OB2 24.8 °C. The percentage of overheating hours (> 26 °C in the summer) is 0% in OB1, 0 to 8.6% in OB3 and between 3 and 11% in OB2. OB1 has overhangs in the façade on each floor as shading elements as well as daylight-controlled automated exterior blinds. In OB3, the deep, narrow window areas reduce the solar input, while the stamped concrete façade reduces the transmission losses of the building shell also in summer. In OB2, both daylight-controlled exterior blinds and specific foils on the windows provide the necessary shade.

The results of final energy consumption focus on the HCAC-systems of the buildings. Electricity consumption is 21.4 kWh/m²a in OB1, 19.7 in OB2 and 37.9 kWh/m²a in OB3. The seasonal performance ratio of the heat pumps are 3.8 in OB1, 3.7 in OB3 and 3.1 in OB2. The lower ratio at OB2 is due to a non-optimal parameterization of the heat pump in combination with district heat.

With regard to relative humidity, the measured data show the expected result that compliance with the comfort range in winter can only be ensured by air humidification in the ventilation system. In OB1 steam humidifiers are installed, resulting in an average relative humidity of 47% respectively in winter. In the other buildings, relative humidity is on average 30-34% in winter and below 20% with ambient temperatures below 0°C. However, steam humidifiers have a high power consumption, in OB1 with the highest share of household electricity consumption throughout the entire year (8.3 kWh/m²a). Electricity consumption of the steam humidifier increases the annual electricity consumption of the HVAC-system in OB1 by approximately 64%.

The range of the TQB-scores result in 800 to 900 points for OB1 and OB3 and 700 to 800 for OB2. The sub-scores for the criteria groups “location and facilities” and “economy and technical quality” are close to the maximum points in all three buildings, the differences can be found in the criteria groups “energy and supply” (described above), “health and comfort” and “resource efficiency”. The OI3-indicator is lowest (best) for OB1 with a high share of wood as construction material, whereas the massive concrete building shells of OB2 and OB3 have high OI3-indicators. The disposal indicator EI largely depends on the choice of insolation material, synthetic materials as XPS and EPS have higher (worse) results than mineral materials.

3.2. Other buildings

Results for the other buildings are commented in the following to a lesser extent than the office buildings.

A very special use category is the laboratory building. The ambient temperature-adjusted heating energy consumption is 163 kWh/m²a, cooling energy consumption is 102 kWh/m²a, final energy consumption is 370 kWh/m²a. These values result from special laboratory requirements related to room conditioning, room temperature and relative humidity must be kept in defined and very narrow ranges. Laboratory operation also requires high air exchange rates for safety reasons, resulting in additional energy consumption for the conditioning of the supply air. Steam humidification has the highest share of final energy consumption of the HVAC system (yearly average 45%, in the months of October to April up to 58%), followed by ventilation (40%). The sophisticated operation of the ventilation system with steam humidification, cooling and pre-heating and post-heating registers can therefore not be compared with other buildings and use categories. This building is nevertheless an interesting example of a building and of the high “energy investment” required to keep the room parameters within predefined and very narrow ranges throughout the year under changing ambient conditions.

The nursing home has the simplest HVAC concept in the project. The heating energy is supplied from September to May by district heating, in the remaining months by an electric boiler. The ambient temperature-adjusted heating energy consumption is 47 kWh/m²a. Compared to empirical values in the literature [5] this value is more than 50% lower calculated per care place. The relatively high average room temperatures during summer and the high proportion of overheating hours can be expected in a building without active cooling system. The supply air of the ventilation system is pre-cooled by
underground collectors, which results in room temperatures of about 2-3°C lower than ambient temperatures above 30 °C in summer.

The supermarket is another special use category. This building is known as second passive house supermarket in Mid-Europe. The heating energy consumption is 32.7 kWh/m²a. This value is higher than the maximum heating demand of 15 kWh/m²a for passive houses according to the Passive House Planning Package (PHPP-certification). However, the maximum heating demand in the PHPP refers to the energy balance of the building shell including ventilation, not including the extraction of heat by the refrigerated units. The internal heat sources are negative in this supermarket, which means that the heat extraction is higher than the internal heat sources (resulting in a so-called "cold market"). Therefore, heat needs constantly to be supplied to the building, otherwise the market would cool down. The key finding of this supermarket is that, unlike conventional supermarkets, it can be heated only with the waste heat of the refrigeration system and the compression cooling machine without using a technical heating system.

The hotel is the only renovated building presented in this paper. During renovation, the oil burner was extended by a geothermal heat pump. The monitoring result showed a surprisingly high share of 67% heat supplied by the oil burner for heating energy and warm water. It is interesting to discuss the reason as it represents a basic problem often found in heating systems that combine heat pumps with a second heating system: the heat pump feeds an energy store, which supplies the heating circuits as well as the hot water boiler. Thus, the energy storage must be maintained at the temperature level of the hot water boiler of 70 °C. In consequence the heat pump operates with a very high temperature difference between 2-3 °C temperature of the geothermal source in the primary circuit and 54- 59 °C in the secondary circuit. This results in a low efficiency of the heat pump (seasonal performance ratio 3.1). In order to keep the temperature of the energy storage at the required level for the hot water of 70 °C, the oil burner feeds the energy storage at certain times. During the time the oil burner operates, the heat pump is switched off. This is problem number two: switching on and off the heat pump leads to a lower efficiency of the heat pump, and the potential heat energy that could be generated is only half exploited, thus increases the oil consumption. The conclusion is that the heating and hot water circuits should be separated, in order to keep the temperature requirement of the heating energy storage low and to operate the heat pump with a lower temperature difference efficiently and constantly.

The cultural and event center is an interesting building since the heating energy is supplied by the solar collectors on the roof of the building throughout the year, besides one or two cold months in winter when heat is additionally supplied by the neighboring biomass heating plant of a hotel. Solar energy not consumed by the building is supplied to the neighboring hotel, and electricity from the PV plant also installed on the roof of the building is fed into the grid. Cooling energy is supplied by free cooling with water from a rainwater pool. The annual balance of energy generated by the building and final energy supplied to the HVAC system shows a surplus of 42% which is supplied to the neighboring hotel and the electrical grid.

The last building, a student dormitory, consists of 10 wood containers arranged in two floors around an atrium covered by a roof. Each box has 4 living units. Heating, cooling energy and ventilation is supplied by a combi heat pump. Heating energy demand is 30.1 which is higher than the maximum heating demand of 15 kWh/m²a for passive houses according to the Passive House Planning Package (PHPP-certification). Since the room temperature, especially in the atrium, has been relatively high with more than 23°C in winter time, there is a potential to optimize the parametrization of the HVAC system and the heating energy consumption could be reduced by about 50%.

4. Conclusions and recommendations
The following recommendations focus on project results related to the operation and parametrization of HVAC systems as well as on measurement errors of energy meters. These recommendations are relevant for building operators and owners as well as for planners and maintenance companies.

4.1. Heat pumps - temperature level and operation in an integrated HVAC system
Frequently heat pumps feed into a heat storage in conjunction with other heat generators (gas heating, solar thermal systems, district heating, etc.) to supply both heating energy and hot water, as observed in the monitored hotel and in office building 2. Due to the temperature requirement of the hot water up to 70 to 80 °C, a high temperature level is maintained, although low-temperature heating systems (underfloor heating, component activation, etc.) are frequently installed in energy efficient buildings. As a result, the efficiency of heat pumps decrease, thus losing their advantages as heat generators for low temperature heating. In integrated HVAC systems where other heat generators (for example district heating) operate to cover peak loads or extreme days parallel to the heat pump, heat pumps are often completely switched off. Thus, the heat pump does not reach the possible operation time, and the full potential of energy generated by the heat pump is not used. The recommendation is thus to disconnect high and low temperature storage tanks and maximize heat pump operating time.

4.2. Ventilation - air exchange and humidification
Excessive air exchange provides fresh air, but has the disadvantage that indoor air dries out without humidification, down to 15% relative humidity (45% would be ideal). The installation of humidifiers, especially of commonly used steam humidifiers, however, results in a very high power consumption, in the two investigated buildings in this project (in office building 1 and in the laboratory building) with the highest shares of final energy consumption. Fans for the supply and exhaust air are often operated with only one or two fixed volume settings and cannot be optimally regulated. The recommendation is to control the air volume based on CO2, adapted to the number of persons. Priority should be given to spray humidification instead of steam humidification, and retrofit frequency converters for adapted fan speed.

4.3. Pumping capacities
Frequently pumps in heating circuits are operated at constant power without taking into account the actual heat demand, as observed in office building 3. Also pumps for well water extraction for heating and cooling are often operated continuously. The result is an unnecessary power consumption for pump performance. The recommendation is to install pump controllers.

4.4. Measurement errors of heat energy meters
Heating and cooling energy meters are based on flow and return flow temperature sensors as well as on pulse or ultrasonic flowmeters. The pulse transducers are designed for different heat transfer flow rates, which results in data acquisition in too large steps if the choice is not optimal. This is a challenge for accurate heating and cooling energy measurement based on quarterly hour resolution. Another challenge is the class inaccuracy of temperature measurement in the range of 10%. With small temperature differences of flow and return flow temperatures of a few degrees (e.g. groundwater, heat pump), small measurement errors of a few tenth degrees already have a major impact on the heat energy measurement results. It is therefore important to pay attention to ambient influences on the temperature sensors, especially in retrofitted ultrasonic (clamp-on) heat meters which are externally applied to the heat pipe. For meters that can measure both heating and cooling energy, the differentiation between heating and cooling energy in the energy meter calculator is based on a minimum temperature difference of about 5 °C (manufacturer-specific). However, with the same temperature levels in both heating and cooling energy flow (e.g. groundwater, heat pump), the heating and cooling energy needs to be calculated manually from the flow rate, flow and return flow temperature measurements. The recommendations are: careful choice of measuring instruments, installation of sensors according to standards, avoidance of external influences by insulation, plausibility check of measured data for heating and cooling energy quantity by manual recalculation based on temperatures and flow rates in the lowest possible temporal resolution, and if necessary calculation of correction factors for the temperature measurement data in the context with other measured values.

4.5. Energy monitoring
The HVAC systems are becoming increasingly complex. Often the systems are parameterized and operated based only on general knowledge regardless of the use of the building or the interaction of the technical subsystems. The result is often unnecessary over-conditioning and energy consumption, late detection of errors, as observed in most of the buildings in this project. The recommendation is to use web-based monitoring systems with automated energy reports.

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