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Energy Efficient Renovation with Decentral Compact Heat Pumps

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Abstract

Within the framework of the Austrian project SaLüH! (FFG), high energy efficient and cost-effective concepts with decentral small scale heat pumps for heating and domestic hot water preparation for the renovation of small dwellings in multi-story buildings are developed and investigated. Experience shows that for multi-family houses, a complete renovation including conversion to central heating and domestic hot water (DHW) systems is hardly possible. Measures inside the inhibited flats are often associated with number of complications (technical, legal, financial). Thus the centralization of ventilation, heating and DHW is often dropped. Unfortunately, energy and cost efficient decentralized (and less invasive) solutions are also not available. Therefore, new innovative concepts for heating and ventilation are investigated. Very compact heat pumps are developed in such a way that it will be possible to integrate these units into the window parapet or into a prefabricated timber façade. The wall integration has a high potential in pre-fabrication and leads to an optimal solution for small apartments. The target is to create a complete renovation package with a decentralized (apartment size) exhaust-air HP for ventilation and heating installed in the kitchen and a DHW-HP in the bathroom. The solutions aim to be cost effective, involving components and technologies with high efficiency and minimum noise emissions enabling least disruptive renovation. The performance of the investigated systems is rather comparable, hence other aspects such as handling, noise, maintenance, etc. might be more relevant.

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Keywords: Deep renovation; Compact heat pump; mechanical ventilation with heat recovery; exhaust air heat pump; façade integration

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1. Introduction and Motivation

Old, poor energy performing buildings dominate the existing building stock. The target of reducing energy and CO_2 emissions in the building sector can only be achieved with deep renovation - energy refurbishment has a high potential for energy savings and emission reduction. Technologies and products for deep renovation of the envelope (ATICS, windows) are available since many years and deep energy renovation of multi-family houses to e.g. the EnerPHit [1, 2] standard can be considered mature. However, a complete renovation of a multi-family house including conversion to central heating and domestic hot water (DHW) systems is hardly possible in the majority of cases. There are a number of technical, legal and/or financial complications with MVHR and HVAC installation inside the flats. Hence, renovation to centralized system for ventilation, heating and DHW is often not feasible. An all-electric solution (electric heater [5], electric DHW preparation) with correspondingly poor performance is frequently the solution in case of a renovation of multi-family houses. The objective of this work is to present an efficient and financially attractive alternative.

2. Central vs. Decentral Renovation

In spite of the relative high storage and distribution losses and higher installation costs of the distribution system, the central solution, i.e. one system per building (or staircase) would be always the first choice if possible. The lower investment for the equipment, the better performance of a central system and the lower maintenance costs would normally not favor for decentral (i.e. flat-wise) solutions, see Fig. 1. However, experience shows that in a renovation of multi-family houses a complete renovation including conversion to central heating and DHW systems is hardly possible. Frequently, the small flats have very inhomogeneous mix of heating systems (gas, oil, electrical or wood boilers, see e.g. EU-project Sinfonia [9]) and they are only renovated, when they are empty (after tenants left). This sacrifices the effort to the comprehensive renovation to central heat production, e.g. with district heating, biomass boilers or GW-HP and also solar thermal.

The alternative can be decentralized systems with all benefits such as reliable control, less costly and invasive installation, easy maintenance and no billing. Indeed, for buildings with small flats such affordable and space efficient decentralized solution is currently not available on the market but are being developed.

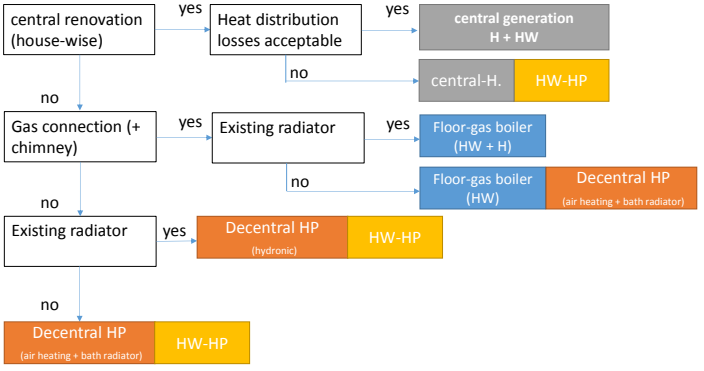
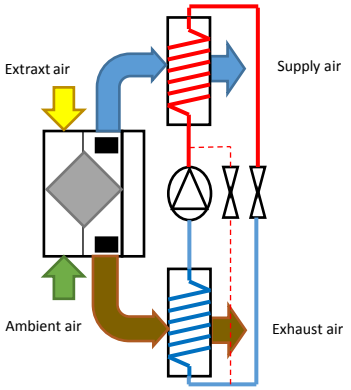


Fig. 1.: Decision scheme for central vs. decentral solution (H: heating, HW: hot water, HP: heat pump)

3. Façade Integration and Compact Evaporator Design

3.1. The Micro-HP (EU-Project iNSPiRe)

With the low heating demand and heating power of a Passive or EnerPHit house [1, 2], application of small capacity and thus more compact solutions is possible. Recently, concepts for compact heat pumps are developed that allow for better integration into flats or for façade integration. Several concepts are subject of investigation, e.g. within the EU-project iNSPiRe (fp7) [6,7] or the Austrian project SaLüH! (FFG). Figure 2 shows an example of a so-called micro-heat pump [6,7], which was tested at UIBK test site and is currently monitored in a demo building in Ludwigsburg, Germany (see [8] for more details and monitoring results).



MVHR with exhaust air heat pump (with hot gas bypass for deicing)



Functional Model and …



…iNSPiRe Demo-Building, Ludwigsburg (WB-L)

Fig. 2.: Compact Heat pumps for Façade integration, Micro-heat pump, EU project iNSPiRe [6,7]

3.2. Compact outdoor unit - background and motivation

Wall mounted outdoor evaporator/condenser units from refrigerant split systems (mini-split) are produced and operated in large quantities. The direct air flow is obtained by means of large axial ventilators. In order to reduce sound transmission these units are wall mounted using sound decoupled consoles. The flow usually enters on the rear side of the unit through a gap and is sucked by the axial ventilator through the air-refrigerant heat exchanger. Usually a 30 cm gap at the rear side and at least 200 cm free space at the front side are recommended by the manufacturer to guarantee low pressure losses and sufficient performance. Sound emissions of these systems are usually not acceptable in particular in case of open windows. The attractiveness of these systems is poor and the acceptance of such a system by architects, building owners and tenants is limited.

Both, from the point of view of sound emissions and with regard to design and quality of the external façade an outdoor unit integrated into the façade and invisible or covered is the better choice. Air inlet and outlet could be limited to relative small slits. Generally, higher pressure losses have to be accepted in case of façade integration in particular if space is tight.

However, with the reduced heating power of a Passive House also the air flow rate can be reduced and façade integration is an interesting option. A design based on existing axial ventilator is not necessarily the optimal solution for façade integration. Basically, three ventilator types exist: axial, radial, diagonal (mixed flow). Acc. to the CORDIER-Diagram, which gives the optimal aerodynamic range where the different types run with optimal efficiency, axial ventilators are optimal with respect to low pressure losses but high volume flows. In contrast, radial ventilators are favorable in case of low volume flows and high pressure differences.

3.3. Concepts for compact façade integrated evaporators

The front design should be attractive and not influencing the façade appearance. At the same time sufficient inlet and outlet volume flow should be guaranteed with acceptable pressure loss. Three different concepts with two variants of façade elements are studied, either shadow gap or with timber grill, see Fig. 6.

Concept 1: axial fan: Compared to the standard design of the outdoor unit of a split system, if integrated into the façade, the depth of the unit should be decreased and space for the inlet air at the rear must be provided. This space can be used for absorbing sound. By means of radial symmetric design, see Fig. 6 top, left, a homogeneous air flow through the evaporator can be guaranteed.

Concept 2 radial fan: In order to achieve sufficiently high air flow rates with radial ventilators two (or more) can be installed in parallel. A possible solution with shadow gap for inlet and outlet air is shown in Fig. 6, right.

Concept 3 cross-flow: Less deep and thus possibly easier to realize is the concept with cross-flow fan. With such a design the flow can be equally distributed through the evaporator. Disadvantage of this concept is the more difficult access and thus higher maintenance effort.

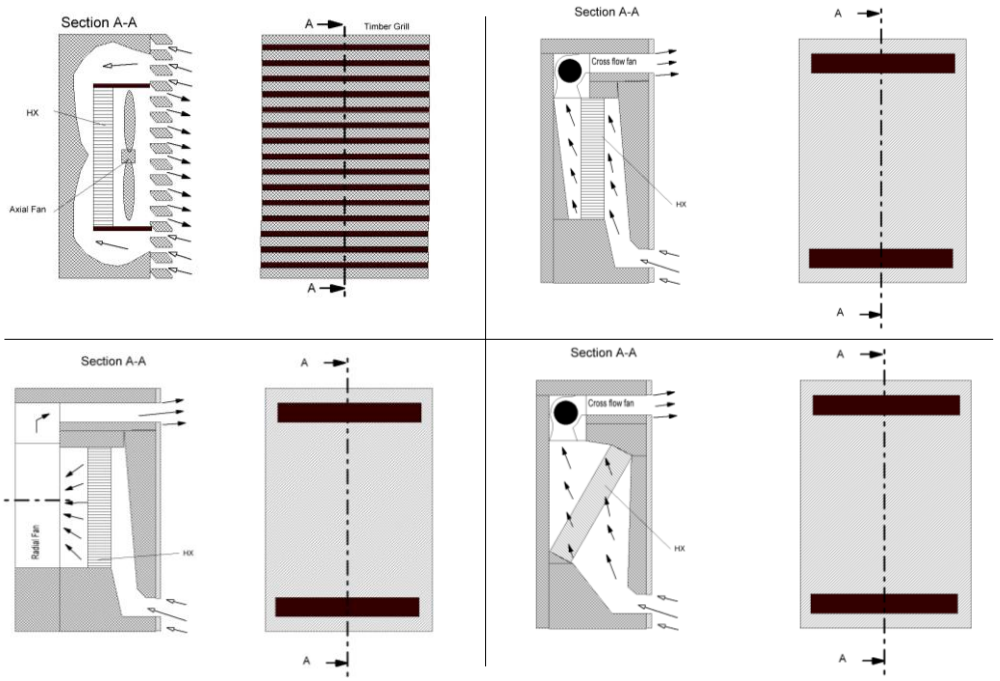


Fig. 6.: (top, left) Façade integrated evaporator with axial ventilator with grill for inlet and outlet air and (bottom, left) with one or more radial ventilators, shadow gap for inlet and outlet air and (top, right) with cross-flow ventilator and shadow gap for inlet and outlet air (bottom, right) variant with sloped evaporator.

3.4. Qualitative comparison of the concepts

For the final decision several aspects have to be considered. In addition to the technical properties (such as electric efficiency, homogeneous flow through the evaporator, sound emissions) also maintenance (cleaning) and esthetical as well as user specific requirements such as influence on the façade appearance have to be considered. Most relevant technical and non-technical aspects are summarized in Table 1 for the three variants.

Table 1: Summary and evaluation of the three concepts (SFP: specific fan power, ++ good + fair - poor -- negative)

Concept No.	Fan type	SFP	Sound emissions	Design, Façade appearance	Construction depth	Investment costs	Maintenance & repair
1	Axial	++	--	--	++	++	+
2	Radial	+	++	++	-	-	-
3	Cross-flow	+	++	++	+	+	-

A detailed flow and pressure loss calculation and geometry optimization is necessary for a final decision of one of the three variants. At first sight the variant with the cross-flow fan is the most promising one. All variants are designed with a sucking ventilator which guarantees homogeneous flow through the lamellas of the heat exchanger. However, the ventilator losses are dissipated and cannot be used. Independent of the choice for one of the suggested variants, the problem of sound emission of the ventilator has to be solved by floating bearing.

3.5. Advantages and challenges of façade integration

Compact systems allow for façade integration and thus minimal space use. Façade integration offers several advantages

- High degree of prefabrication, installation time can be kept as short as possible;
- No additional space for MVHR, condenser and/or evaporator is required;
- Cold ducts (i.e. ambient air and exhaust air of MHVR) are short and outside the thermal envelope;
- Minimum installation inside the flat and as little as possible numbers of break-through;
- Minimum disruptive renovation: renovations with minimum intervention are enabled (minimum disturbance of tenants).

However, façade integration of active components is challenging. Several aspects have to be considered and problems in the following fields have to be solved: structural aspects (statics); building physics (thermal bridge, condensation risk, mold growth, air- and structure-borne sound; fire protection; energy performance (COP of MVHR & micro-HP considering thermal losses). Furthermore, there are some practical challenges:

- Condensate removal (MVHR and evaporator) and control of deicing (evaporator);
- Access for maintenance (in particular filter change) and repair.

4. Compact HP Concepts for Decentral Application

Several concepts for compact heat pumps for decentral heating and suitable for façade integration are available and are investigated and compared with respect to performance in this study

- Refrigerant split unit (mini-split)
- Brine cycle air-to-water or air-to-air HP
- Exhaust air heat pump in combination with MVHR with or without moisture recovery, with or without additional ambient air and recirculated air
- Extract air heat pump (without MVHR)

Furthermore, low capacity split or brine cycle DHW heat pumps (boiler HP) are considered as an interesting option for renovation. Return flow heat pumps, which use the return flow of the floor heating as source are usually not an option for renovation. DHW heat pumps are also investigated within the SaLüH! project, but are not further discussed in this paper. The investigated HP concepts are shortly introduced in the following sections:

4.1. Split HP

A single- or mini-split system typically supplies conditioned air to a single room and optionally to a few adjacent rooms. Multi-split systems or so-called ductless systems allow suppling several zones with conditioned air using only one outdoor unit. Mini-split systems typically produce between 2.5 kW and 12 kW. In a variable refrigerant flow (VRF) system the refrigerant is conditioned by a single outdoor unit, and is circulated within the building to multiple fan-coil units (FCUs). The advantage of being able to simultaneously heat and cool with a VRF system is normally not required in residential buildings and extra investment costs are normally not justified.

Advantages of these ductless systems include smaller size and flexibility for zoning (i.e. heating and cooling individual rooms). The primary disadvantage is their cost which is usually about 30% more than central systems. Another disadvantage of multi-split units is the need of relatively high refrigerant fill.

Split units have a long tradition in Asia and are widely used in south Europe for cooling, but there is not yet a culture for using refrigerant split systems in central Europe. Hence, a further possible disadvantage is that in some countries there is a lack of experience and skilled installers might not be available. This fact can further increase installation costs.

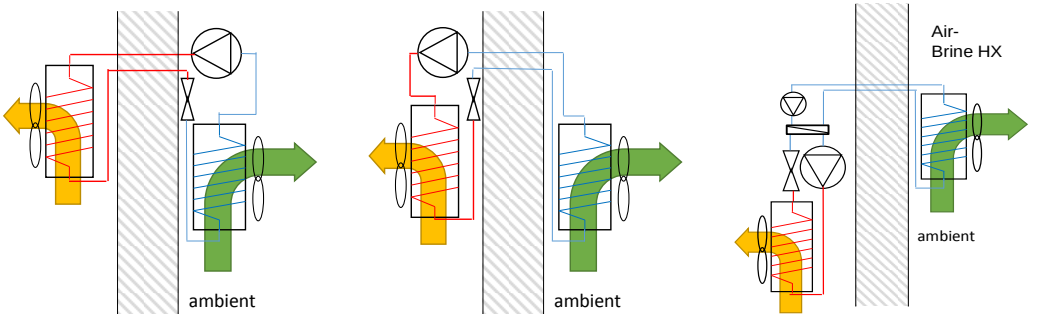
In modern systems speed controlled compressors are used to drive variable refrigerant flow in the refrigerant cycle to control heating or cooling output. The additional electronics and system hardware adds cost to the equipment installation but can result in substantial savings in operating costs. Eliminating stop-start cycles increases efficiency and can be beneficial for the life-time of the system.

A challenge when designing the heating and/or cooling of a building with one or two indoor units (either as two single split or as a small multi-split) is to guarantee sufficient distribution of air to all zones in order to transport the required energy. Fully individual zone control would require an indoor unit in each zone with correspondingly high investment costs. The challenge is to find a good compromise between cost-effectiveness, performance and sufficient thermal comfort. Careful planning is required to guarantee sufficient distribution of heat (and cold) inside the flat/building. Under nominal operation conditions (nominal volume flow of inside unit) sound emissions are usually in an unacceptable level. In the so-called silent mode with reduced volume flow of e.g. 175 m³/h sound emissions are acceptable however, heating capacity is reduced and efficiency decreases.

As a variant to the standard configuration, where the compressor is integrated into the outside unit (see Fig. 3, left), a split unit with inside compressor installation is investigated (Fig. 3 center). The performance of the system (in heating operation) can be improved, however, sound emission protection has to be carefully solved.

4.2. Brine Cycle

The most widely used refrigerants for split units and low capacity heat pumps are R134a, R407A and R410A (R22 phased out 2010). Alternative refrigerants should be considered for environmental reasons. There are however some limits. CO_2 (R-744) is because of the high pressure requirements usually not economic for low capacity systems. In case of flammable refrigerants such as R290 the refrigerant mass is limited to 150 g in case of indoor installation. Split units usually use much higher refrigerant mass (typically between 200 and 800 g/kW). Keeping the refrigerant mass below the maximum allowed limit is possible with a compact HP design and a brine cycle (so-called brine bus instead of refrigerant split), see Fig. 4 right hand side. Brine cycle HP usually feature lower performance because of the additional exergy loss in the additional heat exchanger.



Heating split unit (refrigerant split/mini-split), compressor outside (as usual)

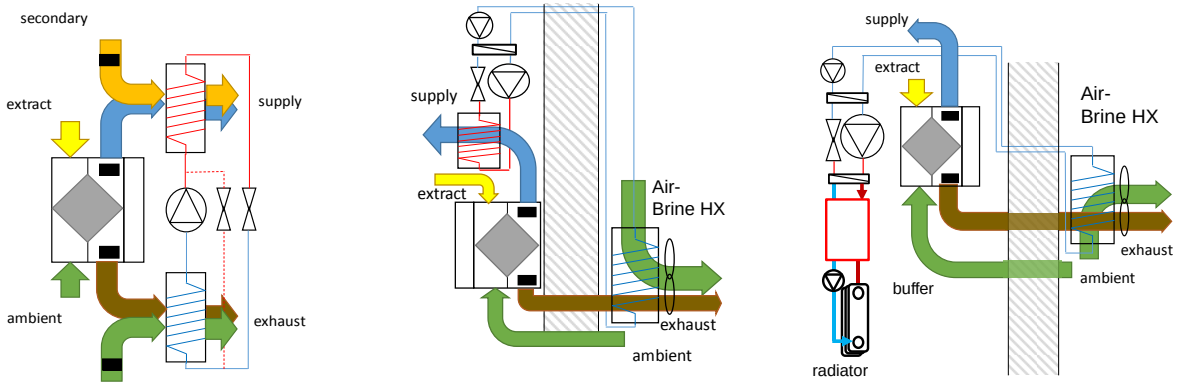
Heating split unit, compressor inside for better heating efficiency

Air-to-water brine cycle HP

Fig. 3: Simplified scheme of "classic" split unit design with compressor outside and improved design for heating with compressor inside.

4.3. Exhaust-Air HP

Heating of a house with very low heating demand and very low heat load can be done with a Passive House compact heat pump with air heating. An exhaust air heat pump (EAHP) extracts heat from the exhaust air of a building and transfers the heat typically to the supply air, see Fig. 4 left hand side. But also variants with hydronic heating system (floor heating, radiators) and DHW preparation exist. This type of heat pump works in combination with a MVHR and its output power is coupled to the hygienic air flow rate (e.g. 120 m³/h). The inside air temperature is approximately 20 to 22 °C all over the heating period and the MVHR together with the preheater damps the influence of the ambient temperature. The performance of the heat pump is not varying much with the seasons and outdoor temperature. However, the output power depends on the ambient temperature. Newer versions take in additional ambient air to increase the power, usually with an inverter controlled compressor. Heating power of the heat pump can vary from about 1 kW to 6 kW. So-called compact units that cover MVHR, heating and DHW preparation have been proposed already about 20 years ago and different solutions are on the market. However, because of size and sound emissions they are typically not the first choice in multi-family homes and in renovations. A review on compact units, boiler-HP and split units can be found in [10]. See [3,4] for details on supply air heating.



MVHR with exhaust air heat pump with secondary air and ambient air

Air-to-Air Brine Cycle HP in combination with MVHR

Air-to-Air Brine Cycle HP in combination with MVHR and hydronic circuit

Fig. 4: Simplified schemes of different concepts for compact heat pumps

Air-to-air membrane energy recovery ventilation (ERV) is increasingly discussed as a solution in residential buildings for reducing the energy consumed for heating and cooling as well as for improving the indoor air quality by dehumidifying or humidifying the ventilation air. Membrane based so-called enthalpy exchangers allow for simultaneous heat and moisture transfer through a selectively permeable membrane. In cold climates, the problem of dry air in winter may be reduced and frosting may be prevented or at least reduced when the exhaust air is sufficiently dry after the moisture recovery. However, there is the disadvantage of significantly higher investment costs for a membrane ERV compared to a sensible ERV.

Very promising can be a combination of membrane ERV and exhaust air heat pump due to the potential to operate with higher flow rates, the performance of the heat pump can be improved in both, heating and cooling mode. In case of supply-air heating, the performance of the heat pump depends on both, the exhaust air temperature/enthalpy and supply air temperature, which are both influenced by the effectiveness of the ERV. The effectiveness depends on the size (i.e. area) of the heat exchanger and on the membrane properties and is in high-end MVHRs between 80 and 87 % with regard to the temperature effectiveness (η_T) and in the range of below 70 % up to 77 % with regard to the humidity ratio (ω). Membrane HX have reduced temperature effectiveness. Furthermore, there is an influence from the volume flow (stronger on η_ω than on η_T) and of the boundary conditions (i.e. indoor RH). With moisture recovery the limit for pre-heating the cold ambient air for frost protection can be decreased from typically -2 °C to -8 °C. Electricity consumption can be significantly reduced.

$$\eta_T = \frac{\vartheta_{\sup} - \vartheta_{amb}}{\vartheta_{ext} - \vartheta_{amb}}, \quad \eta_\omega = \frac{\omega_{\sup} - \omega_{amb}}{\omega_{ext} - \omega_{amb}} \tag{1}$$

4.4. Extract-Air Heat Pumps

With an extract air heat pump the extract air is directly used as source for the evaporator. Such a system works without MVHR. It requires at least mechanical exhaust air, while mechanical supply air is optional. The unit is extracting heat from the air that needs to be changed (hygienic air exchange rate). Air leaving the building when the HP is in operation can easily be as low as -15 °C (evaporator outlet air). For most extract air heat pumps there will be a relatively low output for heating and DHW preparation of some 1 KW. An electric post-heater is usually required. The supply air is usually not heated. Thus, the occasionally very cold air can lead to discomfort (cold air down draught).

5. Performance Simulation Study

The different HP concepts are compared by means of steady-state simulation with a simplified physical HP model (developed in Matlab, CoolProp). The simulations are performed for the following boundary conditions and the parameters listed in Table 2:

- Ambient air temperature -8°C; Ambient air relative humidity 80 %
- Indoor air temperature +22 °C; Indoor air relative humidity 30 %
- Pre-heating of ambient air to 0 °C (no pre-heating in case of moisture recovery)
- Max. supply air temperature +52 °C

The assumptions are that for all concepts the same compressor is used with an electric efficiency of 80 % and a typical isentropic efficiency as a function of the compression ratio as indicated in Table 2. By means of inverse simulation, for each concept the electric power of the compressor is determined such that the condenser power is equal for all concepts. The performance of the concepts is compared. The reference case is an electric supply air heating. The maximum possible heating power (condenser power) depends on the volume flow and is shown in Table 3. The ventilation enthalpy losses (extract – supply) depend strongly on the indoor rel. humidity (30 % is

assumed here, 50 % and 40 % rel. humidity as variant should be further investigated in future work). The simulated performances of the different HP concepts are summarized in Table 4. The COP is calculated as shown in equations (2) to (7).

Remark: The simplified physical models for the split unit and the exhaust air HP used in this study have been validated against measured data (Toshiba split unit, Micro-HP – iNSPiRe, see [6,7]). In this study some simplifications were introduced. In a further step, the models will be refined and calibrated against measured data. In particular, the assumption of the effectiveness of the heat exchanger (evaporator with mixed exhaust air and ambient air and condenser with mixed supply air and recirculated air) are strongly influenced by their design and the models have to be calibrated against measured data.

Table 2: Parameter for the simplified physical HP model

Parameter	Formula	Value	Unit	Remark
Specific Fan Power	SFP	0.2	Wh/m³	MVHR, per fan;
		0.06	Wh/m³	Split unit evaporator and condenser fan
Temperature effectiveness	η_T	0.85	-	at 120 m³/h, at 30 %
Moisture effectiveness	η_w	0.62	-	at 120 m³/h, at 30 %
Pre-heating	ϑ_{lim}	0	°C	in case w\o moisture recovery (typically -8 °C w\)
Refrigerant	R	R134a	-	R290 only possible with brine cycle HP
Sub-cooling	ΔT_{sub}	5	K	Condenser
Super-heating	ΔT_{sup}	5	K	Evaporator
Temperature difference evaporator	ΔT_{evap}	3	K	Between evaporation and source outlet temperature
Temperature difference condenser	ΔT_{cond}	3	K	Pinch point temperature difference
Brine temperature difference	ΔT_{brine}	5	K	Difference between brine inlet and outlet
Temperature difference brine HX	$\Delta T_{brine-air}$	5	K	Difference between brine air and brine (inlet)
Pump power	P	10	W	Brine circulation pump
Electric efficiency	η_{el}	0.85	-	Compressor
Isentropic efficiency	η_{is}	f(τ)	-	max 0.82 at τ = 4; 0.75 at τ = 8 and τ = 2

Table 3: Reference heating power (air heating from supply air temperature to max. air temperature of 52 °C) and ventilation losses depending on the hygienic volume flow;

Hyg. volume flow / [m³/h]	dry effectiveness MVHR η_T	Heating Power / [W]	Supply air temperature / [°C]	Exhaust air temperature / [°C]	Enthalpy Difference supply – extract / [W]
90	0.885	1076	19.5	2.5	85
120	0.852	1466	18.7	3.3	145
150	0.822	1869	18.1	3.9	218

MVHR:

$$COP_{MVHR} = \frac{\dot{Q}_{MVHR}}{P_{el,fan}} \quad (2)$$

$$COP_{MVHR,sys} = \frac{\dot{Q}_{MVHR} + \dot{Q}_{pre-heat}}{P_{el,fan} + \dot{Q}_{pre-heat}} \quad (3)$$

Split-HP:

$$COP_{HP} = \frac{\dot{Q}_{cond}}{P_{el,fan,inside} + P_{el,comp} + P_{el,fan,outside}} \quad (4)$$

$$COP_{sys} = \frac{\dot{Q}_{cond} + \dot{Q}_{MVHR} + \dot{Q}_{pre-heat}}{P_{el,fan,inside} + P_{el,comp} + P_{el,fan,outside} + \dot{Q}_{pre-heat}} \quad (5)$$

Exhaust air HP:

$$COP_{HP} = \frac{\dot{Q}_{cond}}{P_{el,comp}} \quad (6)$$

$$COP_{SYS} = \frac{\dot{Q}_{cond} + \dot{Q}_{MVHR} + \dot{Q}_{pre-heat} + \dot{Q}_{post-heat}}{P_{el,fan} + P_{el,comp} + \dot{Q}_{pre-heat} + \dot{Q}_{post-heat}} \quad (7)$$

The performance of the MVHR is shown as reference, but cannot directly compared with the COP of the HPs, because the transferred heat is different (at 120 m³/h: HR: 826 W; HR + pre-heat: 1178; MR:1127 W). It is obvious that the moisture recovery has significant influence when defrosting is required. But also the performance of the exhaust-air-HP is influenced. The system performance decreases with the hygienic volume flow (here 90, 120 and 150 m³/h), because the heat delivered increases (see Table 3). With moisture recovery the system performance increases, even though the HP COP decreases. The additional secondary and ambient air does not only improve the performance, for a given heating power, but the maximum heating power can be significantly increased (e.g. at 120 m³/h from 1466 W to 3145 W). The performance of the split unit strongly depends on the inside air flow rate. In case of the split unit the condenser volume flow is independent from the hygienic air flow rate and can theoretically be varied in a range from some 175 m³/h to about 300 m³/h, see Fig. 7. In silent mode with 175 m³/h the HP-COP is with 2.4 some 15 % less compared to the nominal volume flow of 300 m³/h with a HP-COP of 2.8.

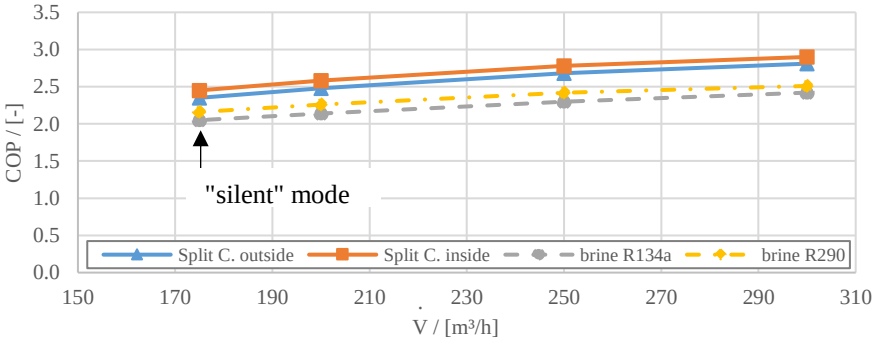


Fig. 7: HP COP (without MVHR) of split HP with compressor (C.) inside and outside, see Fig. 3 as a function of the air volume flow of the condenser, brine HP with R134a and R290 in comparison

If the compressor is inside (i.e. the compressor losses contribute to heating), the COP could be slightly increased from 2.4 to 2.5 in silent mode. The evaporator air flow rate is assumed to be 1500 m³/h - lower outside flow rate as required when using façade integrated solutions would result in lower performance. If instead of the refrigerant split, a brine cycle is assumed, the COP drops from 2.4 to 2.1 (R134a), or 2.2 (R290) at 120 m³/h. The system performance (i.e. including MVHR) of the standard mini-split unit with compressor outside is - taking 120 m³/h as an example - with 2.6 only slightly lower than that of the exhaust air heat pump, see Table 4. The performance drops significantly if electric post-heater has to be used excessively. Only if the air flow rate can be increased, i.e. secondary air is recirculated through the condenser, the performance can be increased (COP of 3.7 for additional 120 m³ of secondary air instead of 2.7 with hygienic air flow rate of 120 m³/h).

Table 4: Performance of different HP concepts for MVHR, heat pump and system (in brackets); COP, acc. to eq. (2) through (7); HR: heat recovery, MR: moisture recovery; n/a: not available;

Volume flow / [m³/h]	MVHR-HR	MVHR-MR	Exhaust air HP with HR RH=30 %	Exhaust air HP with MR RH =30 %	Exhaust air HP with HR; sec. (120 m³/h), amb. (240 m³/h)	Split compressor outside, silent mode, HR	Split compressor inside, silent mode, HR
90	17.9 (3.0)	24.4	2.69 (2.8)	2.3 (4.2)	n/a	2.4 (2.6)	2.5 (2.6)
120	17.2 (2.9)	23.5	2.71 (2.8)	2.3 (4.1)	3.7 (3.0)	2.4 (2.6)	2.5 (2.7)
150	16.6 (2.9)	22.7	2.72 (2.8)	2.4 (4.1)	n/a	2.4 (2.6)	2.5 (2.6)

6. Conclusions and Outlook

The objective of this investigation is to find the most cost-effective HVAC solution for renovation. Different compact HP concepts were compared by means of steady state simulation and are evaluated with respect to performance and heating capacity. Simulated COP is in the range between 2.3 and 2.7 for standard flow rates. The system performance (including MVHR) is slightly higher.

For deep renovated buildings good performing, cost-effective compact HVAC solutions for decentral application are still rare on the market. However, from the technical point of view heat pumps can be designed with arbitrary heating capacity and several concepts exist with several options regarding heat source, heat sink and position of compressor, evaporator and condenser. In order to compare different concepts, the performance needs to be known, however, eventually, for a final decision other aspects such as handling, noise, maintenance, etc. might be more relevant, as difference in performance is rather small.

Table 5: Source and sink options for compact heat pumps for renovation

Source	Remark	Sink	Remark
Ambient air w\ or w\o MVHR	Low temperature, high volume flow, outdoor evaporator unit	Room air (circulation)	Challenge with heat distribution, compromise between performance (flow rate) and noise emissions
Exhaust air (combined with MVHR)	Higher temperature, hygienic flow rate, compact	Supply air	Lower inlet temperature, hygienic flow rate, no additional installation
Extract air (w\o MVHR)	Highest temperature level, hygienic flow rate, poor system performance, discomfort risk	Water (with existing or new radiators)	best performance and individual control options, but if not existing highest installation cost and effort

Several combinations of sources and sinks are possible. Compact exhaust-air-to-supply HP can be installed inside, outside or façade integrated. If ambient air is used as source either a refrigerant split (or multi-split) system or a brine bus system can be used. In case of brine bus and with hydronic heat emission systems storage can be included. In the other cases a speed controlled compressor (and variable air volume flow) and an appropriate control strategy is required to maintain comfort conditions. Speed control increases the robustness of the HP.

So-called (mini) split units represent an interesting alternative for heating. They are available in the power range required for Passive Houses and due to the extremely high quantities at low prices. In contrast to exhaust air heat pumps, split - or multi split units operate independent from the ventilation with recirculation of air. This air-to-air-split HPs (usually reversible heat pumps with separate condenser and evaporator) are offered now by almost all well-known companies with high efficiency inverter technology. However, the visually little attractive indoor units emit noise when operated at nominal conditions. In the so-called silent mode, noise emissions are

acceptable, but efficiency decreases. Compact heat pumps with brine to air HX allow to use alternative (usually flammable) refrigerants also when installed inside, however by compromising the performance. The air distribution has to be carefully planned when only one or two mini-split systems are applied.

A PH compact unit, i.e. an exhaust-air-to-supply-air heat pump has a limited power as it is coupled to the hygienic flow rate (usually 10 W/m²). Higher flow rates should be avoided because of the risk of too dry air. Most compact units do no achieve the maximum allowed supply air temperature of 52 °C (dust). If necessary, the supply air temperature might be increased by means of an electrical post-heater. With air heating in the bathroom (and optionally in other extract air rooms) an additional heat emission system (e.g. towel radiator) should be provided (with demand control). Increase of power (and performance) can be obtained by using recirculated air in the condenser and by mixing ambient air to the exhaust air in the evaporator. Exhaust-air heat pumps are most suitable for façade integration and require no additional installation work inside the flat (supposed the ducts for the ventilation are installed anyway).

For all concepts applies that periodically the evaporator has to be deiced. Depending on the HP system design different deicing concepts can be employed (electric, hot gas bypass, etc.). For further investigations the deicing concept and control strategy has to be taken into account in the energy performance calculation. Eventually, the objective must be reducing the "winter gap", i.e. the non-renewable primary energy use in winter, when there is a lack of renewable energies. Dynamic building and system simulation considering air distribution, moisture buffer and air quality (CO_2) will be performed in future work in order to evaluate and compare the concepts with respect to the annual energy performance considering thermal comfort and indoor air quality.

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