ENERGY PERFORMANCE COMPARISON OF VENTILATION BASED HEATING VERSUS WATER BASED HEATING SYSTEMS IN AN EFFICIENT RESIDENTIAL BUILDING

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ABSTRACT

The application of air-based heating systems as a possible approach to reduce the construction costs in highly efficient residential buildings is becoming popular. Air-based heating systems have been well-known for their usage in passive houses during the past three decades.

Available studies on such systems tend mostly to focus only on comparing exhaust air heat pump technology with conventional systems in efficient buildings. Moreover, most of the existing studies ignore the usual presence of the electrical heaters as backup. Besides, a comprehensive study and comparison between different air-based heating system concepts is still missing. In this study, four different air-based heating system concepts separated by the type of heat source of heat pump for heating and domestic hot water are defined. These systems are compared to four conventional heating system, including floor heating and direct electrical system employing dynamic annual simulations.

According to simulation results, the systems with floor heating have shown the best system efficiencies and the lowest energy demand in comparison to the other systems. The main reason for this was the lower supply temperatures of the floor heating systems. Between the air heating systems, the system equipped with an outdoor air heat pump showed a better energy performance than an exhaust air system. The main reason for this could be attributed to the power limitation of exhaust air heat pump systems.

ABBREVIATION

CH	Central Heating
DHW	Domestic Hot Water
EHA	Exhaust Air
ETA	Extract Air
HRV	Heat Recovery Ventilation
SUP	Supply Air
ODA	Outdoor Air

STATE OF THE ART

Efficient and airtight buildings are often equipped with Heat Recovery Ventilation (HRV) systems to reduce the ventilation heat losses and to ensure high indoor air quality **[1]**. Due to rising construction costs, a possible approach to limit these costs is to distribute the heat via air instead of a second water-based distribution system, such as floor heating or radiators. Several publications have addressed the topic of heating systems in efficient buildings in different terms. In the study of Schnieders et al. **[2]** it was shown that a passive house could be heated actually using hygienically required minimum air change rates. Exhaust air heat pumps (EHA-HPs) are well known as one of the main heating concepts in passive houses (Figure 1). An EHA-HP is a combination of a heat recovery ventilation unit with usually a small-sized air-to-air heat pump. In winter conditions the enthalpy of the exhaust air leaving the HRV unit is higher than the enthalpy of the outdoor air due to its higher moisture content and temperature. This source is made use of with EHA-HPs **[3]**.

In the study of Luzern et al. **[4]** the air-based heating system was compared to a conventional heating system (water-based) based on interviews with specialist planners and passive house users. According to this study, although air-based heating still remaining a controversial topic, users are satisfied in the case of professional planning and implementation. However, higher airflow rates compared to normal ventilation rates should be avoided unless several comfort problems such as dry air and possible ventilation noise in the system could occur.

A comprehensive study on heating via air was done in Austria as a part of the project "Home of future" by Rojas et al. In this study, air heating was compared to water-based heating systems based on interviews, measurements and dynamic simulations. However, this study has focused more on the feasibility of this system and not on the comparison of heating sources. According to this study, heating efficient buildings via air could fulfill the highest comfort class as well as water-based systems for living rooms. However, for the common problem of warm bedrooms, a solution should be found **[5]**.

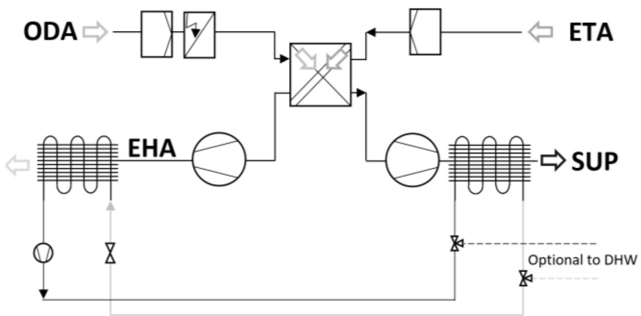


Figure 1: Schematic illustration of an integrated EHA HP in a HRV unit

An extensive theoretical and experimental investigation about exhaust air heat pumps (also known as compact systems) was done in a dissertation by Buehring **[6]**. Exhaust air heat pumps used in common single-family homes normally have a limited maximum power of 1 kW to 1.8 kW (depending on air volume rates) and are generally appropriate for passive houses.

A comprehensive practical comparison of compact systems is done by Haessig Sustech **[7]** in Switzerland. In this practical study different energy and comfort measurements were taken in eight multiple family apartments with MINERGIE-P[1] standard for over a year. This study confirms again that in all measured objects the room temperatures and indoor air quality were in a "very pleasant range". Nevertheless, the air humidity occasionally dropped under the minimal supposed value. Moreover, for only half of the eight apartments the measured heating for heating and hot water were below the maximum allowed value according to regulation requirements **[7]**.

In Gustafsson et al. **[8]**, four different heating system variants including an EHA-HP, are compared by dynamic simulations. The EHA-HP is introduced as the "more favorable" system in colder climates for buildings with low heating demand due to its significant potential for heat recovery. A similar research study by Schibuola et al. **[9]** has compared three air heat recovery systems with high air volume rates (for classrooms). It has shown that an EHA-HP could save up to 48% primary energy consumption in comparison to a normal HRV System. However, Paiho et al. **[10]** have shown, that the combination of an air water heat pump and a normal HRV system has a lower life cycle cost than an EHA-HP over 25 years.

Besides compact systems, another possible air based heating concept is combining an outside air source heat pump with HRV unit (Figure 2). This concept allows higher heat pump power and application of such a unit not only in passive houses but also in other efficient buildings with higher heat demands.

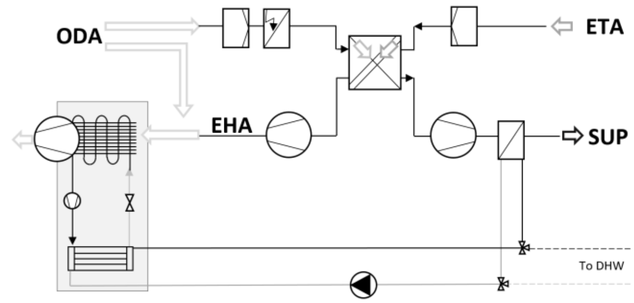


Figure 2: Schematic illustration of combing ODA HP with HRV, second air heating system concept

OBJECTIVES AND APPROACH

The main aim of this study is to compare different air-based heating system concepts with each other as well as conventional heating systems in terms of system efficiency. Therefore, eight different system variants were defined: Four different air-based heating concepts and four conventional systems. The system variants should fulfill the main needs of an efficient residential building, namely: heating demand, domestic hot water demand and heat recovery ventilation.

All selected systems are equipped with heat recovery ventilation (either central or decentral systems). Two air-based heating systems are designed using the compact system (system C & D) and the other two using the second system concept. All the systems except systems D and H are equipped with a 260-liter warm water storage with the same parameters and the same loading strategy.

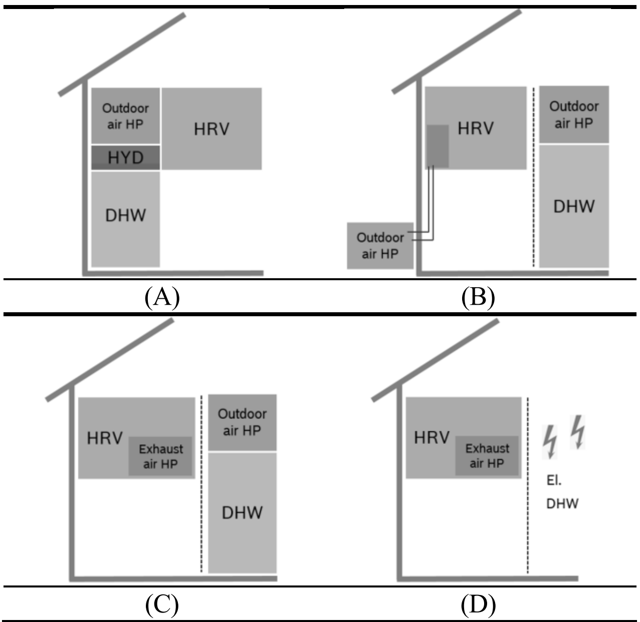
Selected air-based heating systems:

A. ODA/W heat pump for CH and DHW
B. ODA/W heat pump for CH and DHW heat pump
C. EHA/A heat pump for CH and DHW heat pump
D. EHA/A heat pump for CH and electric DHW

[1] A building standard in Switzerland; heating and hot water primary energy demand must be under 30 kWh/m²a

In all air-based heating systems, electric heaters are installed in extract air zones. The maximum power of EHA heat pump was assumed 1.5 kW. That is why in systems C and D, due to this limited power an electric backup is added to the central system to ensure meeting the heating energy demand. In each one of systems C and D a conventional DHW heat pump is included, which provides hot water demand independent from room heating.

Table 1: Schematic illustrations of the air-based heating systems



Reference heating systems with conventional heat distribution:

E. Floor heating with ODA/W heat pump for CH and DHW and central HRV
F. Floor heating with ODA/W heat pump for CH and DHW and decentral HRV
G. Direct electrical room heating and DHW heat pump and decentral HRV
H. Direct electrical room heating and electrical DHW and decentral HRV

Both systems E and F were equipped with a single outdoor air heat pump for CH and DHW. The heating system in both was a floor heating system with a conventional control strategy. In both systems, DHW storage loading had priority over heating.

The only difference between them is the HRV system. System E includes a central HRV unit while system F is equipped with decentral HRV units, in both HRV units an air exchange rate of 0.4 1/h was set. Systems G and H represent the low investment cost system variants for heating, ventilation and hot water providing. Both systems include decentral HRV units with the same air exchange rates similar to other systems.

Building category and heating power demand:

Figure 3 indicates the specified U-values of external walls, ground, rooftop and windows of the selected building. The heating load of the selected building (184 m² in Stuttgart, three persons household) is calculated with 19 W/m².

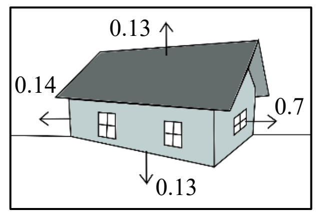


Figure 3: U-Values of selected building in [W/m²K]

In Table 2 the different zones of the building are described and the floor area of each zone is stated.

Table 2: Specifications of the modelled building

Zone number	Zone description	Heated floor area [m^2]
Zone 1	Living/Dining Room	46
Zone 2	Kitchen/Bath/Lobby	46
Zone 3	Children's rooms	56
Zone 4	Bedroom	36
Zone 5	Attic	(unheated)

SIMULATION

The simulations in this work were carried out using Building Technology Simulation Library (BTSL); a Bosch Thermotechnology internal Simulink library. This library is similar to TRNSYS software, it contains different blocks for dynamic simulation of the different parts of heating, venting and hot water providing in a building. From models of basic components like valves and pipes to more complicated models such as heat pumps. Every single model was validated against measurement data. There were also different blocks to simulate the boundary conditions, such as different user behaviors and weather data. Figure 4 shows a sample of a reference model in BTSL.

For simulation of the building behavior in BTSL the TRNSYS type 56 is used. Since both TRNSYS and MATLAB components can be generated as Windows DLL files, the integration of TRNSYS components in

MATLAB or vice versa is feasible. The suggested integration method by Riederer et al. **[11]** is implemented to adapt the TRNSYS Type 56 to the BTSL Simulink library. Type 56 models the dynamic thermal behavior of the building using multi-zone building modelling approach. In this modelling approach, every zone modeled with one air node, which represented the thermal capacity of the zone air volume and its belongings **[12]**.

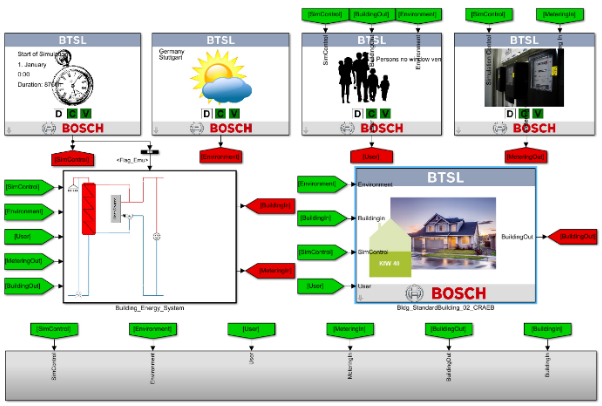


Figure 4: Sample of BTSL environment

Controls:

The *floor-heating system* controller was based on a conventional control strategy, a combination of a weather compensation controller with the influence of room temperature on the heating curves. It was assumed that the room temperature sensor was installed in the corridor of the building. The set point for the heating systems was 21 °C, without any nighttime reductions in temperatures.

In the systems with *direct electric heaters*, in every zone of the building electric heaters were implemented. A simple hysteresis controller was employed with upper and lower dead-bands of 1 K. The set point for the heating was 21 °C, without any nighttime reductions.

For the *air-based heating systems,* a control strategy was developed based on two simple principles. Firstly, the air volume rates had to be kept as low as possible, to reduce problems with low air humidity in winter and keep the air distribution system as simple as possible. Moreover, the maximum supply temperature should also not exceed 55 °C to avoid dust burning or smoldering. This means in the heat load case (19 W/m²) for the three supply zones (135 m²) the needed power of around 2.5 kW should be met through an air volume rate[2] of around 220 m³/h (0.48 1/h). If the heat demand decreased, firstly the air volume rates would be reduced until 0.4 1/h and secondly the supply temperatures both linearly.

Heat pump model:

The used heat pump model in the current study was based on static characteristic curves of a heat pump (black box model). The Model stationary calculates the power consumption of the compressor and the heating power of the HP depending on the evaporator and condenser temperature through algebraic equations, which were derived from measurement data of an outside air HP. Table 3 shows the performance of the implemented heat pump.

In this study due to the lack of measurement data of EHA HPs, the ODA HP static curves were implemented for this type of heat pump as well. This simplification may influence the results obtained. Further data collection on EHA heat pumps was required to determine exactly the performance of these type of heat pumps.

Table 3: COP of the implemented heat pump at different evaporation and condensation temperatures

Condensation \ Evaporation	-2 °C	2 °C	7 °C
35 °C	4.6	4.8	5.3
45 °C	3.7	3.9	4.2
55 °C	3.0	3.1	3.3

RESULTS AND DISCUSSION

The heat pump performance is highly dependent on its sink and source temperatures. Regarding this, it is interesting to compare firstly the performance of heat pumps with the floor heating system and the air based heating system in detail (see Table 4). Both HPs showed almost the same thermal output (same boundary conditions). However, the average sink temperature for the air-based heating system was nearly 50% higher than for a floor heating system. This led to approximately 20% lower heat pump annual COP.

It is worth noting that in both systems the DHW loading performance of HP and the storage loading behavior were the same.

[2] 2500 W ~ 220 m³/h * 1 h/3600 s * 1.2 kg/m³ * 1000 J/kg.K * (55-21) K (assumption; inside: 21°C)

Table 4: Comparison of heat pumps in floor heating system and air-based heating system

System	Unit	System A	System E
Heat pump power	[kW]	5	5
Thermal output	[kWh/a]	6728	6711
Sink temperature (Annual average)	[°C]	44.8	29.0
Source temperature (Annual average)	[°C]	3.7	3.0
Annual COP	[-]	2.7	3.3

Figure 5 shows the specific yearly electrical energy demands of systems. "CH" represents the needed energy for room heating. In the first six systems, it shows the needed electrical energy for the heat pump and in systems G and H it shows the needed energy for the electrical heaters. The "DHW" proportion shows the needed energy for domestic hot water.

As expected, the systems with floor heating (system E & F) showed the best system performances and the lowest energy demand in comparison to others. The main reason for this may have been the lower supply temperatures of the floor heating system. Furthermore, no direct electrical heaters in the systems with floor heating were necessary. The best air-based heating system (system A) has shown around 33% higher electrical energy demand compared to the best floor heating system (system E).

Between floor heating systems, the system with the central HRV unit has shown the best system performance. System F has shown 7% higher electrical energy demand, due to the lower heat recovery performance of decentralized ventilation units.

As already mentioned, in the air-based heating systems, due to the absence of heated supply air in the extract rooms, the installation of backup heaters (in Figure 5 "El. heater bath") in extract rooms was necessary. Besides, in the systems with exhaust air heat pump (C & D) an auxiliary heater after the condenser of the heat pump was installed (in Figure 5 "SUP el. heater") to meet the heating energy demands bigger than 1.5 kW.

Between air-based heating system concepts, system A with a single ODA heat pump has shown the best performance. By employing an ODA HP instead of the exhaust air heat pumps (system C) around 22% reduction in the electrical energy demand of the system could be achieved. The main reason for this could be attributed to the limited power of EHA HP and the lower performance of DHW HP. It can be said that among the two compared air-based heating concepts, the one with the more powerful heat pump has shown better performance.

In all the systems, except for the two all-electric systems (G & H), the DHW heat demand showed the main share proportion was bigger than others and had a significant impact on the system performance.

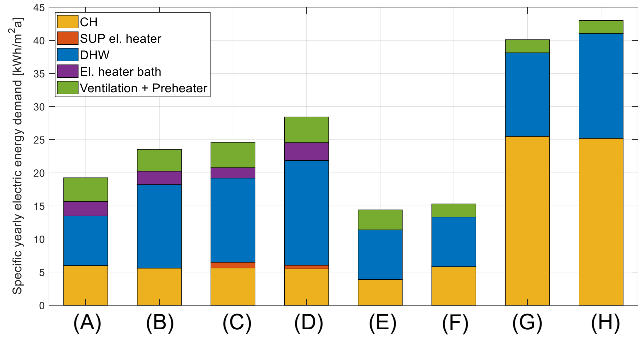


Figure 5: Simulated specific yearly electrical energy demands of the eight selected systems

CONCLUSIONS

The main findings can be summarized as follows:

- Due to lower supply temperatures of the floor heating system, the water-based heating systems have shown better system efficiencies than other heating systems.
- The best air-based heating system (system A) has shown around 33% higher electrical energy demand compared to the best floor heating system (system E)
- Between the air heating systems, the ones equipped with an outdoor air heat pump (system A & B) showed a better performance than with exhaust air system (system C & D).
- Using the air-based heating system with a more powerful heat pump, 22% reduction in the electrical energy demand of the system compared to EHA HP could be achieved.

KEYWORDS
Heat recovery ventilation, Air based heating, Floor heating, Heat pump, Efficient buildings, Electrical energy demand

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