EXPERIMENTAL AND SIMULATION RESULTS ON A SOLAR-ASSISTED HEAT PUMP PROTOTYPE FOR DECENTRAL APPLICATIONS

Ruschenburg, Jörn, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany;

Baisch, Katharina, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany;

Courtot, François, EDF R&D Energy in Buildings and Territories Department, Les Renardières, 77818 Moret-sur-Loing, France;

Oltersdorf, Thore, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany;

Herkel, Sebastian, Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany;

Abstract; The combination of heat pumps and solar thermal collectors is widely regarded as a promising concept to provide low-exergetic space heating to buildings. Apart from being solar-thermally assisted, the heat pump system presented in this paper is characterised by its decentral application as well as its façade integration. Because of the decentral heating of only one room, the designed power of the heat pump is just about 1 kW. Façade integration means that both the heat pump and its solar source – a plastered absorber – are included in an exterior wall.
The heat pump built for this system and the solar absorber are examined as single components at test facilities. Afterwards, the parameters are used for dynamic systems simulations in IDA Indoor Climate and Energy. The results are presented on annual basis and in detailed analysis. Here, the focus lies on the interaction of heat pump and solar collector. It is demonstrated how the solar collector can boost the heat pump considerably, resulting in higher system efficiency. To examine potential improvements to the systems, further simulations are carried out and presented comparatively.

Key Words: heat pump, solar thermal collector, multifunctional façades

1 INTRODUCTION

1.1 Scope

The combination of heat pumps and solar collectors in domestic heating systems is widely regarded as promising concept to provide low-exergetic space heating to buildings. Economical and ecological advantages were demonstrated in comparison to conventional heat pump systems, both by simulations [Citherlet et al. 2008] and field tests [Thole 2009].
Because any heat pump is sensitive to temperature levels, on source side as well as on building side, various combinations with solar energy can be imagined. During the last years, numerous distinguishable concepts have indeed entered the German market [Henning/Miara 2009]. In the most popular concepts, the solar collector is exclusively used for the preparation of domestic hot water (DHW), which means that no interaction between heat

pump and collector occurs. But there are also more sophisticated approaches, e.g. the utilisation of solar energy for the regeneration of a ground source. One attempt to classify the combinations was presented by [Frank et al. 2010]. In this paper, a façade-integrated solar heat pump system for space heating purposes is presented.
While there are many standards and guidelines defining the performance rating of either heat pumps or solar collectors, there is, however, no standard or generally accepted method for the rating of combined systems. This poses a problem to manufacturers, customers and scientists. To overcome this situation was one of the reasons for the Solar Heating and Cooling Programme (SHC) and the Heat Pump Programme (HPP) of the IEA to start Task 44 / Annex 38 as a combined effort (www.iea-shc.org/task44). Within this paper, the overall system efficiency will by expressed by means of a seasonal performance factor (SPF) on an annual basis, including heat pump, circulation pumps, fans, valves etc. The coefficient of performance (COP) is used for the heat pump on its own and without being averaged.

1.2 The façade-integrated solar heat pump system

The presented system is in fact a solar-thermally assisted heat pump space heating and chilling system, characterised by its decentral approach as well as its façade integration. DHW generation is not addressed. The main motivation for actively using façades can be found in the fact that high-rise buildings – non-residential buildings in particular – generally feature only a small roof area compared to their floor area. In such cases, solar collectors can be installed on or embedded in the façade, even though the consequence is an undesired high solar incidence angle for most of the time.
The term “decentral” means that a system supplies only to a limited part of one storey, or, like the configuration presented in this paper, just to a single room. Especially in Southern Europe, there is a long tradition of decentrally installed split-units for space heating and primarily chilling. The designed power of the presented system, and in particular of the heat pump, is therefore low compared to products offered for single-family houses.
In Figure 1, the basic system concept is shown. It is a product of the on-going project “Resource- and cost-effective integration of renewables in existing high-rise buildings”[1], supported by the Seventh Framework Programme of the European Union and coordinated by Fraunhofer ISE [Kuhn et al. 2010]. As it can be seen, there are two sources available for the heat pump. The intended main source is a tank that is filled with brine and heated by the collector, i.e. a solar source, actually. The alternative source is given by ambient air, and whichever is warmer is chosen. Direct electric heating is excluded, and an additional tank as part of the heating circuit is not planned. Expansion vessels, the valve for supply temperature control and other hydraulic components are ignored in the scheme for the sake of simplicity.

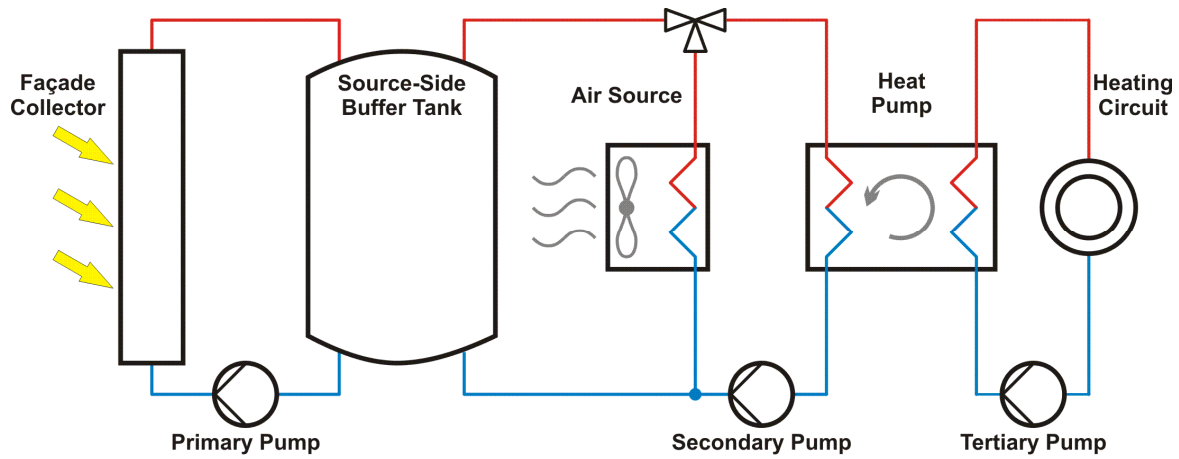


Figure 1: The concept of the “cost-effective” project

[1] “cost-effective” as short form

Among the general advantages for buildings with decentral HVAC systems, low circulation losses can be named as well as unneeded central HVAC rooms and intermediate ceiling space for heat and cold distribution. Furthermore, façade-integrated systems designed for either new buildings or refurbishments provide a high degree of prefabrication.
The required heat pump is special in several aspects. First, its designed heating power is very low, namely just about 1 kW. As an intended result, the sum of all components is small enough to be integrated in the façade. Second, the heat pump has to be capable of both heating and chilling operation, switching internally. Third, direct evaporation cannot be applied, so it is a brine/water heat pump. More information is given in section 2.
The second component to be developed especially for this system is the façade collector. Aesthetical and practical reasons demand a vertical, unglazed collector of rather light colour. Unfortunately, all these aspects contradict the best solution in efficiency terms, namely a tilted, glazed collector of dark colour. The design is shown in Figure 2, supplemented by an infrared image from the test rig, so that the embedded capillary tube mat can be seen in reality.

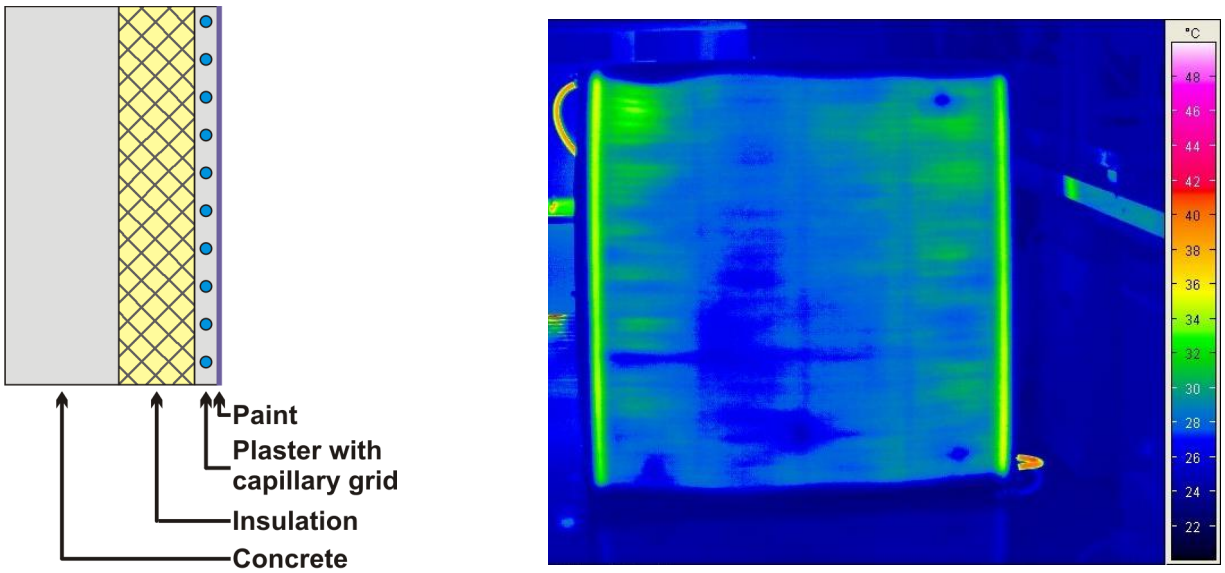


Figure 2: Design (not to scale) of the façade collector and IR image taken during a temperature shock test

Though this absorber cannot feature the high efficiency of modern flat-plate collectors, it can still contribute to the system by warming brine at low irradiation. Compared to ambient air, this is meant to provide a more valuable source for heat pumps in general.

1.3 Objective and Methodology

The main components of the presented system – the heat pump and the collector – are prototypes that were characterised on test rigs as soon as they were completed. In this paper, results for the heat pump are included while the characteristic of the collector is of minor relevance for the scope of the conference and thus omitted.
Furthermore, the assembled system requires a proof of concept. Benefits caused by the solar source are to be quantified to justify the complexity of the system. Dynamic simulations are the preferred tool for gaining know-how about a system with many potential configurations. The concept introduced in the previous section is a result of various simulations. For this paper, simulations in IDA Indoor Climate and Energy (IDA ICE) are applied to determine energy balances, the overall efficiency and other numbers. The building model of IDA ICE allows to simulate the façade collector as part of the heating system and

as part of the building simultaneously [Crawley 2005]. Additionally, options for further development have to be demonstrated.
In principle, the system is designed to provide both heat and cold, so that very similar systems can be installed in moderate Central and in subtropical Southern Europe. However, simulations for Germany are in the focus of this paper, so the chilling mode will be completely ignored.

2 HEAT PUMP PROTOTYPE

It was explained in the introduction that the requirements of the brine/water heat pump to be developed are special in several ways. First, the decentral concept and its low heating demand are incomparable to state-of-the-art applications. Calculations for the reference building that was agreed on (cf. section 3.1) resulted for climates as cold as –15 °C in a heating load just about 1 kW. Second, it was mentioned that the system should be capable of chilling operation as well. The result is commonly known as reversible heat pump. R134a was chosen as refrigerant according to the expected air-source temperatures. In general, inflammable refrigerants are to be objected in decentral concepts. A first impression of the physical outcome is given in Figure 3.

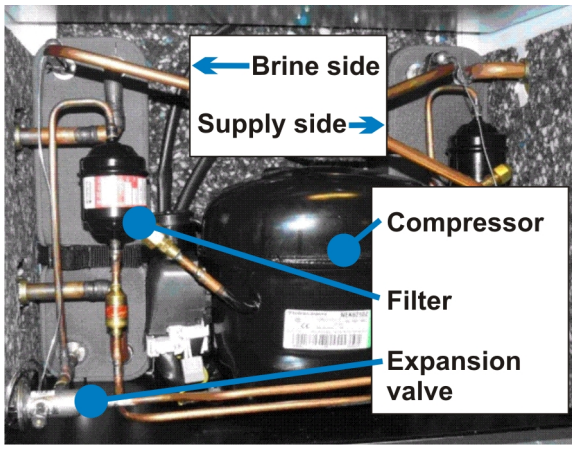


Figure 3: Photograph of the heat pump prototype

After the completion in the course of 2010, the prototype was set up at for rating at the Fraunhofer ISE test rig. All measurements followed the standard [EN 14511]. The test rig's commissioning has taken place not long before, which is the reason why a certification has not yet been achieved. Furthermore, special procedures had to be used to meet the demanded accuracy for low volume flow measurement.
The nominal rating point for brine/water heat pumps is B0/W35. Here, a COP of 2.9 was determined. This result does not meet the expectations, as the design process implicated better values. Table 1 compiles designed and measured values for the heating power $\dot{Q}$, the electrical power consumption P and the COP as ratio of these quantities.

Table 1: Designed and rated performance at B0/W35

Quantity	Unit	Design	Measurement	Deviation
$\dot{Q}$	W	1300	1050	–19 %
P	W	350	360	+3 %
COP	-	3.7	2.9	–22 %

Surprisingly, the measured COP is 22 % below the designed value. But even the designed COP is low compared to state-of-the-art heat pumps. Several points are offered as explanation:

- On such a low power heat pump, certain efficiency losses become more visible, e.g. heat losses of compressor and piping as well as internal heat transfer in the 4-way-valve.
- The small reciprocating compressor has a comparatively low isentropic efficiency.
- The prototype character of the heat pump is evident. For example, it can be seen in Figure 3 that no thermal insulation is applied internally.

As a result, both the concept and the components undergo a redesign process. A second prototype of clearly higher heating power and efficiency is built and rated in 2011.

3 SYSTEM SIMULATIONS

In this paper, the focus lies on the interaction of heat pump and solar collector. It has to be found out under which conditions benefits can be expected from the solar source. Furthermore, potentials for further developments have to be identified before a market-ready system could be the final outcome of the “cost-effective” project. Because several partners in this project carry out simulations as well, a common reference building and boundary conditions were agreed upon early to guarantee comparability of the results. These definitions are presented in section 3.1, followed by results in 3.2.

3.1 Setup

Object of all simulations is an imagined office room plus parts of a corridor. The implementation in IDA ICE is visualised in Figure 4. Only one wall is regarded as external, namely the southern façade. Then, the non-glazed part can be simulated as unglazed collector. An appropriate heat load is generated via ventilation, thermal bridges etc.

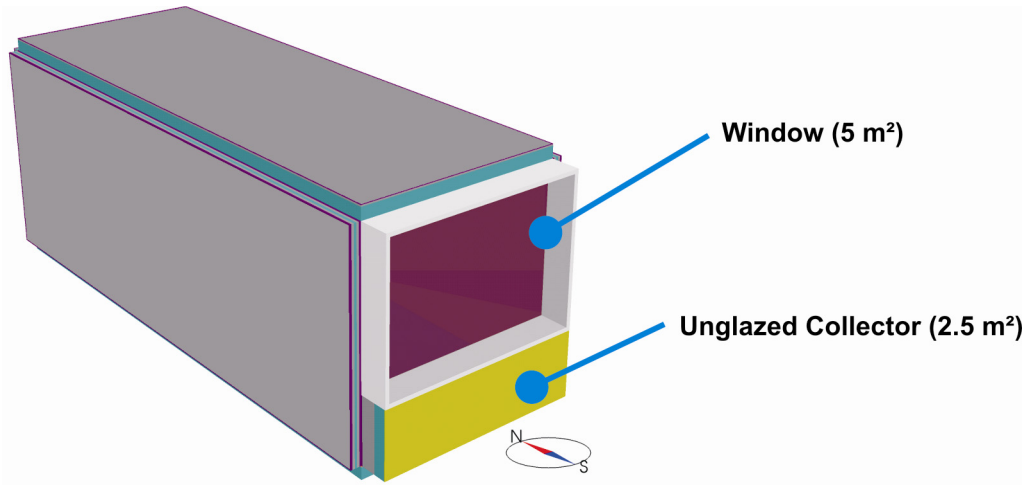


Figure 4: Reference room in 3D view (irrelevant colouring)

The most important parameters of the reference room comprise:

- Location: Freiburg, Germany
- Weather data: German Test Reference Year 12 [Christoffer et al. 2004]
- Inner dimensions: 2.7 m width x 2.8 m height x 7.5 m depth (6 m room and 1.5 m corridor)

- Window: 5 m², oriented to south, U = 1.1 W/m²K including glazing and frame, solar transmittance = 0.7
- Shading: external blinds, only used while room temperature above 23 °C
- Controlled room temperature: 20 °C
- Heating demand: 38 kWh/m²a
- Internal gains: 200 Wh/m²d representing lighting, equipment and occupancy, equally distributed between 7.a.m. and 6 p.m. on weekdays
- Air change rate: 1/h without heat recovery, between 6 a.m. and 7 p.m. on weekdays, between May and October non-stop

Freiburg is certainly no representative location for German or European climates. However, outdoor tests are planned for the compiled system, and a comparison is of course aimed for.
The reference room can be modelled in all details with the IDA ICE standard library. For the heating system, some modelling and programming had to be conducted. The new, yet unvalidated heat pump model, for example, uses the measurement results for rating points to deduce continuous heat pump characteristics (COP and heating power). These characteristics are represented by second degree polynomial functions of source temperature and supply temperature as variables.
In the following, additional parameters of the system compiled. They are derived from the real components that were chosen for the physical system test.

- Brine: Ethylene glycol at 30 wt%
- Air-source unit: Fan consuming 80 W
- Auxiliary pumps: Consuming 10 W each
- Valve: Consuming just during shifting, to be ignored
- Tank: 200 L of brine
- Heat distribution: Via floor heating, design supply temperature of 35 °C

3.2 Results

The simulated SPF of the system, i.e. including all auxiliary energy consumptions, is just 2.3. Thus, it is obvious that a system with the tested prototype cannot be competitive to conventional central heating systems. However, it is anticipated nonetheless that the designed performance can be converted into reality with today's technology. It was already mentioned that a second prototype is in the process of being assembled. Based on these considerations, all further results refer to the designed performance of the heat pump.
The benefits of combining solar collector and heat pump can be found in detailed analysis, demonstrated by Figure 5. Here, the heat pump is parameterised according to the design conditions and simulated with respect to the boundary conditions stated above. Because the time step in IDA ICE simulations is event-controlled, the data points are not necessarily equidistant.

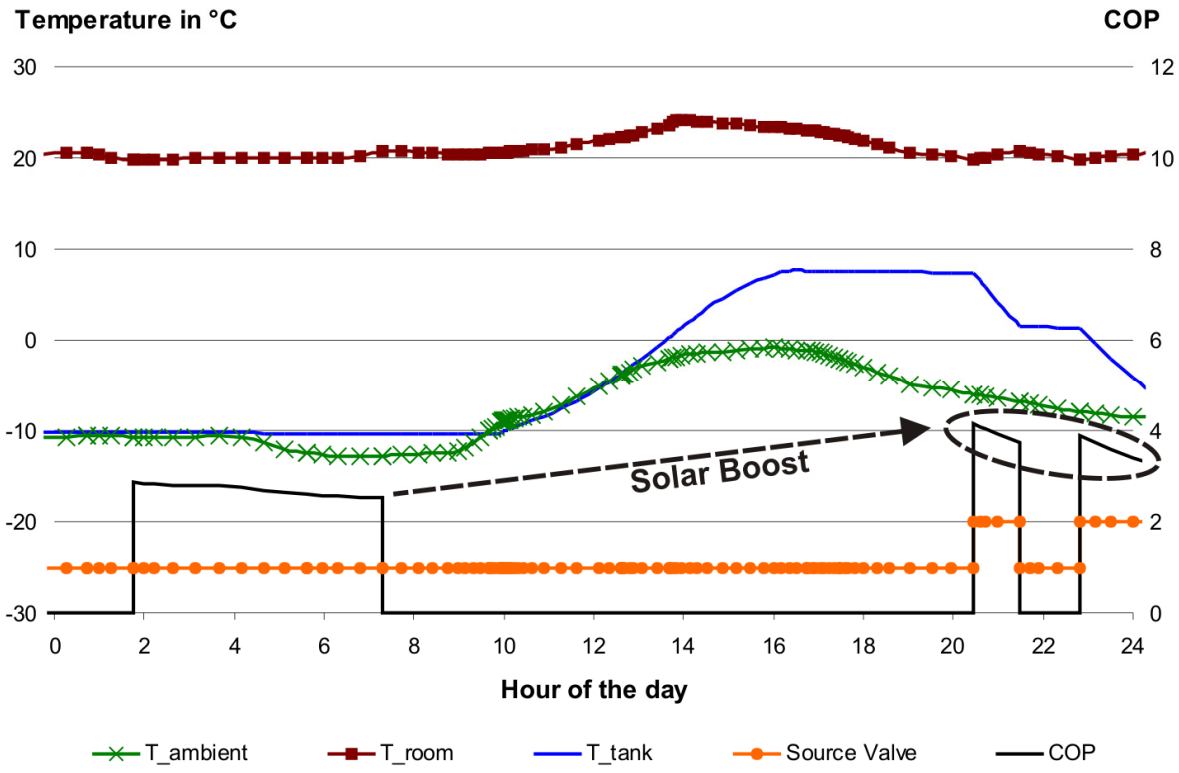


Figure 5: Simulation results for February 2nd

For one day of the coldest season, the ambient air temperature is shown in green. It is well below 0 °C during the whole day. In red, the room temperature is shown. 20 °C is the controlled minimum. The heat pump operation is indirectly shown by the COP, which is set to 0 for no operation. The valve position is defined as 1 for the air source and 2 for the solar-buffer source. Between 2 a.m. and 7 a.m., the heat pump operates via the air source, reaching a COP lower than 3. During the day, the room temperature rises without heat pump operation due to a combination of internal gains and solar irradiation. At the same time, the solar-source buffer tank, its temperature shown in blue, is heated up by the collector to about 9 °C, which is equal to 4 kWh. Later, the tank is then discharged by the heat pump. A COP of more than 4 can be achieved here, which proofs that the solar boost contributes to the system.

To provide a reference case, the system is also simulated without having a solar source. This case is shown as system I in Table 2. The solar system with at heat pump parameterised by designed efficiency is shown as II. The quantities presented in this table are:

- E_{hp} as the electricity consumed by the hp, in fact only the compressor,
- E_{aux} as the electricity consumed by the 3 auxiliary pumps and the fan of the air unit,
- Q_{hp} as the heat delivered by the heat pump,
- SPF as the seasonal performance factor of the system, i.e. Q_{hp} in relation to the sum of E_{hp} and $E_{aux,}$
- $f_{sol,source}$ as the solar fraction of the source, which is the proportion of the source energy provided by the façade collector, the complementary provided by the air source
- $T_{source,av}$ as the average source temperature over the running time.

Table 2: Simulation results on annual basis

Quantity	Unit	Without solar source	Design per-formance	Increased collector surface	Increased collector absorptivity	III and IV combined
		I	II	III	IV	V
E_{hp}	kWh	220	206	198	196	186
E_{aux}	kWh	66	62	72	57	67
Q_{hp}	kWh	778	778	778	778	778
SPF	-	2.7	2.9	2.9	3.1	3.1
$f_{sol,source}$	%	0	28	36	36	45
$T_{source,av}$	°C	–1.4	0.5	1.8	2.2	4.7

For system II, the average source temperature is 2 K higher when compared to the reference case. The SPF is raised from 2.7 to 2.9, and it can be seen that the additional auxiliary energy required for running the solar circuit pump is excelled by savings of other auxiliary energy like for the air source fan. However, the solar source is used rather sporadically with just 28 % of the source energy. This contradicts the intention to utilise solar energy as main source. This fact raises the question how the impact of the solar source can be increased. So, some possibilities for system optimisation are simulated.
For case number III, the collector surface is doubled from 2.5 to 5 m². The nominal power of the circulation pump for the solar circuit is doubled as well. In total, the solar fraction of the source increases as well as the average source temperature, but the savings in compressor energy are counterweighted by the additional auxiliary energy for the doubled collector. Thus, the SPF has not improved in this case. Additionally, the window has to be halved in area to make this possible. This method is therefore questionable in several regards.
For variation IV, the collector was improved not by higher area but by higher efficiency. In fact, the absorption coefficient was increased from 0.6 to 0.95. In reality, this would be done by means of darker paint. Unlike case III, no additional auxiliary energy is required when compared to case II, but comparable to the approach III, the aesthetical effects have to be discussed as well. Regarding the results, the increases in $f_{sol,source}$, $T_{source,av}$ and thus SPF are significant, especially when considering the ratio of efforts and benefits.
In a final step, the two methods of variation III and IV are combined. The outcome is indeed a combination of case IV and V. The improvements in $f_{sol,source}$ and $T_{source,av}$ are evident when compared to any results so far. The SPF is better when compared to case II and III, but not compared to case IV. Once again, additional auxiliary energy for the larger solar collector inhibits a net benefit.

4 SUMMARY, CONCLUSIONS AND OUTLOOK

On the heat pump test rig, the heat pump has proven its functionality regarding heating and chilling. However, its performance regarding heating capability and efficiency is too low to fulfil its role in the system. This is explained by the prototype character of the heat pump. It can be anticipated that a redesign based on the same requirements would achieve the intended characteristics.
The performance of the whole system depends strongly on the interaction between solar source and heat pump. In the original case, the solar source contributed just 28 % of the required source energy. There are several possibilities to overcome this problem.

- First, a solar source boosted by higher collector efficiency was simulated and proofed to add valuable benefits. A boost by higher collector area did not show system improvements because of a higher need for auxiliary energy, namely for the solar circulation pump. Moreover, both ideas are attended by aesthetical, i.e. non-technical problems. For example, a considerable window size is crucial for the acceptance of the system particularly in non-residential buildings.

- Second, the heat pump's characteristic map determined at the test rig – not presented in this paper – indicated that the heat pump is rather insensitive to source temperatures above 10 °C. This phenomenon is ascribed to the thermostatic expansion valves (TEV) that were used. The non-linear relation between source temperature and superheating for TEVs is known and undesired for many reasons [Bruderer et al. 2008]. For solar-assisted heat pumps, this means that relative high source temperatures – up to 25 °C or even higher – do not result in the high efficiency that was technically possible, e.g. by means of electronic expansion valves (EEV). For heat pumps specifically developed for interaction with solar sources, EEV should be regarded as mandatory. However, this explanation has not been verified yet.
- Third, moderate scaling-up might be a desirable solution. If the system is extended to a whole storey, a more efficient heat pump could be applied, and the solar source could be managed with higher flexibility. Of course, the heating distribution system would require more auxiliary energy, and the possibilities to prefabricate the system would be narrowed. Still, such a system has potential to outperform central heating systems.

All these options are considered within the future course of the project. The long-term objective is given by an SPF considerably higher than 3. So, the logical step of scaling up the system will be simulated. At the same time, a second heat pump prototype – with EEVs and of higher capacity compared to the first one – is bound to be rated.

ACKNOWLEDGMENTS

The authors would like to thank all partners within the "cost-effective" project (www.cost-effective-renewables.eu) for their cooperation. First of all Nibe AB for the development of the heat pump prototypes and Sto AG for the façade collectors, respectively, as well as Tecnalia and D'Appolonia.

The research work conducted for this paper is kindly supported by the Evangelisches Studienwerk Villigst e.V.

REFERENCES

Bruderer H. and H. Hohl 2008. „Effects of electronic expansion valves on heat pump performance." 9th IEA Heat Pump Conference, Zurich, Switzerland

Christoffer J., T. Deutschländer and M. Webs 2004. „Testreferenzjahre von Deutschland für mittlere und extreme Witterungsverhältnisse TRY", Selbstverlag des Deutschen Wetterdienstes, Offenbach a.M., Germany

Citherlet S., J. Bony and B. Nguyen 2008. "SOL-PAC. Analyse des performances du couplage d'une pompe à chaleur avec une installation solaire thermique pour la rénovation." Yverdon-les-Bains, Switzerland

Crawley D.B., J.W. Hand, M. Kummert and B.T. Griffith 2005. "Contrasting the capabilities of building energy performance simulation programs." Washington, DC, USA

EN 14511:2007. "Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling."

Frank E., M. Haller, S. Herkel and J. Ruschenburg 2010. "Systematic classification of combined solar thermal and heat pump systems." EuroSun Conference, Graz, Austria

Henning H.-M., M. Miara 2009. ”Kombination Solarthermie und Wärmepumpe. Lösungsansätze, Chancen und Grenzen.” 19. Symposium Thermische Solarenergie, Bad Staffelstein, Germany

Kuhn T. E., S. Herkel and H.-M. Henning and F. Frontini 2010. ”New multifunctional façade components for the building skin.” 5th Energy Forum, Brixen, Italy

Thole F. 2009 „Solare Systemarbeitszahl. Berechnungsmethode und Nachweis aus Feldtestergebnissen.“ 6. Wilo-Forum, Dortmund, Germany