IEA Heat Pump Programme

Annex 32

Economical Heating and Cooling for Low Energy Houses

Executive Summary

Operating Agent: Switzerland

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1. Preface

The work presented here is a contribution to the Annex 32 in the Heat Pump Programme (HPP) Implementing Agreement of the International Energy Agency (IEA).

The full report of Annex 32 is available for downloading at the Heat Pump Centre website, www.heatpumpcentre.org.

2. Introduction

The Annex investigated different configurations of integrated multifunctional heat pump systems for space heating, DHW production, space cooling, ventilation and dehumidification of the ventilation air for the application in low and ultra-low energy houses. The objective was to evaluate, assess and enhance integrated heat pumps systems for low energy houses with regard to overall energy use and costs under the boundary conditions of thermal comfort.

The Annex involved ten countries – Austria, Canada, France, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland and the United States. Switzerland was the Operating Agent and the Annex ran for four years.

3. Motivation IEA HPP Annex 32

In many countries, buildings are responsible for 40-50% of the CO_2-emissions. Thus, low energy houses with considerably reduced space heating energy needs are a key strategy to achieve climate protection targets.

Since the mid of the 1990ties, the energy consumption of new buildings was successively lowered by introducing more stringent legal requirements for the space heating energy needs in building codes and directives. By thermal insulation of the building envelope, a compact air-tight building design, high-quality glazing with optimised gain-loss ratio and summerly heat protection by external shading, buildings with significantly reduced space heating needs down to about 15 kWh/(m^2·a) in houses according to the German passive house standard (http://www.passiv.de) have been introduced. While much attention has been paid to the building envelope, two main directions can currently be distinguished with regard to high performance buildings:

- On the one hand, the passive house approach is widely recognised. The basic idea is to use passive gains to the largest extent possible by making the building envelope as good as possible. Thereby, typical space heating (SH) needs of passive houses as low as 15 kWh/(m^2a) are reached. Efficient system technology can further improve the performance, but due to the investment in the building envelope, system costs are more important.
- On the other hand, a net zero energy house approach is pursued. According to current definitions, a net zero energy building (NZEB) is a grid-connected house, which produces (exports) as much energy as it consumes (imports) on an annual

basis by renewable energies. This target can be reached on the one side by a high-performance envelope on ultra-low energy house level leaving only little remaining energy to be covered by renewable energy or, on the other hand, by a good low energy house and a highly efficient system technology with higher quantity of installed renewable energy systems.

While net zero energy houses are more in the pilot and demonstration phase, low- and ultra-low energy houses have reached considerable market shares, mainly in the three central European countries Germany, Austria and Switzerland, but also in Norway. Figure 1 left shows the development of energy saving houses according to the requirements of the German governmental bank KfW (Kreditanstalt für Wiederaufbau, http://www.kfw.de) and Austrian passive houses.

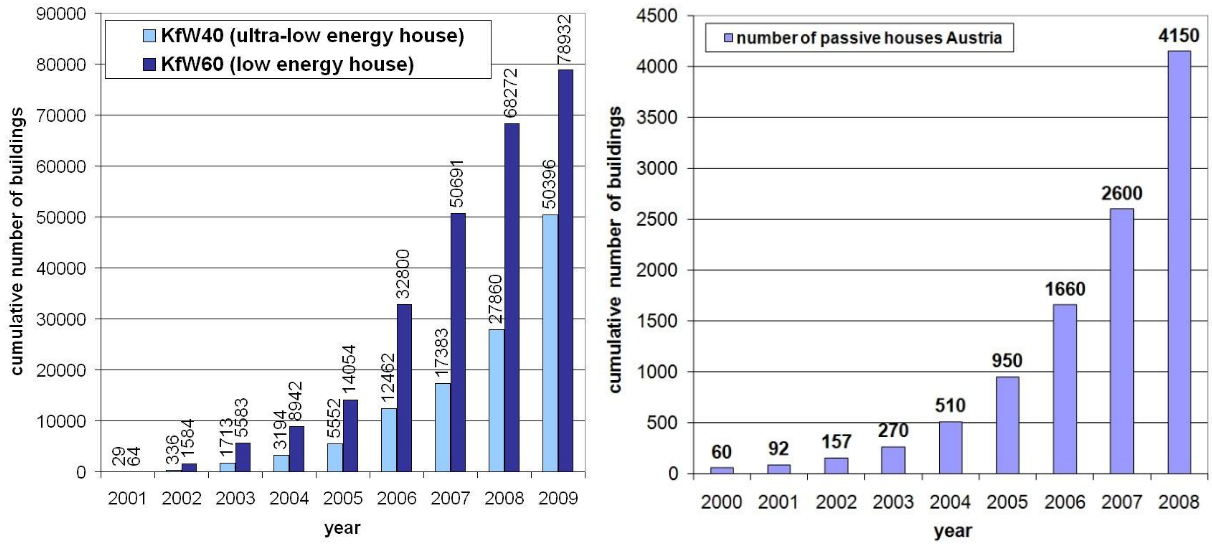

Figure 1 Development of energy saving houses acc. to KfW requirement in Germany (left) and passive houses in Austria (right) in the last decade.

Due to low-interest credits almost 80'000 low[1] and about 50'000 ultra-low[2] energy houses of have been built in the last ten years. In Austria, the number of built passive houses has more than doubled from 2006 to 2008. For 2010 about 10'000 passive houses are expected. In Switzerland certified MINERGIE® buildings exceed 15'000 buildings (http://www.minergie.ch) and reached a market share of 25% for new residential buildings.

Regarding such market growth rates, it is obvious that also the building technology should be adapted to the specific requirements of these low energy houses in order to guarantee an efficient operation and to maximise the possible reduction of CO_2-emissions, which are

- reduced space heating needs, so domestic hot water (DHW) production constitutes a higher fraction of required heating energy

[1] Main requirement: Primary energy for SH and DHW < 60 kWh/(m²a) according to German EnEV 2002
[2] Main requirement: Primary energy for SH and DHW < 40 kWh/(m²a) according to German EnEV 2002

- air-tight building envelope, so mechanical ventilation is often required and installed
- risk of overheating in summertime, so comfort cooling may increasingly become an issue

With these different building services, multifunctional integrated heat pump system configurations are attractive, since

- waste heat, e.g. from space cooling operation, can be internally recovered for other building needs, e.g. DHW production
- different building needs can be covered simultaneously with efficiency gains, e.g. in case of a combined space heating and DHW operation by desuperheating

Even though multifunctional systems with heat pump (HP) are already available on the market, in particular for ultra-low energy houses, developments are not finished, yet. Therefore, Annex 32 in the Heat Pump Programme (HPP) of the International Energy Agency (IEA) entitled "Economical heating and cooling systems for low energy houses" has been launched with the participating countries Austria, Canada, France, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland (operating agent) and the USA in order to assess the systems on the market and support the further development of heat pump systems for the use in low- and ultra-low energy buildings and to prove the feasibility of marketable units and new developments. Table 1 gives an overview on national contributions.

Table 1 Overview of national contributions to IEA HPP Annex 32

Country	Focus of work
AT	• Prototyping, lab-test and simulation of a 3-5 kW CO_2 brine-to-water (B/W) heat pump • Field test of 9 heat pumps for SH & DHW and 2 compact units with passive cooling
CA	• Design and monitoring of two EQuilibrium™ houses (NZEB) in Eastern Canada
CH	• Integration of energy efficient cooling in common heat pump systems for SH & DHW • 2 field tests of heat pump systems for space heating and cooling
DE	• Field test of ≈100 heat pumps in low energy houses and ≈70 heat pumps in existing buildings in co-operation with 7 manufacturers and 2 utilities
FR	• Development and field test of air-to-air (A/A) HP solutions for low energy houses
JP	• Design optimisation of systems for moderate climate regarding capacity and operation • Feasibility studies and field test of ground-source heat pumps for the cold climate zone
NL	• Development of HP concepts for the market introduction of low energy houses
NO	• Feasibility of heat pumps with natural refrigerants in Norwegian low energy houses • Field test of propane water-to-water (W/W) HP prototype for passive houses
SE	• Calculation and field test of Swedish heat pumps for low energy houses
US	• Prototyping, lab-testing and simulation of highly-integrated multifunctional heat pump prototypes for SH, DHW, ventilation and cooling incl. de-/humidification for NZEB

Focus of the research in IEA HPP Annex 32 is on the one hand in the field of prototype systems of highly integrated heat pumps and, on the other hand, the collection of field experience with the practical operation of marketable integrated heat pumps with regard to functionality, performance and optimisation potential for further development.

4. Results of Task 1: Market overview of integrated heat pumps

Integrated heat pump systems have been introduced into the market mainly in countries with an already significant number of low energy houses. Due to the reduced heat load and the installed mechanical ventilation system exhaust air is an interesting heat source, in particular for ultra-low energy houses.

Ventilation-based systems can be distinguished in exhaust air systems and systems with balanced ventilation, i.e. an exhaust and supply air duct. Exhaust air systems are common for DHW production, but also integrated systems with space heating function are on the market. Balanced ventilation systems offer the possibility to integrate a passive ventilation heat recovery, which is required in ultra-low energy houses, and reduces ventilation losses by 60-80%. Heat pump systems coupled to balanced ventilation systems are mostly designed for the space heating and eventually active space cooling function by reverse operation, where the exhaust air is used as source (heating) or sink (cooling) and the supply air is used for distribution and emission. By switching the exhaust air heat pump to a storage, an additional DHW-function can be integrated. This system configuration is called ventilation compact unit, which has established in particular in passive houses.

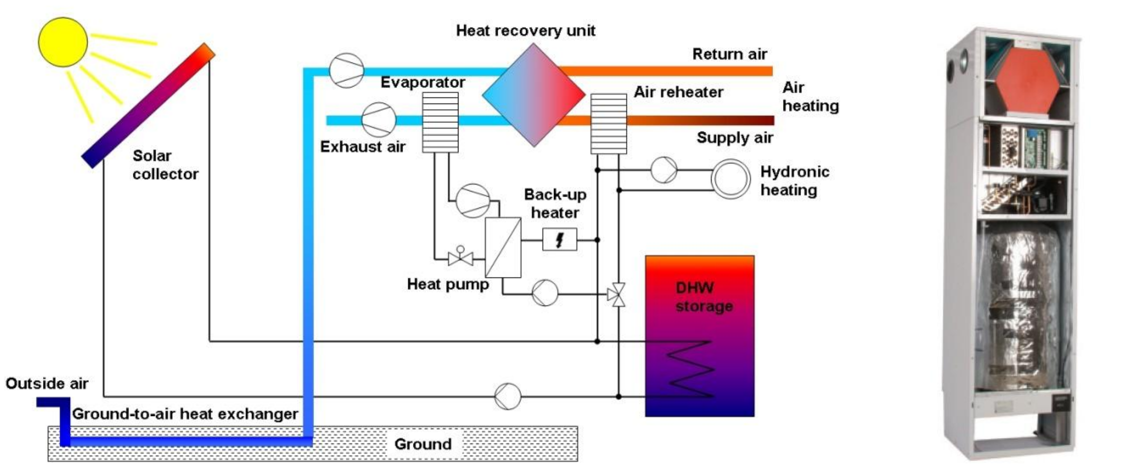

Figure 2 Sample hydraulic of heat pump compact units with optional components and cut-away of a compact unit

However, due to the limited capacity of the exhaust ventilation air heat pump combined with a passive heat recovery of about 1.0-1.5 kW depending on the volume flow rate, optional system extensions are applied in marketable systems to increase the heating capacity of the units. For instance, a ground-to-air heat exchanger, an additional outdoor air source for the evaporator, an additional small ground-source, an entirely ground-coupled unit or solar collectors mainly for the DHW operation are used. Figure 2 left shows typical system variants for compact units with exhaust air heat pump and Figure 2 right a cut-away.

Systems with an integrated cooling function, which is not coupled to the ventilation, can be differentiated in ground- or water-coupled passive cooling and active cooling by reverse operation of the heat pump. Moreover, they can be distinguished by the heat source.

For combined operating space and water heating heat pumps, alternate and simultaneous operating systems can be differentiated. In Europe, mainly alternate operation by switching the heat pump from space heating to DHW is found, while in North America, simultaneous operation using a desuperheater is more common. Systems with single functionality, in particular space heating heat pumps, reach high market shares in different countries, e.g. ca. 75% of the new single family houses are equipped with heat pumps in Switzerland. CO_2 heat pump water heaters for DHW-only operation reached a considerable market share in Japan.

5. Results of Task 2: Prototype system developments

Based on the market state the developed prototypes mainly address three aspects which were not covered by many of the marketable integrated heat pumps for the application in low energy houses in the beginning of Annex 32:

- Additional passive cooling function or simultaneous active cooling and DHW function
- Additional dehumidification function
- Use of natural refrigerants with reduced global warming potential

Most of the developed prototypes in IEA HPP Annex 32 are multifunctional integrated heat pumps in the typical capacity range of residential low and ultra-low energy houses of 3-5 kW. Meanwhile, a passive cooling has been integrated by some manufacturers, also in collaborations within the IEA HPP Annex 32.

Feasibility studies of CO_2 heat pumps and prototype propane water-to-water HP in Norway
In Norway, feasibility studies of CO_2-heat pumps have been carried out. Simulation results of a central 26 kW CO_2 heat pump water heater applied in low energy apartment houses yielded a seasonal performance factor of 3.7 with a water heat source of 7°C and a DHW temperature of 65°C. Considerable primary energy saving compared to common Norwegian designs of DHW systems are reached, making the system also economically beneficial.

- about 75% primary energy saving compared to direct electrical immersion water heating
- about 25% primary energy saving compared to a solar water heater with a solar fraction of 50% and direct electrical back-up heating

For combined space and water heating lab-testing and simulations of a residential 6.5 kW CO_2-HP prototype in Figure 3 left showed that a CO_2 heat pump outperforms the best conventional HFC heat pumps at a DHW share of 55%. For improved CO_2-technology (improved compressor, ejector) with a 10% increased Coefficient of Performance (COP) the break-even point is shifted to 45% DHW share as shown in Figure 3 right.

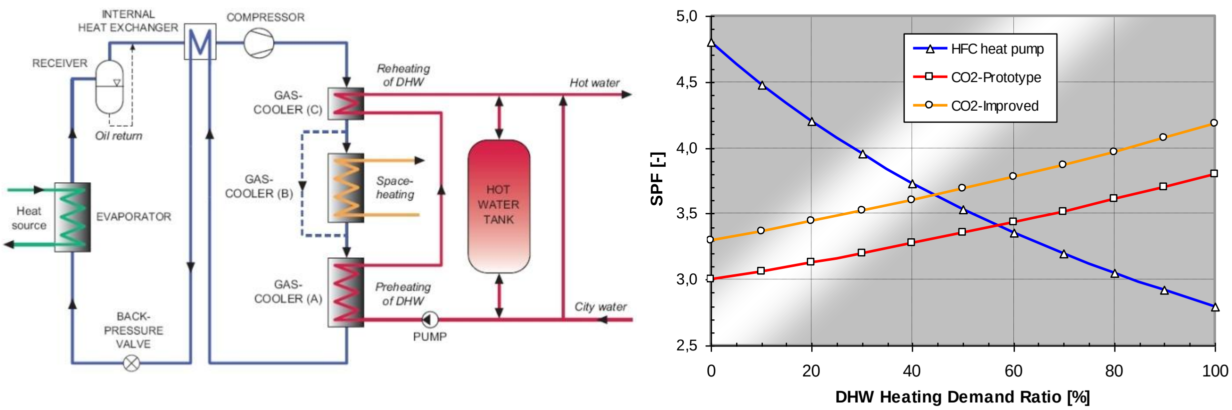

Figure 3 Layout of the prototype B/W-CO2 heat pump and comparison of a prototype and improved CO2 heat pump to state-of-the art (Stene, 2008)

Moreover, an integrated 2.9 kW water-to-water heat pump has been developed using the natural refrigerant propane. The integrated system is designed for space heating and DHW production including a simultaneous mode by desuperheating. The layout of the system is shown in Figure 3 left.

The system incorporates two storage tanks, a 300 l low temperature tank for the preheating of the DHW and the floor-heating system and a high temperature tank for the reheating of the DHW. The suction gas heat exchanger is mainly used to increase the discharge gas temperature at the compressor outlet to augment the potential of the desuperheating for the DHW production, as depicted in Figure 4 right.

The prototype has been installed in a 2.9 kW passive house in Flekkefjord in Southern Norway with lake water as heat source and field monitored for 2 years. The overall seasonal performance factor is 3.7 based on delivered energy after the storages and compressor energy of the heat pump and 3.1 including additionally the source and distribution pump.

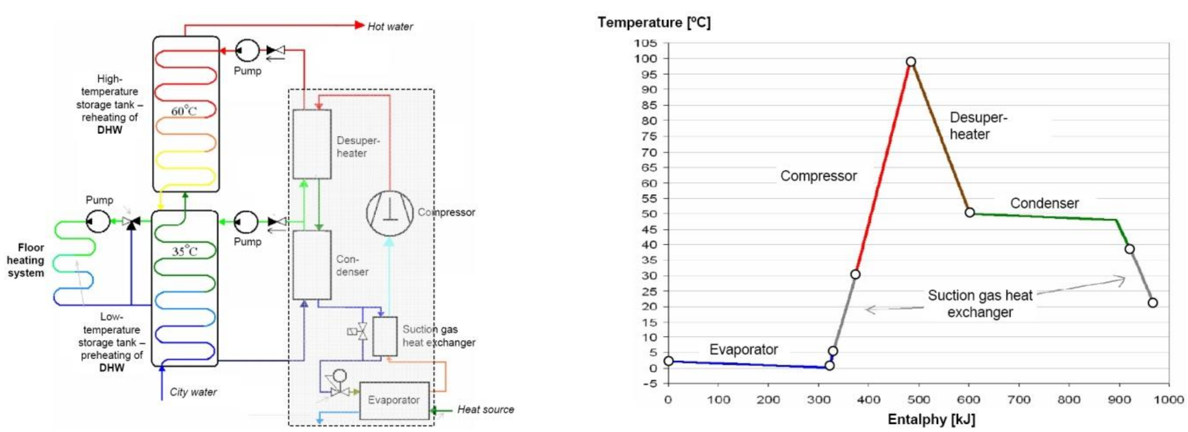

Figure 4 Layout of the prototype water-to-water heat pump with propane (Stene, 2008)

Prototype B/W-CO_2 heat pump in Austria

Based on a system layout and cycle comparisons, a 5 kW CO_2-B/W heat pump prototype has been built and lab-tested in Austria. System simulations for space heating, DHW, passive and active cooling operation in a typical low energy house yielded an overall system performance of 3.2 based on the delivered energy to the floor heating and DHW heat exchanger without the DHW and the SH distribution pumps. In case of higher cooling loads in extreme summers, the performance increases due to a high efficiency of the passive cooling operation. Possible system improvements are seen in improved components (compressor efficiency for low capacities, ejector) as well as in the system integration of the buffer storage and control.

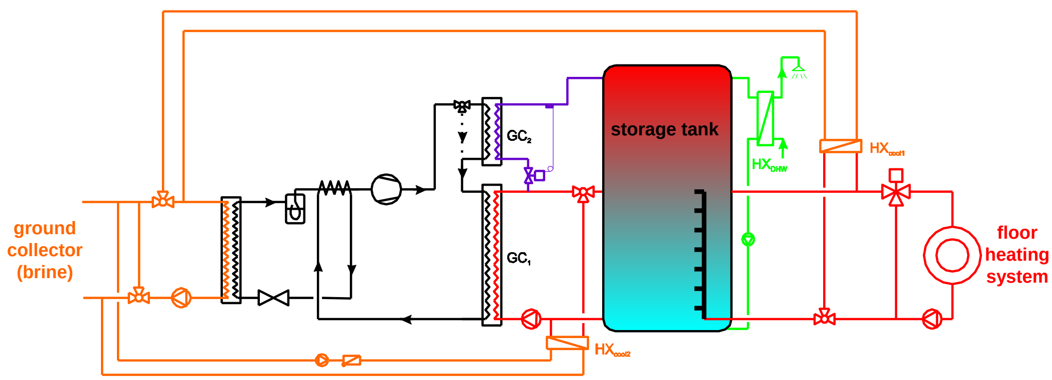

Figure 5 System layout of the Austrian prototype system (Heinz and Rieberer, 2010)

Building integrated PV/T and heat pumps for NZEB in Canada

In Canada, two field monitored houses in the frame of the EQuilibrium™ Net Zero Energy House Initiative of the Canadian Mortgage and Housing Corporation are equipped with a building integrated solar PV/thermal system (BIPV/T) for direct heating as well as a heat source for a heat pump in the cold climate of the Montreal region. System simulations show that the buildings reach almost an annual net zero energy consumption.

Integrated air-source and ground-source heat pump prototype in the USA

At the Oak Ridge National Laboratory (ORNL), USA, an air-source and ground-source integrated heat pump (IHP) prototype covering all building services including dehumidification has been developed, lab-tested and simulated. Annual simulations for a 167m^2 residential NZEB for 5 climate zones of the US show energy saving potentials for 47%-67% (52%-65%) for the air-source (ground-source) prototype compared to common technology according to minimum efficiency requirements of the Department of Energy (DOE). Estimates of the simple payback time are 5-10 years (6-15 years incl. borehole) for the air-source (ground-source) prototype.

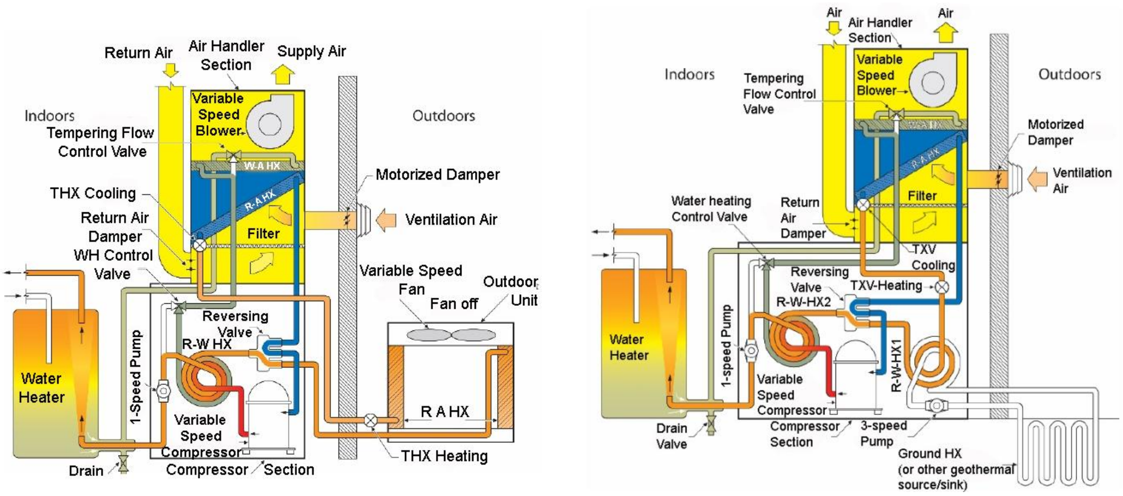

Figure 6 Air-source IHP (left) and ground-source IHP (right) in dedicated dehumidification and water heating mode (Baxter, 2008)

6. Results of Task 3: Field monitoring

In the frame of Annex 32 more than 100 marketable heat pumps for combined SH and DHW installed in newly built low energy houses have been field-monitored in Germany. Year-round seasonal performance factors of the generator (SPF-G) of 2008 based on produced energy and source electricity are shown in Figure 7. The average overall SPF-G (SH&DHW) of the heat pump of about 43 ground-source heat pumps (both horizontal collector and vertical borehole) is 3.8. The electrical source energy consumption makes-up 6% on average, the direct electrical back-up energy is with 2% negligible. The average DHW share is 22%. 6 outdoor air-to-water (A/W) heat pumps reach an average SPF of 3.0 with 7% auxiliary consumption for the source fans and negligible direct electrical back-up energy of 2%.

The results of an Austrian field monitoring of 9 heat pumps for SH and combined SH&DHW confirm the results of the German field test. The overall SPF values based on produced energy of ground-source heat pumps are in the range of 4, outdoor-air heat pumps in the range of 3. Due the measurement equipment the auxiliary energy for the source could not be evaluated separately.

In Germany, another field test for ≈70 heat pumps used in existing buildings as replacement for boilers has been carried out. The average overall SPF in 2008 for 35 B/W heat pumps is 3.3, while 34 air-source systems reach an overall SPF of 2.6. These results demonstrate the impact of the required higher supply temperature in existing buildings. DHW shares are in range of 13% and thus lower than in low energy houses.

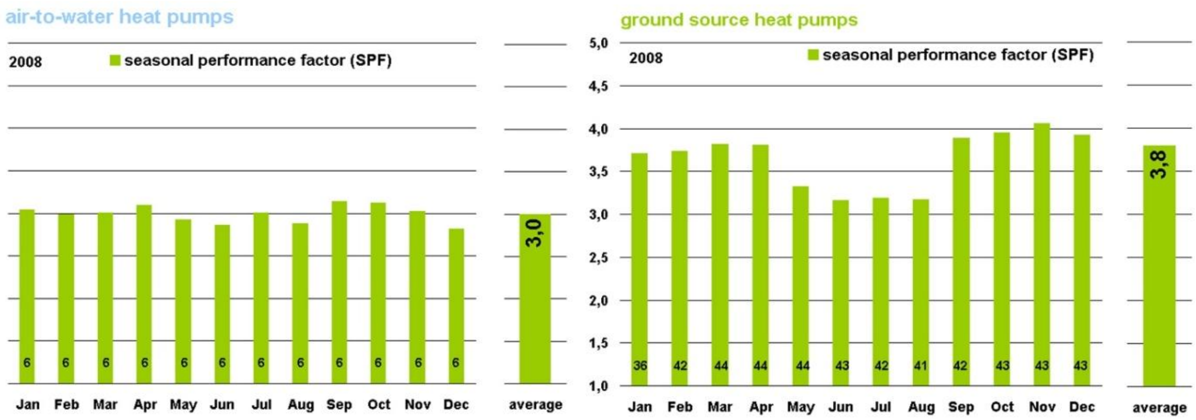

Figure 7 Seasonal performance factor of B/W- and A/W heat pumps in new low energy houses (Miara, 2009)

Some of the field-monitored systems had a ground-coupled passive cooling function, also called direct, natural or free cooling, since only the pumps are operated in the passive cooling mode. The performance values mainly depend on the cooling load, since the auxiliary consumption is nearly constant at constant runtime. The field-monitored systems reach an SPF of 8, while simulations show possible values up to 25 at higher cooling loads and applying today's highly efficient pumps.

In Japan, two inverter-controlled ground-source heat pumps installed in low energy houses have been field-monitored in the cold climate of the Hokkaido Island. Space heating COPs above 5 were reached in combination with a low temperature floor heating system of 35°C/ 30°C design temperatures, and overall seasonal performance is in the range of 3.8. Compared to conventional buildings of the region equipped with oil boilers, CO_2-emission savings are in the range of 50-60%, which stem from both the building envelope improvement to low energy level (≈40-50%) and the building technology (≈50-60%).

Figure 8 left shows the environmental impact in terms of primary energy of the documented Best-Practice systems of Austria, Germany and Switzerland. Compared to a condensing boiler with natural gas, all field-monitored Best-Practice systems contribute to primary energy savings based on primary energy factors of 3.0 for electricity and of 1.15 for natural gas.

Figure 8 right gives a categorisation of the system performance according to the system configuration, which shows that the simpler system configuration reaches better system performance factors in many field tests, i.e. complex system configurations including storages often do not meet the expected performance in field tests, as stated in former field tests, too.

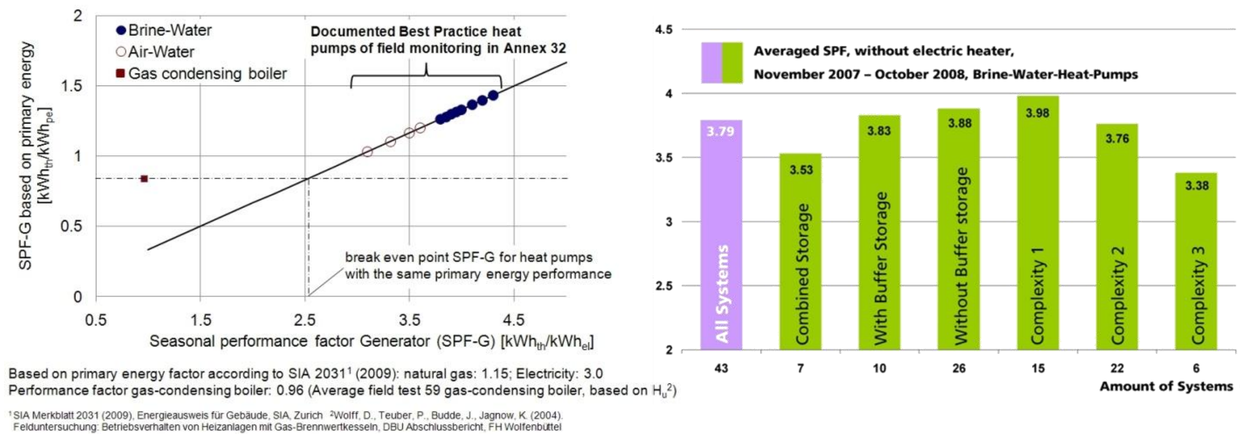

Figure 8 Comparison of primary energy performance factors (left) and system performance acc. to categories of the system configuration for B/W heat pump (right, Miara 2010

In fact, some typical operational problems found in the field monitoring of the systems can be classified regarding the system design, installation and control.

One problem often encountered is the integration and control of combi-storages, which cause too high temperatures for the space heating mode and therefore decrease the SPF. Furthermore, complex hydraulic configurations with many valves are error-prone: Valves, which do not entirely close or installation errors of non-return valves can cause heat losses or discharge the storage.

Moreover, optimisation potentials were found for the circulation pumps. In particular the source pumps in ground-coupled systems are often over-dimensioned and have longer running times than required, both contributing to excessive auxiliary energy consumption. The following recommendations have been derived by the experience of the field monitoring in Germany, which partly confirm recommendations of former field tests:

- Thorough design of the system and the components (heat source, storage, emission system) to the requirements of the house, lowest possible flow temperatures
- Check of storage loading control strategy and supply temperature of the heating system
- Hydraulic balance, thorough and continuous thermal insulation of storage ports

and pipes, in particular for combi-storages

- Deactivation of supporting direct electrical back-up heaters in case of B/W heat pumps (except for drying-out phase of the building due to the danger of damaging the borehole heat exchanger by excessive heat extraction)
- System design as simple and robust as possible, since in many field tests complex hydraulic systems with integrated storages do not meet the expected performance targets.

7. Results of Task 4: Design recommendations

For some systems, design recommendations and calculation methods have been derived.

Design of heat pump air conditioners in Japan

In Japan, the design of heat pump air conditioners of single or multi-split type, which are the Japanese standard heating and cooling systems in the moderate climate zone, used to be a simple catalogue method, which led to over dimensioned systems with lower performance in low energy houses. In the frame of IEA HPP Annex 32 a new design method considering the operation control (continuous or intermittent operation) and the cumulative frequency of the heating and cooling load of the house led to an improved design.

Integration of a ground-coupled passive cooling function in Switzerland

In Switzerland, design recommendations for the integration of a cooling function into typical heat pump system layouts for SH & DHW were derived by simulations. A system comparison shows that energy-efficient A/A-split units for the heat source/sink "air" and ground-coupled systems for the heat source/sink "ground/water" reach the best performance values, while A/W heat pumps with reverse operation have lower seasonal performance.

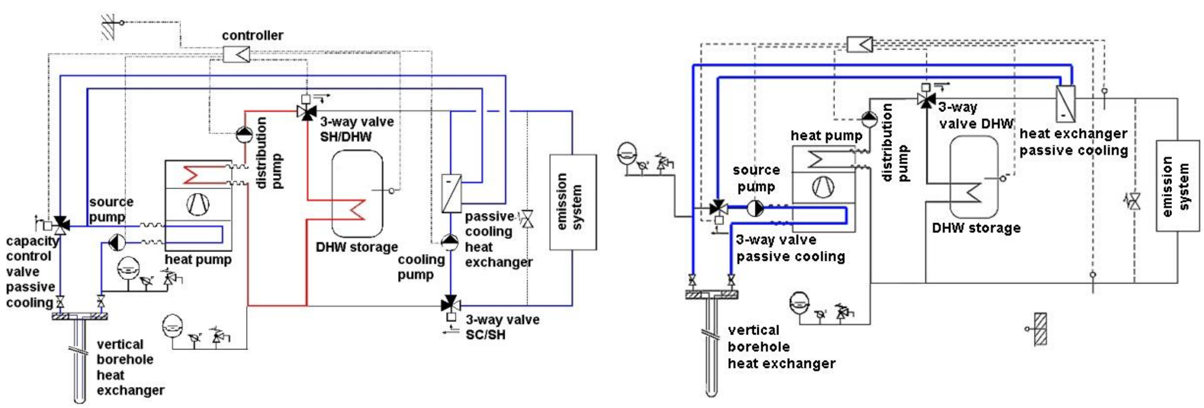

Figure 9 Hydraulic integration of passive cooling in B/W heat pump systems with borehole heat exchanger with (left) and without (right) simultaneous cooling option

Figure 9 shows the recommended integration of the cooling operation in common system layouts for B/W heat pumps for combined SH & DHW with vertical borehole heat exchanger.

Following recommendations on the design have been derived:

- Design of the borehole heat exchanger (BHX) for the space heating operation is sufficient to cover about 90% of the cooling energy, i.e. at present ambient conditions, no active cooling operation is required in Switzerland with adequate building and system design
- The design of the cooling heat exchanger to connect the BHX with the floor emission system is crucial for the degree of provided cooling energy. For instance, a design to a temperature difference of 1 K (3 K) yields 94% (66%) cooling energy at a guaranteed minimum capacity of the BHX of 26 (13) W/m in space cooling operation.
- The simultaneous SC & DHW is not recommended, since the improvement is with 1.7% negligible due to a short-term storage of the rejected heat in cooling mode in the ground for DHW operation. Thus, a simplified hydraulic as shown in Figure 9 right is useful.
- The design for self-regulation (max. design supply temperature 30 °C) yields a further simplification of the hydraulic (no thermostatic valves) and maximises COP and capacity.
- The SPF for the passive cooling function is in the range of 10-25 mainly dependent on the cooling load, since the auxiliary energy stays more or less constant at equal runtime. Thus, the use of highly efficient pumps is recommended.
- The reached indoor air temperature reduction is in the range of 2-4 K by the passive cooling. A dew point control is not necessary for Switzerland, since the local comfort requirements of the floor surface temperature set stronger limits than the dew point. However, rooms with higher humidity (bathroom, kitchen) should not be cooled by floor systems.
- The additional cost for the passive cooling option are about 1500 € for the required additional system components (heat exchanger, valves) and about 12 €/a additional electricity costs.

8. Conclusions and Outlook

Multifunctional integrated heat pumps have several advantages for the application in low energy houses, in particular:

- only one generator is necessary to cover the building services
- different building services can be covered simultaneously with efficiency gains
- a high seasonal performance can be reached with proper design due to the use of waste and ambient heat
- heat pumps are independent of fossil fuels (except for electricity generation) and can be operated entirely CO2 free with renewably generated electricity.

IEA HPP Annex 32 has mainly contributed to the further development of integrated heat pump systems for low energy houses by developing prototype concepts and gathering field experience with the prototypes and commercially available heat pumps.

Several prototype systems have been developed and lab-tested, mainly addressing the extension of functionalities and the use of natural refrigerants rarely found in common marketable systems. System simulations with calibrated lab-test results and including the low energy building show promising results of energy reductions up to 50% compared to conventional system designs. Some of the prototypes (US integrated heat pump prototype, Canadian PV/T systems, Norwegian propane heat pump) are or will be field-monitored in the near future in order to prove the functionality in real operation. By the field results, it will be analysed, if the promising results of simulations are reached under real boundary conditions, as well. Moreover, field testing of the prototypes is useful to reveal operational problems and further optimisation potentials. However, only field results of the Norwegian prototype could be covered in the time frame of IEA HPP Annex 32.

Extensive field tests of marketable heat pumps installed in low energy houses carried out in the frame of IEA HPP Annex 32 confirm a better performance and a reduced environmental impact compared to conventional heating systems like condensing gas boilers. Moreover, the system design is backed-up by design recommendations for system configurations with extended functionality derived from simulation studies. While Annex 32 had a focus on the system integration and design, current market trends show an integration of solar components and heat pumps. In particular for Net Zero energy houses, where the integration of renewable energies is a central part of the concept, integration of solar components is essential, offering further opportunities of a building integration regarding energy and cost savings.

Future buildings will be built-up of multifunctional components, which contribute to cover the energy demand efficiently and cost-effective. Due to the above mentioned unique features, heat pumps are a core component for integrated and environmentally-sound modern building designs enabling the transformation to a sustainable society.

Results of IEA HPP Annex 32 have been summarised in four final reports according to the tasks and research fields. Systems with good performance have been documented in Best-Practice Sheets and prototypes and upcoming layout have been described in System Concepts Sheets.

All deliverables can be downloaded from the Annex 32 website at www.annex32.net or the Heat Pump Centre website, www.heatpumpcentre.org.

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