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# Contributions to building energy renovation: a compact heating and ventilation system, evaluation of a versatile energy auditing tool

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# Kurzfassung

Die vorliegende Dissertation trägt zur energetischen Gebäudesanierung bei. Eine innovative Heizungs- und Lüftungsanlage wird präsentiert und ein einfaches Berechnungstool als „Energie Audittool" bewertet. Die Entwicklung einer Luft-Luft Wärmepumpe (mikro-WP) kombiniert mit mechanischer Lüftung mit Wärmerückgewinnung (WRG) wurde mit Hilfe dynamischer Simulationen und Analysen von Monitoringdaten unterstützt. Die Verwendung des Passivhaus Projektierungspakets (PHPP) als Audittool, wurde mit Hilfe der Simulationsprogramme TRNSYS und Matlab/Simulink evaluiert.

Dynamische Simulationen der mikro-WP wurden durchgeführt, um die Energieeffizienz des Systems zu untersuchen und die Entwicklung zu unterstützen. Die Simulationsstudien beziehen ein saniertes Einfamilienhaus im Passivhaus- oder EnerPHit-Standard ein, das an sieben repräsentativen europäischen Standorten simuliert wurde. Ein Vergleich mit anderen Wärmepumpenkonzepte, wie einem mechanischen Abluftsystem mit einer Abluftwärmepumpe und mit Konvektorheizungen, hat gezeigt, dass die mikro-WP das effizienteste System ist, wenn sehr hohe Gebäudestandards angewendet werden (z.B. Passivhaus oder EnerPHit). Außerdem zeigt sich, dass die Verwendung von einem geregelten Verdichter die Energieeffizienz des Systems um ca. 15% erhöht und gleichzeitig das Risiko einer falschen Dimensionierung verringert.

Ein funktionales Muster der mikro-WP mit WRG, integriert in einer vorgefertigten Holzfassade, wurde in einer Wohnung während der Sanierung eines Mehrfamilienhauses in Ludwigsburg (Deutschland) installiert. Dieses System und die zugehörige Wohnung wurden vor und nach der Sanierung im Detail vermessen und die Monitoringdaten analysiert. Die Jahresarbeitszahl (JAZ) der Heizung und Lüftungsanlage für eine komplette Heizungsperiode lag bei 2,8 und die JAZ der mikro-WP allein ergab 2.5. Nach der Sanierung zeichnete sich die Wohnung mit guten thermischen Komfort und einer deutlich verbesserten Raumluftqualität aus.

Die Simulationsmodelle der mikro-WP und die durch die mikro-WP beheizte Wohnung wurden mit den Monitoringdaten verglichen. Anschließend wurden die evaluierten Modelle für dynamischen Simulationen verwendet, mit dem Ziel, das System weiter zu optimieren. Ein Optimierungspotenzial wurde in den Ventilatoren der WRG, in

der Auslegungsleistung der Wärmepumpe und bei der Regelung des Abtauzyklus und des Vorheizregisters (für den Frostschutz des Wärmetauschers) gefunden. Durch Optimierung aller dieser Punkte kann eine gesamte Reduzierung des Stromverbrauchs von weiteren 25% erreicht werden.

Das monatliche Berechnungstool PHPP wurde mit dem dynamischen Simulationstool TRNSYS verglichen, mit dem Ziel PHPP als Energie Audittool zu bewerten. Der Vergleich enthält zwei Gebäudetypen (Ein- und Mehrfamilienhaus) und drei Gebäudeenergieniveaus (vor der Sanierung und zwei unterschidliche Sanierungskonzepte) an sieben repräsentativen europäischen Standorten. Eine gute Übereinstimmung wurde erzielt. Die durchschnittliche Abweichung beträgt 8% beim Heizbedarf und 16% beim Kühlbedarf (nur für die Standorte mit relevantem Kühlbedarf). Zusätzlich wurde der in PHPP entwickelte Wärmepumpen-Algorithmus mit einem dynamischen Simulationsmodell in Matlab/Simulink verglichen. Hier lag die durchschnittliche Abweichung um 4%.

Darüber hinaus werden vier Fakten diskutiert, wie der so genannte „performance gap“ in der Realität vermieden werden kann.

# Abstract

The present thesis aims to contribute to the energy building renovation by presenting an innovative compact heating and ventilation system, and evaluating an easy to use calculation tool as an energy auditing tool. An air-to-air heat pump (micro-HP) combined with a heat recovery ventilation (HRV) unit was developed with the assistance of dynamic simulations and monitoring results. Passive House Planning Package (PHPP) was evaluated as an auditing tool by comparing to the dynamic simulation tools, TRNSYS and Matlab/Simulink.

Dynamic simulations of the micro-HP and the HRV were performed to investigate the energy performance and the feasibility of the system, and to support the design phase of the development. The simulation studies include a single-family house that was renovated according to Passive House or EnerPHit standards located in seven representative European locations. A comparison to other heat pump systems, such as exhaust ventilation with an exhaust air heat pump and ventilation radiators, showed that the micro-HP is the most efficient system when energy efficient building standards are applied (e.g. Passive House or EnerPHit). In addition, the use of a variable speed compressor is beneficial, increasing the energy performance by a maximum of 15%, and at the same time, it reduces the risk of having an improperly dimensioned system.

The micro-HP combined with HRV was integrated into a prefabricated timber façade, and a functional model was installed in a flat within the renovation of a multi-family house in Ludwigsburg, Germany. The system and the flat (before and after renovation) were monitored in detail. The seasonal performance factor (SPF) of the heating and ventilation system was 2.8 for a complete monitored heating season, and the SPF of the micro-HP alone was 2.5. Inside the flat, good thermal comfort conditions were observed and the indoor air quality was strongly improved after renovation.

The simulation models of the micro-HP and the flat (in which the micro-HP was installed) were evaluated using the monitoring data. Using these models, additional dynamic simulations were performed to further optimise the system using the monitoring data as boundary conditions. An optimisation potential was shown in the ventilators of the HRV unit, the capacity of the heat pump, and the control of the pre-heater (for the

frost protection of the heat exchanger) and the defrost cycle, resulting altogether in a 25% electricity savings.

A monthly calculation tool, PHPP, was compared to a dynamic simulation tool, TRNSYS, aiming to be evaluated as an energy auditing tool. The comparison includes two building types (single- and multi-family house), three building energy levels (before the renovation and two renovation concepts) in seven representative European locations. The average deviation between the tools was 8% in heating demand and 16% in cooling demand (taking into account only the locations with relative cooling demand). Additionally, the heat pump algorithm in PHPP was compared to a dynamic simulation model in Matlab/Simulink resulting in an average deviation of 4%.

Moreover, four facts are described presenting why the so-called ‘performance gap’ is a misleading observation.

# Contents

# 1 Introduction

The building sector in the European Union consumes 40% of the total energy consumption [1], and space heating is the largest part of it [2]. Considering that old, poor performing buildings dominate the existing building stock, renovation is key to energy conservation. Passive House [3,4] and EnerPHit [5] standards are already well-known and used worldwide. The first Passive House was built in 1991 [6]. The low energy demand of such highly energy-efficient buildings can be even further reduced with the use of heat pumps. This can lead to a significantly low residual energy demand during the heating season, when renewable energy sources, such as photovoltaics, are limited, and thus, the requirement of energy from fossil fuels is decreased.

Heat pumps have significant advantages compared to other heating systems such as supplying both heating and cooling. The appropriate exergy source is mechanical energy, which is easy to get from electricity. The electric grid is available almost everywhere. Especially in Passive Houses with such a reduced heating load, heat pumps can be scaled down to very small heating capacities (1000 W and even lower). The heating capacity reduction leads to cost reduction, and gives the opportunity for the development of more compact and “plug-and-play” solutions. Such a promising and innovative concept of a small-scaled heat pump combined with heat recovery ventilation is presented in this thesis [**Publication A, B, C, D, E**].

Energy audits play a key role in a successful renovation identifying the appropriate energy conservation measures (ECMs) through the building energy consumption analysis. Several energy auditing tools are available on the market, as shown in [7–11]. The auditing tools can be distinguished based on the algorithm, in dynamic simulation tools (hourly time step or less) and calculation tools (monthly or annual energy balance). Thus, the complexity and the required user-knowledge of these tools vary significantly. In this thesis, a calculation tool (PHPP [12]), which requires less user-knowledge compared to simulation tools, was evaluated as an energy auditing tool [**Publication F, G**], and in addition, the so-called ‘performance gap’ is discussed [**Publication H**].

The main objective of this thesis is to contribute to building renovation by (a) presenting an innovative heating and ventilation system suitable for renovation of residential buildings and (b) evaluating an easy to use energy auditing tool. The novelty of the thesis lies in the development, evaluation, and optimisation of a micro-heat pump combined with a heat recovery ventilation unit suitable for space heating and ventilation, and in the evaluation of a versatile energy auditing tool.

The present study is structured as follows: Chapter 2 describes the methods used, followed by Chapter 3, which presents the main results. Chapter 4 gathers the main conclusions as well as possible future work. In Chapter 5, the relevant scientific articles are attached.

# 2 Methodology

## 2.1 Development of a micro-HP assisted with dynamic simulations and in-situ monitoring

Within the framework of the European project iNSPiRe [13], a functional model of a micro-heat pump (micro-HP) combined with a heat recovery ventilation (HRV) unit was developed. The air-to-air heat pump extracts the remaining enthalpy of the exhaust air flow after the heat exchanger, and further heats up the supply air of the HRV unit. The proposed system was developed to be integrated into a prefabricated timber frame façade for minimally disruptive renovations. The applied methodology is the following: first, energy performance simulations were performed to prove the feasibility of the system and to assist in the development process [**Publication A, B, C]**. At the same time, a functional model was developed and measured in the laboratory [14]. As a next step, another functional model was installed within the renovation of a multi-family house in Ludwigsburg, Germany. The proposed system was evaluated through in-situ monitoring data analysis, and the simulation models were evaluated using these data [**Publication D, E**]. Finally, further optimisation potential was investigated using the evaluated models [**Publication D, E**].

In the energy performance simulations, the climate locations and the energy performance of the building were varied. A single-family house (SFH) was renovated according to EnerPHit or Passive House standards for seven representative locations over Europe (as defined in the iNSPiRe project [15]). The simulation platform was Matlab Simulink [16] with the Carnot toolbox [17]. In relevant **Publication A**, the proposed system (heat recovery ventilation combined with the micro-HP called system A) was compared to exhaust ventilation with an exhaust air- (system B) or ambient air-to-water heat pump (system C) with ventilation radiators, and exhaust ventilation with an air-to-water heat pump with panel radiators (reference system D). Since no measured data were available for the micro-HP, a generic performance map was used in the EFKOS simulation model [18]. In relevant **Publication B**, a heat pump model was developed in Matlab/Simulink, based on a performance map. At the same time, a physical steady state model of the refrigerant cycle was also developed [19] to assist the design of the heat pump, and to produce the required performance map. The physical model was validated using the laboratory measurements [14]. The seasonal performance factor (SPF) of the heat pump and an auxiliary heater (an electric radiator was located in the bathroom for comfort reasons) was calculated in dynamic simulations. In addition, the influence on the energy performance of a variable-speed or a fixed-speed compressor was investigated. In relevant **Publication C**, the aim was to reach a goal of 50 kWh/($m^2$a) primary energy for heating, domestic hot water, and lighting as defined in the iNSPiRe project [13]. Therefore, the micro-HP system was used for space heating and ventilation, and an air-to-water heat pump or a gas boiler was added for the DHW supply system.

As a next step, a functional model of the micro-HP was installed in one flat of a multi-family house (MFH) in Ludwigsburg, Germany. The flat, in which the micro-HP was installed, was also modelled in Simulink by Leonardi [20]. The monitoring started in February 2016, thus, only a part of the heating season was monitored. In relevant **Publication D**, these first monitoring data were used for the evaluation of the simulation heat pump model and for proper adjustment of the system for the next winter. The monitoring data of the complete heating season (2016/2017) were analysed in detail in relevant **Publication E**. The energy performance of the HVAC system, as well as its components, were presented. The thermal comfort and indoor air quality (IAQ) in the flat were measured and analysed for the case before and also after renovation. The heat pump model was enhanced based on the monitoring data, and then both the simulation models of the flat and the heat pump were evaluated by a comparison to the monitoring data.

To investigate the energy performance in extreme cases [**Publication D**], the neighbouring flats (below and above) were simulated with lower heating set point temperatures compared to the one of the experimental flat. This leads to a significantly increased heating demand of the experimental flat due to high transmission losses to the neighbouring flats. Moreover, the influence of the minimum operation time of the heat pump on the energy performance and thermal comfort was investigated. As a final step, annual simulations were performed using the monitored data as boundary conditions to investigate the potential for further system optimisation [**Publication E**].

## 2.2 Tools for building energy renovation

A monthly calculation tool (here PHPP [12]), with less required inputs and user-knowledge compared to dynamic simulation tools, was evaluated as an energy auditing tool by comparing it to numerical simulation tools. In relevant **Publication F**, PHPP [12] was compared to TRNSYS [21]. The annual demands and the maximum daily loads for both heating and cooling were compared between PHPP and TRNSYS. The study includes two building types (SFH and MFH), three building energy levels (before renovation, and after renovation with a heating demand of 45 kWh/($m^2 \cdot$a) and

25 kWh/($m^2$·a) - EnerPHit standard), and seven representative European climates (as defined in the iNPRiRe project [15]). Furthermore, in the relevant **Publication G**, the heat pump algorithm in PHPP [22] was presented and compared to a dynamic heat pump model in Matlab/Simulink.

In relevant **Publication H**, an overview is presented about energy tools in Europe simulating not only one building but a district or even a whole region. In addition, the so-called 'performance gap' is discussed, and an equivalent heating reference temperature (EHRT) is proposed as input for the simulations.

# 3 Main results and discussion

## 3.1 Micro-heat pump combined with a heat recovery ventilation unit

### 3.1.1 Energy performance simulations assisting the development

In relevant **Publication A**, the comparison of the micro-HP combined with an HRV unit (system A) to three different heat pump systems showed that system A had the best energy performance from the four systems almost in all investigated climates and energy standards. The maximum energy savings were observed in the coldest climates (Stockholm and Gdansk) in the case of low heating demand (Passive House), with a value of 36% compared to reference system D (exhaust ventilation with an air-to-water heat pump and radiator panels). However, when the heating demand increases more than the one defined in EnerPHit standard (25 kWh/($m^2$·a)), system A becomes less efficient and system B (exhaust ventilation with an exhaust air-to-water heat pump and ventilation radiators) shows the highest savings. Thus, micro-HP is preferable in highly energy-efficient buildings such as EnerPHit or Passive Houses.

A simulation study was performed to investigate the influence of the climate, building standard, and variable- or fixed-speed compressor on the micro-HP energy performance [**Publication B**]. The SPF of the heat pump was slightly influenced by the climate due to the dampened fluctuation in the source temperature (because of the heat recovery). The system performance of the micro-HP and the additional auxiliary heater increased slightly in the Passive House compared to the EnerPHit standard. The use of a variable-speed controlled compressor instead of a fixed one increased the energy performance of the system by a maximum of 15%.

The type of the domestic hot water supply system (air-to-water heat pump or gas boiler) was added as a parameter in the simulation study, while the micro-HP was used for space heating [**Publication C**]. In the case of Passive Houses, the primary energy goal of 50 kWh/($m^2$a) was achieved in all climates for both DHW systems, while in the case of EnerPHit an additional photovoltaic system was required. The use of a heat pump instead of a gas boiler for the DHW supply was preferred from an energy point of view.

### 3.1.2 Monitoring data analysis

A monitoring system was installed to collect information about the energy performance of the micro-HP system, and the comfort level inside the experimental flat. The monitoring campaign included a complete heating period. The energy performance was promising and the required comfort level inside the flat was reached (see relevant **Publication E** for more details).

Although the heating demand of the flat was relatively high, the SPF of the HVAC system (including the micro-HP, HRV, and auxiliary heaters) was 2.8. The SPF of the micro-HP was 2.5. The heating demand was high mainly due to lower indoor temperatures of the neighbouring flats (compared to the experimental flat). The identical flat above had an 82% lower heating demand, and the flat below was unoccupied for one month. This high demand (due to high transmission losses to the neighbouring flats) resulted in the auxiliary heater operating at a high level, and thus, suppling 30% of the supplied heat. Comparing the electricity consumption share of each component, significant were those of the ventilators with 24%, the auxiliary heater with 36% and the compressor with 28%.

Thermal comfort conditions were achieved in all rooms except the bathroom (the installed electric radiator was never in operation). The average indoor temperature increased by 1 K after renovation, even though the tenants were the same. After renovation, the heating system was controlled by the corridor temperature (air-heating system), while before renovation, it was controlled individually in each room (heating with radiators). There was an increase in the temperature difference between the rooms by 0.8 K (or 0.2 K excluding the bathroom). There was no indication that the tenants noticed the difference.

The indoor air quality was significantly better after the renovation when the HRV unit was in operation. The occupants often switched off the ventilation system (and thus the heating system) even in the middle of winter (37% of the heating season the ventilation was not in operation). However, the average $CO_2$ concentration of the flat was below 1000 ppm during 77% of the heating period, while the corresponding value before the renovation was 21%.

### 3.1.3 Simulations results for further optimisation

The performance map of the heat pump was enhanced using the monitoring data [**Publication E**]. The heat capacity and the electric power were modelled as functions of the source temperature, the compressor speed, and additionally the source absolute humidity. As a next step, both the heat pump and the building model of the experimental flat were compared to the monitoring data showing acceptable deviations.

In relevant **Publication D**, the micro-HP performance in extreme cases, such as in high heating demands, was investigated by varying the set point temperatures of the investigated flat and its neighbouring flats. The results showed that even in the worst scenario of having a 2 K temperature difference between the experimental flat and its neighbouring flats above and below, the micro-HP could supply comfortable conditions, however, the performance was not high with a total SPF of 2.6. An additional parametric study presented that the minimum operation time of the micro-HP had a negligible influence on the energy performance.

Further building and heat pump simulations were performed targeting system optimisation using the monitoring data as boundary conditions [**Publication E**]. The highest potential was saving 12% of the consumed electricity by optimising the ventilators of the HRV unit. In that case, the SPF of HRV would be 11.6 instead of the monitored 5.2. The implementation of a bigger heat pump, e.g. with double heat capacity, reduced the electricity by 7%. The other two options were to use a pre-heater with variable power and optimise the controller of the defrost cycle, resulting in a 5% electricity savings in each one. Considering all four optimisation measures, the required electricity was reduced by 25%.

### 3.1.4 Discussion

As shown in the monitoring results, good thermal comfort and IAQ were achieved inside the flat. Improved energy performance can be expected in coming years. A potential for further optimisation was presented through dynamic simulations.

As for the economics, the proposed system has a potential for cost reduction compared to conventional systems due to (a) saved costs for the equipment and the installation of the heat emission and distribution system (the ducting is installed anyway to provide sufficient IAQ), (b) lower heating capacity and size than conventional heat pumps, and (c) less onsite working time due to prefabricated elements. The limited available space in MFHs is the main reason for façade integration; however, it is difficult to monetarise its economic benefit.

Thus, the developed system represents a compact solution with promising energy performance, appropriate for minimally disruptive renovations, and has the potential to be cost-effective.

## 3.2 PHPP as energy auditing tool

A short overview about the user-knowledge, time to use, and the number of required inputs is discussed to enable a better understanding for the comparison between the PHPP and TRNSYS. PHPP is based on the well-known program, Microsoft Excel, which has many predefined values for non-experts, and automatically calculates the results of complex influence chains even after changing only one input. On the other hand, TRNSYS requires special building simulation expertise and knowledge in programming to fill in the required inputs, since the simulation level can be detailed such as: more than one thermal zone, use of profiles, detailed control strategies etc. Thus, PHPP has the advantage of requiring less time and skills compared to detailed building simulation tools such as TRNSYS. It is also noted that the probability of user errors is significant in simulation tools, as shown in [23]. As also shown in the overview of district tools in Europe [**Publication H**], the majority of the tools includes monthly energy calculations, which avoids more complex dynamic simulations.

An adequate agreement was found between PHPP and TRNSYS regarding the heating and cooling demands [**Publication F**]. A better agreement was shown for heating than for cooling (considering only the warm climates when cooling is relevant). The generalised outcome regarding the heating demand was that the deviation between the tools was lower for better energy standards and in cold than warm climates (mainly due to better envelope quality). The cooling demand was slightly reduced after renovation, while it was not affected by the renovation level. Deviations can also be found among numerical simulation tools. For example, in relevant **Publication A**, TRNSYS compared to Matlab Simulink resulted in a good agreement with some deviations in warm climates, similar to the comparison between PHPP and TRNSYS. The daily average heating and cooling loads comparison showed similar behaviour between the tools with higher values in PHPP in most cases. A certain amount of this overestimation in PHPP is intentionally for designing on the safe side [24].

As a next step shown in relevant **Publication G**, an algorithm was developed in PHPP in order to calculate the required electricity when a heat pump is chosen as HVAC system [22]. The algorithm is based on the bin method and the Carnot performance efficiency. The developed method was compared to a dynamic heat pump model in Matlab/Simulink [**Publication G**]. The comparison includes an air-source heat pump implemented on a Passive House in six European locations. The maximum deviation was 8% for the climate of Stockholm, and the average deviation for all climates was 4%.

## 3.3 The so-called ‘performance gap’

In **Publication H**, the so-called ‘performance gap’ is discussed as a misleading observation. There are several studies [25–30] in literature showing a quite good agreement between measurements and calculations, when the following facts are taken into account:

a) The consideration of the broad distribution of the different consumption due to different user behaviour should comply with the rules of statistics. A statistical sample with a sufficient number of users/homes (e.g. 20 or 25) has to be measured in order to include a broad variety of users. Only then, the average consumption can be compared to the calculated one, as was done by Peper and Feist [25]. If the number of the measured homes is small, the statistical sample is not sufficient and the uncertainty increases significantly. This implies an inappropriate estimation of the expectation value of the measured quantity.

b) Appropriate calculation methods, suitable boundary conditions, and relevant heat source distribution have to be implemented in the models. For example, if thermal bridges are not taken into account, or if infiltration or shading are not properly incorporated in the calculation, or if the g-value is not a function of the incident angle of solar radiation, the calculation results can deviate by tenths of a percent leading to an irrelevant comparison with the measurements. It is noted that building simulation tools may provide quite different results just by modifying one of these parameters [31]. As also shown by Strachan et al. [23], algorithm deficiencies and tool-user errors could be the reason for significantly different results among building simulation approaches.

c) Appropriately measured characteristic values of construction materials and components have to be used in the calculations. Use of characteristic values from manufacturer datasheet, instead of those from certification, can lead to incorrect calculation results. Even characteristic values, which are measured according to standards, can be misleading if the algorithm of the tool is not compatible with the laboratory method. For example, the heat recovery rate of a ventilation unit has a different value if the calculation method is based on the supply/extract air side instead of the exhaust/ambient air side. In that case, the rate may be 92%, instead of 85%. Therefore, it is essential to use the exhaust/ambient air side method to remain on the safe side of the calculation results.

d) Another important issue is to update the energy calculations with the changes that have occurred between the first design and the end of detailed planning, and the changes during commissioning. However, this is often not the case, and as a consequence, the inputs in the calculations are not actual, leading to incorrect results. Of less importance is the quality assurance control after construction and component installation. Usually, the technicians and installers are able to do their part correctly, when the detailed plans are transparent.

It has to be mentioned that the difference between measured and calculated energy is significantly reduced in highly energy-efficient buildings, such as Passive Houses (compared to poor performance buildings) [25,32].

Since the heating set point temperature in the calculations significantly influences the results, the choice of the appropriate temperature is quite important. Based on the simulation work [**Publication H**], a formula has been developed to estimate an equivalent heating reference temperature (EHRT) as a function of living area, outdoor temperature, and building envelope. EHRT is recommended to be used as the input set point temperature in the simulation models to represent the appropriate average indoor temperature. As shown in the simulation results, the use of EHRT can further reduce the difference between calculated and measured heating demand.

# 4 Conclusions and outlook

This thesis focuses on building energy renovation according to EnerPHit or Passive House standard. An innovative compact heating and ventilation system, consisting of an exhaust air to supply air heat pump (micro-HP) combined with a heat recovery ventilation (HRV) unit, was developed and evaluated through dynamic simulations and in-situ detailed monitoring. In addition, in this context, PHPP was evaluated to be used as an energy auditing tool for building renovation.

The dynamic simulations of the combined micro-HP and HRV proved the feasibility of the concept. In addition, the proposed system consumes less electricity in highly energy-efficient buildings compared to other innovative systems (e.g. exhaust ventilation with an exhaust air-to-water heat pump and ventilation radiators). Moreover, the use of a variable-speed compressor is recommended leading to approximately a 15% increase in the performance and a reduced probability of improper dimensioning of the HVAC system.

The monitoring data analysis showed an SPF of the HVAC system with a value of 2.8 (of the micro-HP alone 2.5), and a good indoor air quality and thermal comfort in the experimental flat. The simulation models of the micro-HP and the flat were compared to the monitoring data and further used in annual simulations for further system optimisation. The possible improvements can decrease the electricity consumption by 25%.

PHPP is recommended to be used as an energy auditing tool. The extensive comparative study between PHPP and TRNSYS showed that the monthly energy balance algorithm of PHPP is accurate enough compared to a dynamic numerical simulation model. The better the building envelope quality is, the lower the deviation between the tools. The average deviation in heating demand was 7% and in cooling demand 16% (disregarding the climates without relevant cooling demand).

Furthermore, the reasons the so-called ‘performance gap’ can be characterised as a misleading observation are discussed.

In future work, for further development of the micro-heat pump, recirculated air could be incorporated with the advantages of increasing the heating (and the optional cooling) power, and reducing the supply temperature, which increases the energy performance. Future simulation studies that compare the energy performance of the micro-HP system to other solutions should also include the energy system for the supply of the domestic hot water. The latter becomes relevant for the total energy consumption, especially when the space heating is significantly low such as in Passive Houses.

Moreover, in future studies when evaluating PHPP as an energy auditing tool, it is recommended to include an economic analysis and to evaluate PHPP for real case studies.

# 5 Relevant publications

This chapter includes the relevant publications of this thesis. Every publication is in the original format and is included here with the permission of the corresponding editor.

## 5.1 Publication A

**Title**

Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation

**Authors**

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**Own contribution**

Modelling and simulation work of the study was performed using two software tools, TRNSYS and Matlab Simulink, and it was shared correspondingly between the first and second author. My part as second author was the simulation in Matlab Simulink for systems A and D, while the first author simulated in TRNSYS the systems B, C and D. In addition, the calculation work in PHPP was performed by the second author. The first author took over the writing of the paper with some minor contribution from my side about system A. The significant contributions of the co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

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# Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation

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ABSTRACT

In this paper, dynamic simulation was used to compare the energy performance of three innovative HVAC systems: (A) mechanical ventilation with heat recovery (MVHR) and micro heat pump, (B) exhaust ventilation with exhaust air-to-water heat pump and ventilation radiators, and (C) exhaust ventilation with air-to-water heat pump and ventilation radiators, to a reference system: (D) exhaust ventilation with air-to-water heat pump and panel radiators. System A was modelled in MATLAB Simulink and systems B and C in TRNSYS 17. The reference system was modelled in both tools, for comparison between the two. All systems were tested with a model of a renovated single family house for varying U-values, climates, infiltration and ventilation rates.

It was found that A was the best system for lower heating demand, while for higher heating demand system B would be preferable. System C was better than the reference system, but not as good as A or B.

The difference in energy consumption of the reference system was less than 2 kWh/(m$^2$ a) between Simulink and TRNSYS. This could be explained by the different ways of handling solar gains, but also by the fact that the TRNSYS systems supplied slightly more than the ideal heating demand.


## 1. Introduction

About 40% of the total energy use in the EU-27 is accounted for by the building sector. Thus, the building stock plays an important part in the work towards the international goals of lower energy use [1]. Two-third of the energy used in households in the EU-15 goes to space heating [2], and the largest potential for saving energy in this sector lies in renovation and upgrading of old buildings to modern energy standards [3]. Such renovation measures include changing windows, insulating roofs and external walls and changing HVAC systems. The latter of these was the objective of this study.

Many studies have previously been conducted within the field of HVAC systems and energy use of buildings, both residential and commercial buildings. Bojić et al. [4] compared three HVAC systems for heating and cooling of an office building. Wang et al. [5] made a comparison of three HVAC systems for a hypothetical apartment building. The study included 17 climate zones with various temperature and humidity conditions, and the systems compared were a direct expansion split system, a split air-source heat pump system and a closed-loop water-source heat pump with boiler an evaporative fluid cooler.

A study carried out by Gustafsson et al. [6], treating two HVAC systems similar to systems A and B of this study, indicated that these systems may indeed be potential alternatives to other, more established, systems. The results of this and the study by Wang et al. [5] also confirm the necessity to vary the climatic conditions when comparing HVAC systems.

A complete building retrofit includes many more steps and aspects than those covered in this study. Ma et al. [7] proposes a systemic approach, going all the way from planning to post-evaluation. The present study focuses on the choice of HVAC systems after a renovation of the building envelope.

There is a wide range of tools for simulation of building energy performance. In a study by Ochs et al. [8], the simulation tools MATLAB Simulink [9] and TRNSYS 17 [10] are used to model a renovated multi-family house. According to this study, there are major

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**Nomenclature**

| | |
|---|---|
| COP | coefficient of performance |
| HD | annual heating demand of building (kWh/(m$^2$ a)) |
| HVAC | heating, ventilation and air conditioning |
| MVHR | mechanical ventilation with heat recovery |
| *U* | heat transfer coefficient for building parts (W/(m$^2$ K)) |

*Greek letters*

| | |
|---|---|
| $\eta$ | air change rate (h$^{-1}$) |

*Subscripts*

| | |
|---|---|
| inf | infiltration |
| vent | ventilation |

differences between the tools regarding the modelling of walls, zone nodes, windows and shading, and the time step of the solver (fixed in TRNSYS, adaptive in MATLAB Simulink). However, the study also shows good agreement in results between the two tools.

In this study, the energy performance of three innovative heating and ventilation systems was investigated through dynamic simulation and set in relation to a reference system, based on a common air-to-water heat pump. The choice of systems A, B and C was based on their potential suitability for building renovation and on the need to fill a gap in the research, while D is an established type of system, thus suitable as reference. All of the tested systems were implemented in a model of a generic single family house and tested for two renovation levels in seven different climates.

The second objective of this study was to contribute to the comparison of different simulation tools. The reference system was modelled in both MATLAB Simulink and TRNSYS 17, to enable detection of systematic differences.

## 2. Methodology

### 2.1. Building model and boundary conditions

The building modelled in this study is a semi-detached single family house, with a tempered floor area of 78 m$^2$ and a volume of the tempered zone of 187 m$^3$. It was defined within the FP7 project iNSPiRe [11] as a typical European single family house construction. The actual building is located in London, UK, and consists of two floors and an unheated attic, with an insulated ceiling between the top floor and the attic. In the model, the attic was excluded, and the ceiling of the top floor was taken to be the upper limit of the building envelope. Solar gains of the roof were thus disregarded and the ceiling was assumed to exchange heat directly to the ambient air. The western wall, adjacent to the neighbouring house, was taken to be adiabatic. The whole tempered area was modelled as one zone, with stairs and intermediate floor as internal walls. Simulations in TRNSYS 17 comparing the single zone model to a model with one zone per floor and one zone for the attic showed a difference in heating demand and heat load of less than 3% for the climate of London.

For open window ventilation and shading, the boundary conditions used in this study were the same as those used within [11], and to a large extent also within IEA SHC Task 44 [12]. Internal gains from occupants and electrical equipment were based on the same schedule as in [11] and [12], but since the living area for the building used in this study was only 78 m$^2$, compared to 140 m$^2$ in [12], the number of occupants was reduced from four to two and the gains from electrical equipment and lighting were scaled down by 50%. The ventilation rate was taken to be 0.4 h$^{-1}$ and the infiltration rate was calculated from a simplified model of the building envelope to be 0.1 h$^{-1}$. For two of the studied climates, the influence of air change rates on the HVAC systems was tested. The infiltration rate was increased by steps of 0.1 to 0.2 h$^{-1}$ and 0.3 h$^{-1}$. The ventilation rate was both decreased and increased by the same amount to 0.3 h$^{-1}$ to 0.5 h$^{-1}$. While varying one these parameters, the other one was kept at its default value.

The desired indoor temperature, which was used to control the heating systems, was set to 20 °C. Transmission losses to the ground were modelled by setting the disturbed ground temperature as boundary temperature for the ground floor. The disturbed ground temperature was approximated as a sine, which was calculated according to standard ISO 13370 [13].

Beside ventilation and infiltration rates, the sensitivity analysis comprised climatic conditions and heating demand. Climate data for seven different European locations were used, as listed in Table 1. The chosen locations, the same as used in iNSPiRe [11], represent continental and coastal climates as well as a range of average ambient temperature and relative humidity. Data files from Meteonorm [14], based on long-term measurements, were used to generate weather data for the simulations.

For each climate, two renovation levels were defined. EnerPHit standard (HD25) [15] and Passive House standard (HD15) [16] were used to define houses with heating demands of 25 kWh/(m$^2$ a) and 15 kWh/(m$^2$ a), respectively, assuming a heat recovery efficiency of 85% and disregarding cooling demand. For the tested systems which did not include heat recovery, the actual heating demand was higher. The difference in heating demand with or without heat recovery was larger for the colder climates, where the heat recovery has a larger impact. Insulation thicknesses and related U-values were calculated using the passive house calculation tool PHPP [17]. The applied U-values for each climate and renovation level are listed in Table 1.

### 2.2. Investigated systems

All of the tested systems were set to provide space heating and ventilation, while domestic hot water use was left out of the study. The cooling demand was evaluated by measuring the number of hours with indoor temperature above 26 °C. The comparison of the systems did not include an economic analysis, and practical details on installation were not considered. Total energy consumption included heat pump compressor, auxiliary heater, pump for the space heating circuit and ventilation fans. All energy consumed was thus electricity.

The layouts of the investigated HVAC systems are described in Fig. 1.

#### 2.2.1. System A

System A is based on a micro heat pump, in combination with mechanical ventilation with heat recovery (MVHR), with electric radiators as backup for peak heat loads. The heat pump uses the exhaust air of the heat recovery unit as source and provides heat to the supply air of the ventilation system. Thus, one compact unit can be used for combined ventilation and heating or cooling (reverse operation for cooling). Fresh outdoor air flows into the heat recovery unit, where it is heated with a recovery efficiency of up to 95%. It is then further heated by the micro heat pump up to maximum 52 °C, as higher temperatures may cause odour problems, to supply space heating.

In comparison to an air source heat pump, the evaporator uses the benefit of slightly higher source side temperature and of latent heat. The evaporator extracts heat from the air using the latent heat of condensation, and the higher source side temperature improves the coefficient of performance (COP) of the heat pump. However, the air volume flow rate in the evaporator, which is equal to the flow

**Table 1**
Locations for climatic data and corresponding *U*-values used in simulations.

| Location | *U*-values [W/m² K] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | HD25 | | | HD15 | | | Both | |
| | Walls | Floor | Roof | Walls | Floor | Roof | Windows | Doors |
| Stockholm | 0.126 | 0.128 | 0.126 | 0.057 | 0.057 | 0.057 | 0.90 | 0.80 |
| Gdansk | 0.150 | 0.153 | 0.150 | 0.074 | 0.075 | 0.075 | 0.90 | 0.80 |
| Stuttgart | 0.235 | 0.244 | 0.237 | 0.143 | 0.146 | 0.144 | 0.90 | 0.80 |
| London | 0.277 | 0.290 | 0.279 | 0.175 | 0.180 | 0.176 | 0.90 | 0.80 |
| Lyon | 0.320 | 0.337 | 0.323 | 0.198 | 0.204 | 0.199 | 0.90 | 0.80 |
| Madrid | 0.500 | 0.544 | 0.509 | 0.361 | 0.383 | 0.365 | 0.90 | 0.80 |
| Rome | 0.621 | 0.689 | 0.634 | 0.456 | 0.492 | 0.463 | 0.90 | 0.80 |

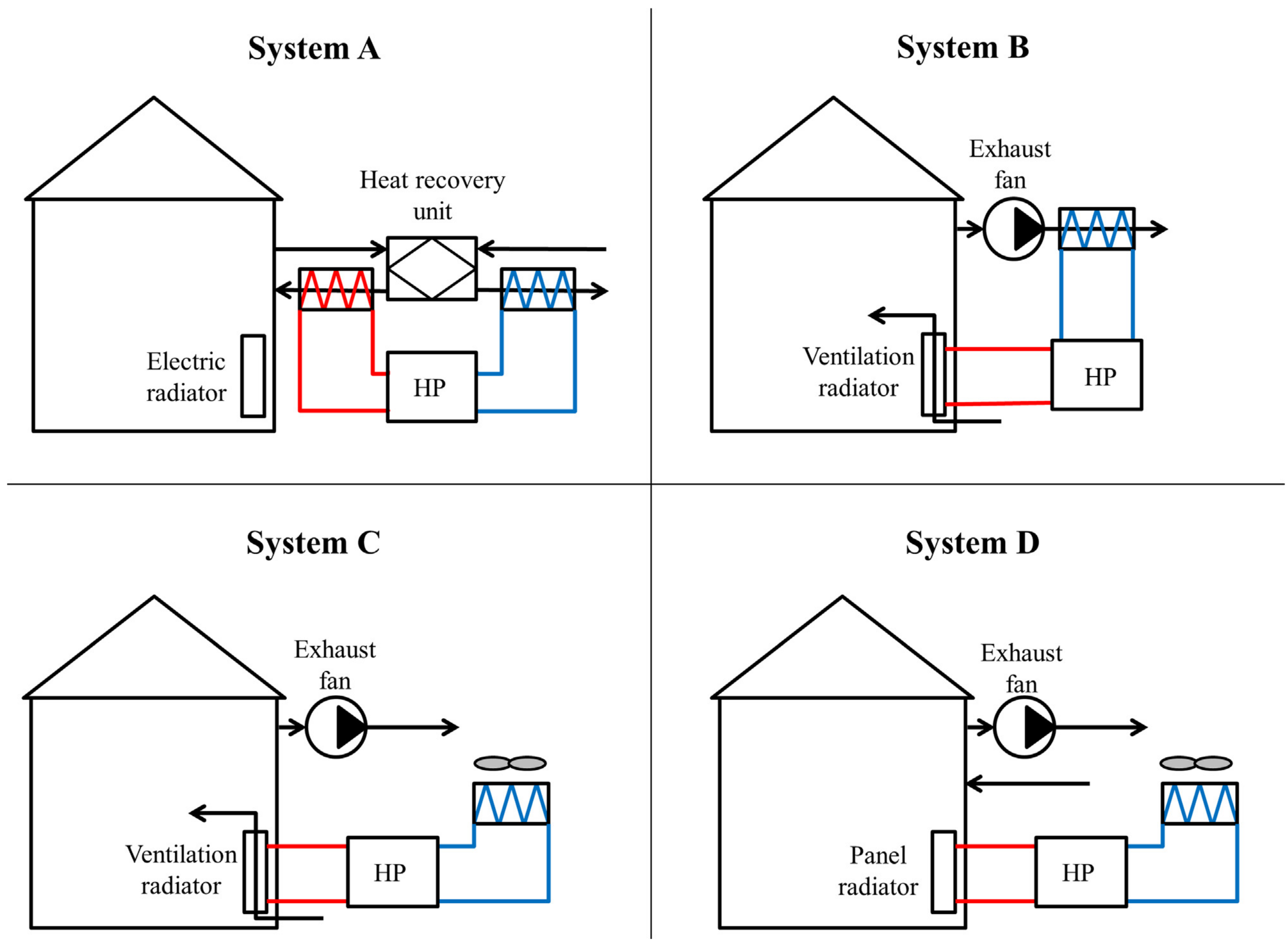


**Fig. 1.** Schematic layout of studied HVAC systems: (A) mechanical ventilation with heat recovery (MVHR), micro heat pump and electric radiators, (B) exhaust ventilation with exhaust air-to-water heat pump and ventilation radiators, (C) exhaust ventilation with air-to-water heat pump and ventilation radiators and (D) exhaust ventilation with air-to-water heat pump and panel radiators.

rate in the condenser, is limited to the hygienic flow rate (too high flow rate leads to dry indoor air). Thus, the source power is limited. The heating capacity of the micro heat pump is in the range of 1 kW. Therefore, this system can only be implemented in flats or small houses with very low energy demand such as Passive Houses. The advantages of the micro heat pump are the compactness, giving the possibility of integration into the façade, and cost reduction [18].

In order to model system A in MATLAB Simulink, the EFKOS model [19] was used. The EFKOS model was originally developed for air-to-water heat pumps, but the micro heat pump is an exhaust air-to-air heat pump. Therefore, the input data for the model were chosen so that the output data would fit to the heating test points of Passive House Component Certificate of the compact unit Aerosmart m Drexel & Weiss [20]. A mean volume flow rate of 160 $m^3/h$ was taken for the measured test points of the certificate. In the studied building with a default ventilation rate of 0.4 $h^{-1}$ and a volume of 187 $m^3$, the volume flow rate is 74.8 $m^3/h$. To adapt to this, the heating capacity was scaled down while keeping the ratio of heating capacity and volume flow rate constant, assuming the COP to be independent of the volume flow rate. Table 2 shows nominal performance data for the micro heat pump for inlet air temperatures to the heat recovery unit, calculated for 78% heat recovery efficiency.

### 2.2.2. System B

In system B, the mechanical exhaust ventilation provides an air-to-water heat pump with air from the living zone, while at the same time creating the low pressure needed to drive the air flow through

**Table 2**
Rated performance of micro heat pump for inlet air temperatures to the HRC unit.

| | Air temperature [°C] | | |
|---|---|---|---|
| | −2 | 2 | 7 |
| Heating output [kW] | 1.03 | 1.18 | 1.34 |
| COP [dimensionless] | 2.22 | 2.73 | 3.07 |

the ventilation radiators into the building. The heat pump extracts heat from the air and delivers heated water to the radiators. The number of ventilation radiators was chosen based on the desired ventilation rate and the ideal air flow and pressure drop for one ventilation radiator [21]. The radiators were then sized to cover the heat load of the building at a distribution and return temperatures of 35/30 °C. The heat pump model was based on performance data for an existing air-to-water heat pump for exhaust air, as presented in Table 3 [22]. The same heating capacity, plus an auxiliary heater of 1.5 kW, was used for all locations and renovation levels. The water flow rate was held constant at the nominal level according to test standards [23].

In the ventilation radiators, outdoor air flows in through a duct in the wall and is heated by the radiator panels before entering the room. The heat output of a radiator, either of traditional or ventilation type is proportional to the mean temperature difference between the radiator surface and the air in contact with the heated radiator surfaces. Because of the lower surrounding air temperature of a ventilation radiator compared to a traditional radiator, it can work with a lower supply water temperature. The direct contact with outdoor air gives the system the quality of fast thermal response, as the heat output is automatically adjusted with any change of ambient air temperature. Ventilation radiators have also been proven to perform well in terms of thermal comfort, giving a stable and uniform indoor climate [24], and the low water temperature is beneficial for the performance of the heat pump. From a renovation perspective, ventilation radiators in combination with mechanical exhaust ventilation can be a competitive solution, given that there is already a water heating system in the house.

#### 2.2.3. System C

System C has the same configuration as system B, but with a regular air-to-water heat pump without heat recovery from exhaust air. The heat pump model was based on manufacturer performance data for an existing air-to-water heat pump, as presented in Table 4, with a nominal capacity of 3 kW and a nominal COP of 3.27 at A2/W35 [25].

Assuming the COP to be independent of size, the nominal heating capacity was scaled down to cover the average heat load over 24 h during the whole year. The nominal water flow rate, as given by test standards [23], was scaled accordingly, to allow using the same performance data. An auxiliary heater of 1 kW was employed when necessary. In Table 5, the nominal capacity and flow rate for each location and renovation level are listed.

For the sensitivity analysis on ventilation and infiltration, the heat pump was sized to fit the new loads, as shown in Table 6.

**Table 5**
Nominal capacity and flow rate of scaled down air-to-water heat pump.

| | HP capacity [kW] | | HP water flow rate [kg/s] | |
|---|---|---|---|---|
| Location | HD25 | HD15 | HD25 | HD15 |
| Stockholm | 1.90 | 1.70 | 0.121 | 0.108 |
| Gdansk | 1.70 | 1.50 | 0.108 | 0.095 |
| Stuttgart | 1.90 | 1.60 | 0.121 | 0.102 |
| London | 1.60 | 1.40 | 0.102 | 0.089 |
| Lyon | 1.70 | 1.40 | 0.108 | 0.089 |
| Madrid | 1.90 | 1.60 | 0.121 | 0.102 |
| Rome | 1.70 | 1.40 | 0.108 | 0.089 |

#### 2.2.4. System D

The heat pump of the reference system D is the same as the one used in system C, and was sized the same way. The traditional panel radiators were assumed to be in place before the renovation and sized to cover the heat load of the building without the extra insulation applied for HD25 or HD15. Design distribution and return temperatures were taken to be 90/70 °C, but in the renovated houses studied, the actual radiator water temperatures would be lower, due to the lower heat load.

### 2.3. Simulation tools

System A was modelled in MATLAB Simulink and systems B and C were modelled in TRNSYS 17, while the reference system D was modelled in both tools, to enable comparison between this and the other systems while reducing the risk of systematic errors. This also allowed for a comparison between the two simulation tools. A time step of five minutes was used in the TRNSYS simulations, while MATLAB Simulink uses an adaptive time step.

**Table 3**
Rated performance of the exhaust air-to-water heat pump of system B.

| | Water temperature [°C] | Air flow rate [l/s] | | | | |
|---|---|---|---|---|---|---|
| | | 30 | 40 | 50 | 60 | 70 |
| Heating output | 35 | 1.14 | 1.30 | 1.42 | 1.46 | 1.50 |
| [kW] | 45 | 1.15 | 1.24 | 1.30 | 1.35 | 1.37 |
| COP [dimensionless] | 35 | 4.46 | 4.76 | 5.12 | 5.24 | 5.43 |
| | 45 | 3.34 | 3.49 | 3.72 | 3.86 | 3.91 |

**Table 4**
Rated performance of the air-to-water heat pump of systems C and D.

| | Water temperature [°C] | Air temperature [°C] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | −15 | −7 | 2 | 7 | 10 | 12 | 20 | 30 |
| Heating output | 35 | 1.70 | 2.60 | 3.00* | 4.50 | 4.60 | 4.80 | 5.00 | 5.50 |
| [kW] | 45 | 1.50 | 2.30 | 2.80 | 4.00 | 4.20 | 4.40 | 4.60 | 5.00 |
| | 55 | 1.30 | 2.00 | 2.70 | 3.70 | 3.80 | 4.00 | 4.30 | 4.70 |
| COP | 35 | 1.90 | 2.85 | 3.27** | 4.64 | 4.83 | 5.00 | 5.27 | 5.70 |
| [dimensionless] | 45 | 1.60 | 2.20 | 2.65 | 3.55 | 3.67 | 3.75 | 4.04 | 4.41 |
| | 55 | 1.16 | 1.70 | 2.12 | 2.74 | 2.87 | 3.10 | 3.30 | 3.45 |

* Nominal heating output.
** Nominal COP.

**Table 6**
Nominal capacity and water flow rate of heat pump for varying ventilation and infiltration rates.

| Location | Parametric variation | HP capacity [kW] | | HP water flow rate [kg/s] | |
|---|---|---|---|---|---|
| | | HD25 | HD15 | HD25 | HD15 |
| Stockholm | $\eta_{vent} = 0.3$ | 1.70 | 1.40 | 0.108 | 0.089 |
| | $\eta_{vent} = 0.5$ | 2.20 | 1.90 | 0.140 | 0.121 |
| | $\eta_{inf} = 0.2$ | 2.20 | 1.90 | 0.140 | 0.121 |
| | $\eta_{inf} = 0.3$ | 2.40 | 2.10 | 0.153 | 0.134 |
| Rome | $\eta_{vent} = 0.3$ | 1.60 | 1.30 | 0.102 | 0.083 |
| | $\eta_{vent} = 0.5$ | 1.80 | 1.50 | 0.115 | 0.095 |
| | $\eta_{inf} = 0.2$ | 1.80 | 1.50 | 0.115 | 0.095 |
| | $\eta_{inf} = 0.3$ | 1.90 | 1.60 | 0.121 | 0.102 |

In MATLAB Simulink the complex building model of the Carnot Blockset was used. The heat pump model in system D was based on performance map data. The heating capacity was approximated linearly depending on the source inlet air temperature and the sink outlet water temperature. The COP was based on Carnot COP and the Carnot performance factor. In the initialization of the model (pre-processing) the Carnot performance factor and the linear coefficients for the heating capacity were calculated in order to achieve the best possible agreement.

In TRNSYS, the heat pump was modelled using a performance map with data on heating capacity and compressor power for a range of testing points. The heat output and COP of the heat pump were calculated in the model through interpolation between these points.

The ventilation radiator model of systems B and C was based on an Excel model provided by a radiator manufacturer, which in turn was based on measurements on their own products [26]. A link embedded in TRNSYS was used to connect the Excel model to the rest of the system.

### 2.4. Controls

All heating systems and auxiliary heaters were controlled by on/off differential controllers with hysteresis. The governing temperature was the indoor air temperature. The set point for the primary heating systems was 20 °C, with upper and lower dead bands of 0.25 K. Similarly, the auxiliary heaters had a set point of 19.75 °C and allowed the temperature to vary between 19.5 °C and 20 °C. The set point for the auxiliary heater was set to a lower value to avoid operation during hours when the primary system could manage the heating. The ventilation was running independently of the heating control signals, but in systems A and B the heat pumps were bypassed when no heating was needed.

## 3. Results

Fig. 2 shows the annual heating supply by heat pump and compressor of the reference system and Fig. 3 the electrical energy consumption of the reference system, comparing MATLAB Simulink and TRNSYS for all locations and renovation levels. In Fig. 2, the solid and dashed lines mark the heating demand with heat recovery for the HD25 and the HD15 houses, respectively. The difference between the two tools exceeded 5% only for Madrid and Rome, where the difference was 7% and 6% respectively for supplied heating and 11% and 8% respectively for electrical energy consumption. The trends were similar for both energy standards of the house. In TRNSYS, all systems overshot the ideal heating demand, which was defined as the heating required to keep the indoor air temperature at or above 20 °C at all times, by 1 kWh/(m$^2$ a) to 2 kWh/(m$^2$ a). In Simulink, system D followed the ideal heating demand more closely. The ideal heating demand simulated in Simulink was higher than in TRNSYS for all climates except for Madrid and Rome, where

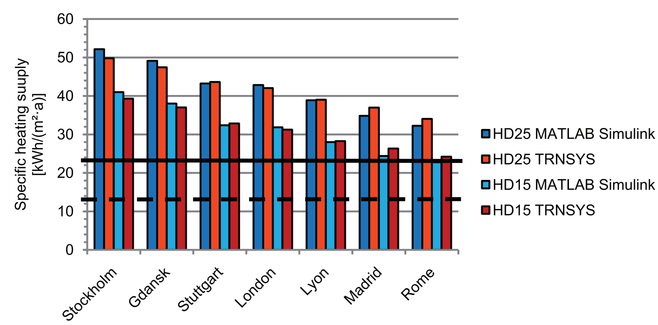


**Fig. 2.** Annual heating supplied by system D in MATLAB Simulink and in TRNSYS. Solid line marks heating demand of HD25 with heat recovery; dashed line marks heating demand of HD15 with heat recovery.

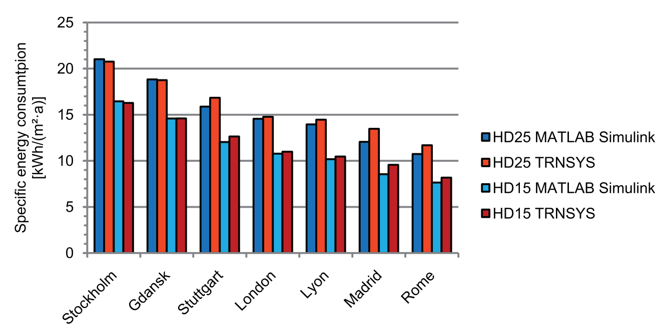


**Fig. 3.** Electrical energy consumption of system D in MATLAB Simulink and in TRNSYS.

it was lower. The seasonal performance factor of the heat pump was around 0.1 higher in Simulink than in TRNSYS. In terms of gains and losses of the house, some differences were noted in absorbed solar energy. The solar gains in MATLAB Simulink were around 3 kWh/(m$^2$ a) higher than in TRNSYS for the climates of Madrid and Rome, while for other climates the solar gains were 2.5 kWh/(m$^2$ a) to 5 kWh/(m$^2$ a) lower in MATLAB Simulink than in TRNSYS.

The relative energy consumption of systems A, B and C compared to the reference system D is shown in Fig. 4. System A is set in relation to the performance of system D in MATLAB Simulink, while B and C are set in relation to the TRNSYS model of system D.

System A had the lowest energy consumption for both renovation levels in all climates. The largest savings compared to system D were seen for the HD15 in cold climates, with a maximum of 36% for the climates of Stockholm and Gdansk.

System B showed a similar trend, but with less difference between the coldest and the warmest climates, and also less difference between the two renovation levels. For the HD25 house it was close to system A in energy consumption in all climates. The maximum energy saving compared to system D was 23% for the HD15 house in Stockholm.

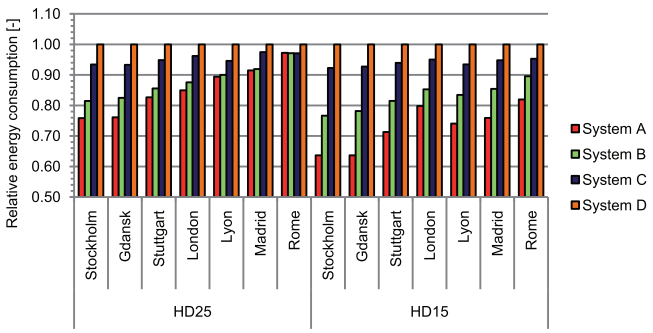


**Fig. 4.** Energy consumption of tested systems compared to the reference system for varying climate and heating demand.

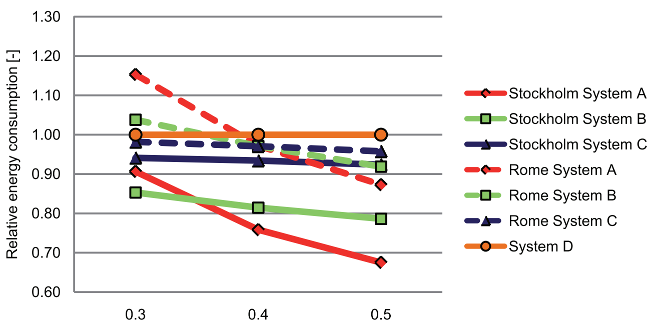


**Fig. 5.** Energy consumption of tested systems (HD25) compared to the reference system for varying ventilation rate.

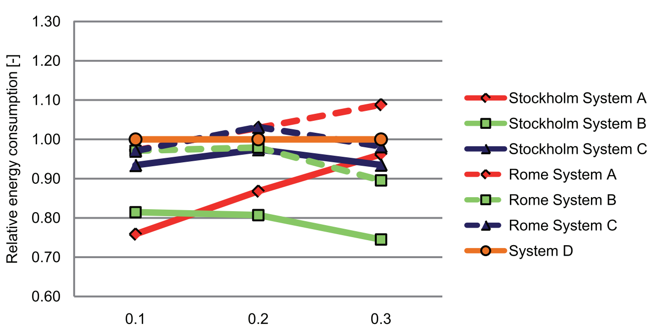


**Fig. 6.** Energy consumption of tested systems (HD25) compared to the reference system for varying infiltration rate.

For system C, the energy use was consistently lower than the reference, with only small variations with the climates. It was the best system, together with A and B, for the HD25 house in Rome. The energy savings compared to system D ranged from 3% for the HD25 house in Madrid and Rome to 8% for the HD15 house in Stockholm.

The influence of ventilation rate on the energy performance is shown in Fig. 5 and the influence of infiltration rate in Fig. 6, both for the HD25 house. System A was affected in a positive direction relative to system D when the ventilation rate was increased and in a negative way when the infiltration rate was increased. With a ventilation rate of 0.5 $h^{-1}$, the energy performance of system A was better than the reference for the climate of Rome. For system B, both ways of increasing the air change rate were favourable compared to system D. With an infiltration rate of 0.2 $h^{-1}$, system B had the best energy performance for Stockholm, and with an infiltration rate of 0.3 $h^{-1}$ it was the best system also for Rome. System C was not significantly influenced in any way in relation to the reference system by either of these parameters.

Fig. 7 shows the number of hours with room temperature above 26 °C for the reference system. In Lyon, Madrid and Rome, the room

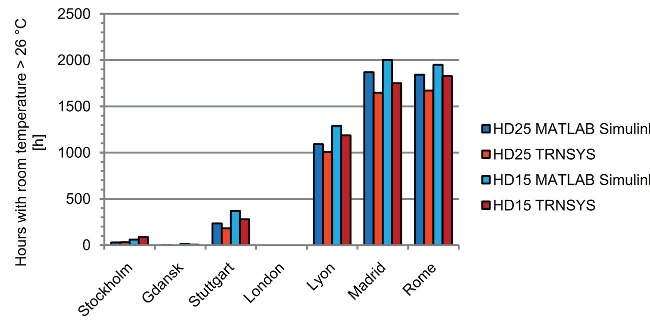


**Fig. 7.** Number of hours with room temperature above 26 °C for the reference system in MATLAB Simulink and in TRNSYS.

temperature reached above 26 °C for 1000 h to 2000 h per year, with slightly higher figures for the HD15 house. All systems met the criteria to keep the temperature above 19.5 °C at all times.

## 4. Discussion

In the comparison between the two simulation tools, some deviations were observed for the performance of system D. The relatively high differences in percentage for Rome and Madrid could partly be explained by the low heating demand for these locations. Also, in TRNSYS all the tested systems provided 1 kWh/($m^2$ a) to 2 kWh/($m^2$ a) more than the ideal heating demand, notably with a mutual difference of less than 1 kWh/($m^2$ a) between them. There also seemed to be a difference in how the two tools handle solar gains of a house. This showed in the number of hours with overheating, where the simulations in MATLAB Simulink gave a higher number in most cases. It could also have influenced the difference in annual heating demand.

The house was modelled as a single zone, disregarding solar gains to the roof. For the heating demand, particularly for London and colder climates, this approach makes little or no difference to the results compared to a model including roof and attic, since the solar gains are relatively small during the heating season. In warmer climates the difference could be more significant, and if the cooling demand is to be determined all solar gains should be taken into account.

Heating systems that are based on heat recovery of ventilation air are always limited by the ventilation rate. For both systems A and B in this study, the relatively low ventilation rate limited the heating capacity of the respective heat pumps and increased the need for auxiliary heating. Varying the ventilation rate, it was shown that the performance of these systems system relative to the reference system improved with a higher ventilation rate, and vice versa. When it comes to varying the infiltration rate, A and B are affected in opposite ways. In system B, the exhaust fan enables the exhaust air heat pump to utilize both the ventilation and infiltration air to deliver energy to the ventilation radiators. In system A, the heat recovery unit can only make use of the ventilation part, while the infiltrated air just adds to the heat losses.

All systems were compared for the same infiltration rate. However, the infiltration rate of a house is dependent on the pressure difference between indoor and outdoor, which in turn depends on the type of ventilation system installed [27]. System A, using balanced ventilation, would have a lower infiltration rate than the other systems for the same house.

In the present study, the use of mechanical ventilation was accounted for only during the months when the house required heating. In Sweden, building regulations [28] do not allow replacing mechanical ventilation with opening windows. Extending the ventilation period would strike the hardest on system A, since the MVHR consumes more energy than a simple exhaust fan. For the

HD15 house in Stockholm, applying mechanical ventilation all year would increase the total energy consumption of system A by 8%, whereas the increase for systems B, C and D would be 2–3% for the same case. However, bypassing the heat recovery unit during summer would reduce the impact on energy consumption for system A.

For system C, some savings were seen due to the lower water temperature enabled by the use of ventilation radiators. However, the water temperature in the reference system was already low, since the existing radiators were sized for a higher heat load. The largest reduction in energy consumption was seen for system A, where the air heat recovery cut down the heating demand significantly compared to that of other systems. System B consumed less energy than system C due to the higher source side temperature of the exhaust air heat pump.

System A was the system that benefitted the most from a higher renovation standard. It had the lowest energy consumption for both renovation level and all climates, but for the HD25 house it consumed almost as much energy as system B, despite the advantage of MVHR. This confirms the premise that the micro heat pump is best applied in very low energy building such as Passive Houses and suggests that a system like B would be preferable in houses with higher heating demand.

In a complete building retrofit, it may not always be feasible from the economic point of view to achieve Passive House standard. For the climates of Gdansk and Stockholm 200-300 mm of extra insulation is required to go from HD25 to HD15 level. This will of course increase the investment costs significantly, even though the total insulation thickness could be reduced by choosing better insulating windows and improve the air tightness in such cold climates. On the other hand, insulation of the floor may not always be feasible, thus increasing the need for improvements on other parts of the building envelope.

The level of insulation can also be important for the choice of heating system in terms of thermal comfort. If ventilation radiators are used in heavily insulated houses, as in systems B and C, there could be problems with cold draft when the outdoor temperature is at or near the balance temperature of the house. As the heating system will not be active above the balance temperature, a lower balance temperature will allow colder air to be supplied through the radiators.

In warmer climates, a thicker insulation leads to slightly higher indoor temperatures during summer, thus occasionally increasing the cooling demand. The observed indoor temperatures for Lyon, Madrid and Rome in this study indicate that the tested house would need a cooling device in these climates; a service which could be provided by reversing the operation of the heat pump.

A complete energy system for a house need also include domestic hot water. Air-to-water heat pumps, like the ones used in systems B, C and D, are normally designed to handle both space heating and hot water. System A, on the other hand, would require a complement to the air-to-air micro heat pump to be able to provide this service. In heavily insulated houses, where heat losses are minimized, the relative importance of hot water use will naturally become larger.

The heat pump used in systems C and D was scaled down from 3.0 kW to heating capacities ranging from 1.2 kW to 2.4 kW, assuming that the COP remained the same. In reality, the Carnot efficiency, and thus the COP, might not be independent of the capacity of the heat pump. For a scaling down of this relatively small magnitude, it may not have a great impact, but it should be taken into consideration that it could affect the result of systems C and D, especially for the warmer climates where the heat pump has been scaled down more.

The TRNSYS heat pump model used was not designed for variable speed. The exhaust air heat pump of system B would, in reality, be able to vary the compressor speed to cope with higher loads, and would therefore need to use less auxiliary heating than the model did. The micro heat pump of system A also has the potential to perform slightly better with a speed controlled compressor. The influence of control strategy could be a subject for future studies.

## 5. Conclusions

In dynamic simulation of building energy performance, the results are to some extent dependent on the choice of simulation tool. The differences between MATLAB Simulink and TRNSYS 17 were in this study found to be larger for warmer climates, possibly because of differences in how solar gains are treated in the two tools. Also, the TRNSYS systems supplied slightly more than the ideal heating demand. Still, the magnitudes of the deviations were acceptable.

Both systems A and B were more favourable in colder climates; system A due to the heat recovery and system B due to the higher source side temperature of the heat pump. According to the results of this study, system A is the best option in well-insulated houses with low infiltration and high ventilation rate. For a less insulated house with higher infiltration rate, located in the same climate, system B would have the best energy performance. The performance of system C shows that some energy can be saved by applying ventilation radiators instead of traditional panel radiators, although in this case the panel radiators were sized for a higher heat load and thus also enabled a low water temperature. System C was better than the reference system, but not as good as A or B.

In future studies of retrofitted buildings, it is suggested to include the use of domestic hot water, as this will make up a larger part of the total energy consumption when the space heating demand is lowered through renovation of the building envelope. In warm climates, cooling demand should also be considered.

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## References

[1] The European Parliament and the Council of the European Union. Directive 2010/31/EU on the energy performance of buildings. Official Journal of the European Union, L 153 (2010) 13–35.
[2] European Environment Agency. Energy and Environment Report, 2008. ISBN: 978-92-9167-980-5.
[3] European Commission Environmental Improvement Potentials of Residential Buildings (IMPRO-Building). Office for Official Publications of the European Communities, 2008. ISBN: 978-92-79-09767-6.
[4] M. Bojić, N. Nikolić, D. Nikolić, J. Skerlić, I. Miletić, A simulation appraisal of performance of different HVAC systems in an office building, Energy and Buildings 43 (2011) 1207–1215.
[5] W. Wang, J. Zhang, W. Jiang, B. Liu, Energy performance comparison of heating and air-conditioning systems for multi-family residential buildings, HVAC&R Research 17 (3) (2011) 209–322.
[6] M. Gustafsson, J.A. Myhren, C. Bales, Comparison of two HVAC solutions: a case study, in: CLIMA 2013, Prague, Czech Republic, 2013.
[7] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: methodology and state-of-the-art, Energy and Buildings 55 (2012) 889–902.
[8] F. Ochs, G. Dermentzis, D. Siegele, A. Konz, W. Feist, Use of building simulation tools for renovation strategies—a renovation case study. Part of European 7th Framework Programme project iNSPiRe, 2013.
[9] MathWorks. Simulink–Simulation and Model-Based Design. ⟨http://www.mathworks.se/products/simulink/⟩ (accessed 25.02.14).
[10] S.A. Klein, A. Beckman, W. Mitchell, A. Duffie, TRNSYS 17—a transient systems simulation program, in: Solar Energy Laboratory, University of Wisconsin, Madison, 2011.

[11] iNSPiRe, European Commission 7th Framework Programme project. Proposal number: 314461; Title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems; Duration: 2012-10-01–2016-09-30.
[12] The Reference Framework for System Simulations of the IEA SHC Task 44/HPP Annex 38–Part B: Buildings and Space Heat Load, 2012.
[13] ISO 13370:2007–Thermal performance of buildings—Heat transfer via the ground—Calculation methods.
[14] Meteonorm. ⟨http://meteonorm.com/⟩ (accessed 25.02.14).
[15] Passive House Institute. EnerPHit: Certification criteria for retrofits, 2012.
[16] Passive House Institute—Passive House requirements. ⟨http://www.passiv.de/en/02_informations/02_passive-house-requirements/02_passivehouse-requirements.htm⟩ (accessed 25.02.14).
[17] PHPP—The Energy Balance and Passive House Planning Tool. ⟨http://passiv.de/en/04_phpp/04_phpp.htm⟩ (accessed 25.02.14).
[18] F. Ochs, G. Dermentzis, W. Feist, Façade integrated active components in timber-constructions for renovation—a case study, NSB, Lund, Sweden, 2014.
[19] The Reference Framework for System Simulations of the IEA SHC Task 44/HPP Annex 38–Part C: Heat Pump Models—A5. Heat pump model EFKOS, 2013.
[20] Passive House Institute, Passive House Institute—Passive House Suitable Component Certificate. Compact Heat Pump System, Drexel & Weiss Aerosmart m.
[21] Acticon (2008). Easy-Vent—Frisk luft i bostäder, 26–27.(in Swedish).
[22] N—Indata, NIBE—Indata till TMF:s program ver 2.1 för NIBE F750.(in Swedish).
[23] European Committee for Standardization. European Standard EN 14511-2—Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling—Part 2: Test conditions, 2007.
[24] J.A. Myhren, S. Holmberg, Design considerations with ventilation-radiators: comparisons to two-panel radiators, Energy and Buildings 41 (2009) 92–100.
[25] Viessmann Vitocal Technical Guide. Vitocal 200-S Type AWB 201.B, 2011.
[26] M. Ivonen, 2007. Purmo Air Simulator Vers. 05.11.2007.
[27] Sveriges Centrum för Nollenergihus. FEBY 12–Kravspecifikation för nollenergihus, passivhus och minienergihus (in Swedish), 2012.
[28] Boverket. Swedish Building Regulations, BBR 19, BFS 2011:26 (in Swedish). ISBN 978-91-86827-41-0, 2011.

## 5.2 Publication B

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**Own contribution**

The presented work, the results, the discussion and the conclusions of this publication were performed by the first author. The significant contributions of the co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

# A FAÇADE INTEGRATED MICRO-HEAT PUMP – ENERGY PERFORMANCE SIMULATIONS

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## ABSTRACT

A façade integrated micro-heat pump in combination with mechanical ventilation with heat recovery is developed in the framework of the European project iNSPiRe. A set of system simulations (building combined with HVAC) has been performed to investigate the energy performance of a micro-heat pump. The performance of the system is investigated for different renovation standards (EnerPHit with 25 kWh/(m$^2$·a) and Passive House with 15 kWh/(m$^2$·a)) and for seven different European climate conditions. The potential of the micro-heat pump and the system optimization are investigated within dynamic simulations. Different control strategies using standard hysteresis on/off or PI controller are investigated.

## INTRODUCTION - MOTIVATION

The majority of existing building stock in Europe and worldwide is low energy performance buildings. Deep renovation solutions in combination with integrated Heating Ventilation and Air Conditioning (HVAC) systems are developed within the framework of the European project iNSPiRe. The present study focuses on one approach about a façade integrated micro-heat pump (µHP) in combination with mechanical ventilation with heat recovery (MVHR). The main advantages of the proposed system are the compactness, providing the possibility of integration into the façade, and cost reduction. A prototype will be later monitored in a demo building in Ludwigsburg, Germany. It is an example of social housing built in the 1970s, which contains four flats on four stories. During the renovation process a timber frame façade will be fitted onto the building. The µHP with the MVHR will be integrated into the prefabricated façade.

The prefabricated unit is designed as a compact system for minimal space use. Renovations with minimum intervention are enabled (minimum invasive renovation). A minimal installation effort is desirable for economic reasons. By means of this system, cold ducts inside the thermal envelope can be completely avoided. As the whole solution will be façade integrated and prefabricated, construction and installation time can be kept very short. Building physical aspects have to be carefully investigated (avoiding/reduction of thermal bridges, avoidance of moisture related damage, sound protection). Solutions for easy maintenance need to be developed and tested. The performance of the mechanical ventilation unit with heat recovery and the micro-heat pump are tested in two PASSYS test cells and in an acoustic test rig at university of Innsbruck.

## CONCEPT

The considered system is developed and integrated in a test façade. The heat pump uses the exhaust air of the MVHR as source and provides heat to the supply air of the ventilation system (Figure 1). Thus, one compact unit can be used for combined ventilation and heating or cooling. Fresh outdoor air flows into the MVHR, where it is heated with an energy recovery coefficient of up to 95 %. It is then further heated by the micro-heat pump up to maximum 52 °C in order to supply space heating (reverse operation for cooling would be possible in future versions).

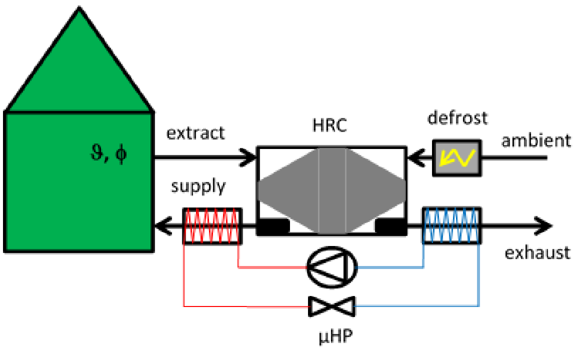


*Figure 1: Simplified concept of the micro-heat pump (µHP with MVHR)*

The concept addresses very good building standards (e.g. EnerPhit 25 kWh/(m² a) (see [Zeno et al., 2012]) or better), corresponding to a specific heat load in the range of 10 W/m². Hence, the typical heat power of the heat pump will be in the range of 1 kW. The proposed system is suggested with a radiator in the bathroom for comfort reasons. If the capacity of the µHP is lower than the design heating load of the building an additional backup heater has to be used.

Basically, the µHP concept would work for water (radiator, floor heating, radiant ceiling) and air based systems (supply air and principally also recirculated air). As source ambient air and/or exhaust air or brine are possible. The exhaust air-to-supply air has the highest potential to be micro and thus compact.

Figure 2 shows the hydraulic scheme of the unit. The ambient air (1) will be heated with the defroster (5) if the ambient temperature drops below -3 °C (optionally -5 °C). The filter for the ambient air (6) is situated in front of the heat exchanger (16). The ventilator for the supply air (8) is situated after the heat exchanger. The supply air will be heated in the condenser (13) of the micro-heat pump. If the temperature of the supply air after the condenser is too low to cover the heat load a supplementary heater (15) will heat the supply air (3) up to 52 °C. The extract air (2) is filtered (7) before the heat exchanger. After the heat exchanger the ventilator for the exhaust air (9) is situated. The frequency controlled compressor (10) of the heat pump is situated in the air flow of the exhaust air in front of the evaporator (11). The optimum position of the compressor is suggested to be in the supply air side. The expansion valve (12) reduces the pressure between condenser and evaporator. Hot gas defrost (14) is necessary in case of ice formation in the evaporator.

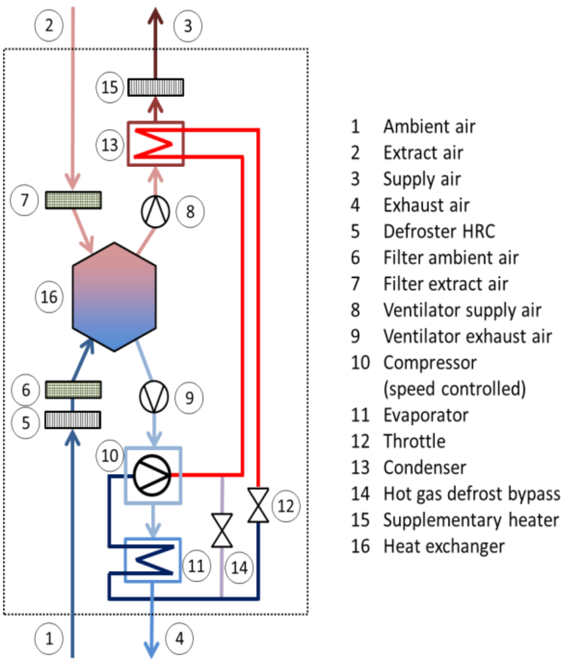


*Figure 2: Hydraulic scheme of the micro-heat pump*

## LABORATORY MEASUREMENTS

Until now two prototypes (dimensions: 2.75 m x 2.75 m) were built for the tests in PASSYS (Passive Solar Systems and Component Testing) test cells.

**PASSYS cells**

One of the test cells is a so called PAS cell (Pseudo Adiabatic Shell) which allows better accuracy. The test cells allow controlling the temperature with high-power heater and cooler. A ventilator and an air distribution system avoid temperature layers in the test cell. Furthermore with a so called cold box the external boundary conditions (temperatures down to -15 °C) can be simulated. For a realistic measurement of the performance of the MVHR and the coefficient of performance (COP) of the heat pump a simple humidifier was installed in the test cells that allow measurements with different relative humidity in the test cells.

**Prototypes**

In the first prototype the ventilation system with heat recovery is integrated in the façade. Special silencers are developed which are also filter boxes. Therefore the filters for the ambient and extract air can be placed outside of the unit – easier accessibility from the windows reveal. Figure 3 shows a sketch of the prototype in the PASSYS cell with description of the components.

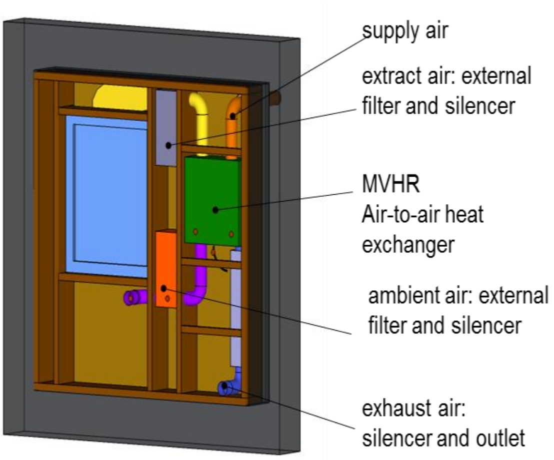


*Figure 3: Sketch of 1st prototype with MVHR unit*

With the second prototype (Figure 4 and Figure 5) the micro-heat pump in combination with the MVHR integrated in the façade is realized. This prototype was primarily designed to measure the performance of the MVHR and of the micro-heat pump.

Figure 6 shows both prototypes installed in the PASSYS test cells at university of |Innsbruck.

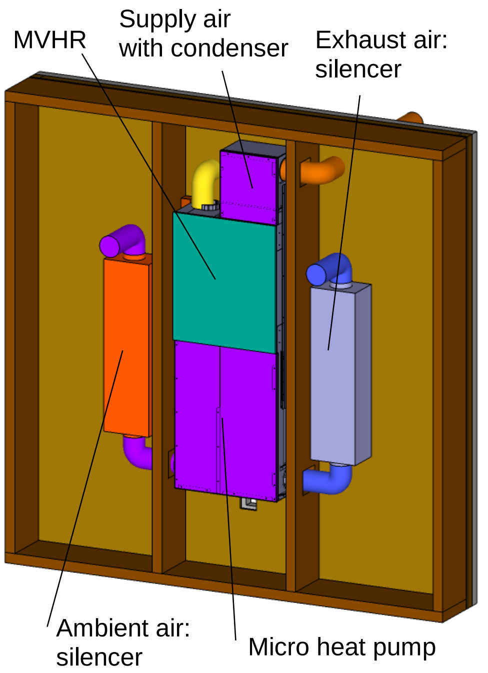


*Figure 4: Sketch of 2nd prototype with μHP*

*Figure 5: Photo of 2nd prototype with μHP*

*Figure 6: Installed prototypes, left cell: 1st prototype, right cell: 2nd prototype*

## SYSTEM SIMULATION

Simulation models are developed to determine the performance of micro-heat pump, MVHR as well as the performance of the whole system (μHP, MVHR, backup heater) in combination with an already existing building model in Matlab/Simulink [Mathworks 2012]. An auxiliary heater (electric radiator) of 1 kW is used as backup.

### Heat pump and MVHR model

A simplified physical vapour cycle model for the heat pump in combination with a MVHR model was developed and presented in [Ochs et al., 2014b]. The vapour cycle and the air heating/cooling are modelled in steady state with Matlab using the CoolProp functions [CoolProp2014] to derive the thermodynamic states of the refrigerant and of the air. The physical model is used for the optimization of the heat pump components as well as for the sensitivity analysis of the system [Ochs et al., 2014b].

For the investigation of the dynamic system behavior, a heat pump model based on performance map data in combination with a MVHR model is developed in Matlab/Simulink.

The MVHR model is based on the model described in [Ochs et al., 2014b]. The influence of humid air is disregarded in this work. The model is validated against measurement data [Siegele, 2014].

The heat pump model in Simulink is based on 2D Look up tables with linear interpolation and extrapolation. Both the heating capacity ($P_{HP}$) and the COP are calculated based on the ambient air temperature and the frequency of the compressor (round per minutes – RPM). The thermal capacities of the evaporator and condenser are not yet included in the present model. Constant volume flow of dry air is assumed in the present simulation study.

The simplified physical model is used to create the performance map data for the specific volume flow. In Figure 7 the outcomes of the Simulink model are presented (solid lines) using as input the performance map data (diamonds markers) derived from the physical model.

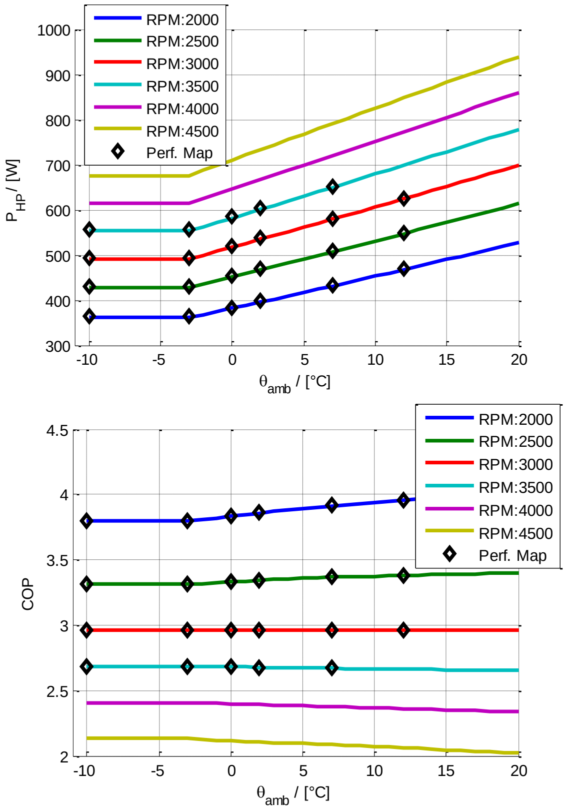


*Figure 7: Heating capacity (top) and COP (bottom) of the μHP as a function of ambient air ($\theta_{air}$) temperature with RPM as parameter.*

### Validation

Measurements are ongoing in PASSYS test cells. There are not enough measured data currently available for the validation of the physical heat pump simulation model. Validation is planned as the next step.

Instead, the results of the physical heat pump simulation model are compared to measured data of existing certified compact units (Figure 8). The compact units cover both heating and domestic hot water demand. From the certificate of compact units, the COP data only for heating are used for the comparison:

a) Comparison of the measured COP (certificate of compact units) and simulated COP (physical model) shows that the simulation results are in the same order of magnitude as the existing compact units.

b) The trends coming from the simulations are verified by the certified measured compact units.

The trend of COP as function of the ambient temperature coming from the simulation is same as the compact units of Genvex, but different to D&W and Nilan. The reason has to be clarified.

Preliminary laboratory measurement results show same trends as the physical simulation model for the COP: a) the ambient air temperature almost does not influence the COP, b) by decreasing the RPM the COP increases. The measured COP values are in a lower range than the simulations results and the compact units measured data, therefore optimization can be realized.

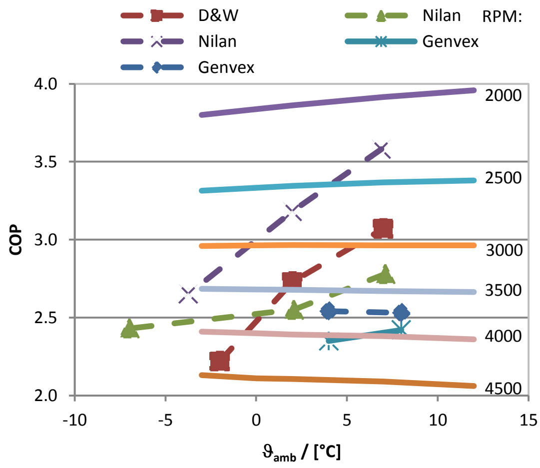


*Figure 8: Performance map data of the physical heat pump model in comparison to performance data of certified compact units (with fixed speed compressor)*

### Building model

The building considered in this study is a semi-detached single family house, with a tempered floor area of 78 m². It is defined within the project iNSPiRe [iNSPiRe, 2014] as a typical European single family house construction. The actual building is located in London, UK, and consists of two floors and an unheated attic, with an insulated ceiling between the top floor and the attic [Gustafsson, et al., 2014]. The ventilation rate is taken to be 0.4 $h^{-1}$ and the infiltration rate 0.1 $h^{-1}$. Climate data for seven different European locations are used. The chosen locations are the ones used in WP2 [iNSPiRe, 2014] and represent continental and coastal climates as well as a range of average ambient temperature and relative humidity.

For each climate, two renovation levels (i.e. U-values of roof, floor, walls and windows) are defined. EnerPHit standard (EN) and Passive House standard (PH) are used to define houses with heating demands of 25 kWh/(m²·a) and 15 kWh/(m²·a), respectively, assuming an air heat recovery efficiency of 85 % according to PHI definition [PHI] and disregarding cooling demand. In MATLAB Simulink the complex building model of the Carnot Blockset is used. The applied U-values for each climate and renovation level are listed in Table 1and Table 2.

In this study only space heating is investigated; see e.g. [Ochs, et al., 2014a] for DHW options. Total energy consumption includes heat pump compressor and backup heater as well as defroster of heat recovery. Thus all energy consumed is electricity. The consumption of ventilator fans of MVHR is disregarded in this study.

*Table 1:*
*U-values for different location in PH standard*

| LOCATION | U-VALUES [W/(m²·K)] | | |
|---|---|---|---|
| | WALLS | FLOOR | ROOF |
| Stockholm | 0.069 | 0.070 | 0.070 |
| Gdansk | 0.095 | 0.096 | 0.095 |
| Stuttgart | 0.175 | 0.180 | 0.176 |
| London | 0.211 | 0.218 | 0.212 |
| Lyon | 0.248 | 0.258 | 0.250 |
| Madrid | 0.437 | 0.470 | 0.443 |
| Rome | 0.544 | 0.596 | 0.554 |

*Table 2:*
*U-values for different location in EnerPHit standard*

| LOCATION | U-VALUES [W/(m²·K)] | | |
|---|---|---|---|
| | WALLS | FLOOR | ROOF |
| Stockholm | 0.146 | 0.150 | 0.147 |
| Gdansk | 0.175 | 0.180 | 0.176 |
| Stuttgart | 0.277 | 0.290 | 0.279 |
| London | 0.310 | 0.326 | 0.313 |
| Lyon | 0.374 | 0.397 | 0.378 |
| Madrid | 0.586 | 0.646 | 0.597 |
| Rome | 0.739 | 0.838 | 0.758 |

### Control strategies

Two control strategies are investigated for the heat pump: a standard on/off controller with hysteresis and a PI controller. The process variable is the indoor air temperature for both cases. The set point is 20 °C, with upper and lower dead bands of 0.25 K for the on/off case. The backup heater is controlled also by on/off differential controller with hysteresis and similarly, the set point is 19.75 °C and the temperature can vary between 19.5 °C and 20 °C. The set point for the auxiliary heater is set to a lower value to avoid operation during hours when the primary system could manage the heating. The ventilation is running independently for the heating control signals; therefore the heat pump is bypassed when heating is not needed.

## SIMULATION RESULTS

### Heating demand and heating load

Figure 9 shows the annual heating supply of the tested systems for all locations and renovation levels. The heating supply energy is the total heat delivered to the building including heat pump and auxiliary heater. Here, heating demand refers to ideal heating, whereas heating supply is the heat which is supplied to the building by the heating system (i.e. heat pump) using an on/off controller with hysteresis.

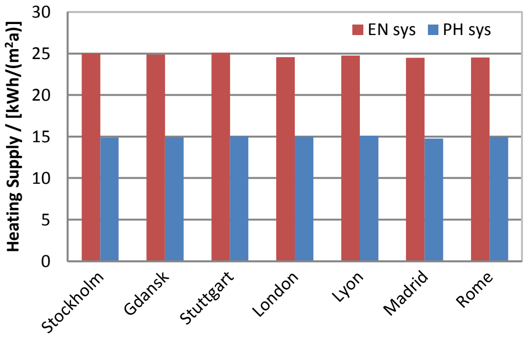


*Figure 9: Heating demand for different locations and renovation standard*

In Figure 10 the load duration curves for the heating load of the building are plotted for Passive House standard. These curves contain daily mean values that are sorted versus time. In warm climates such as Madrid and Rome the load is more homogeneous distributed over the heating period and the heating period is shorter. Interestingly the peak heating load is higher in warm climates. As for the coldest climates (Stockholm and Gdansk), the curves are steeper at higher heating loads (days 1 to 10). For EnerPHit standard the load duration curves are shown in Figure 11. The same shapes of the curves are observed with higher values, i.e. higher peak loads and higher duration of the heating period.

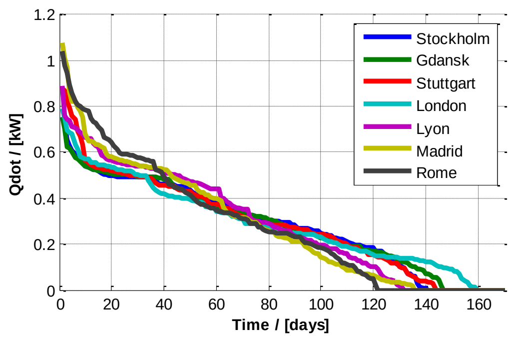


*Figure 10: Load duration curves of the building heating load in Passive House standard for different locations*

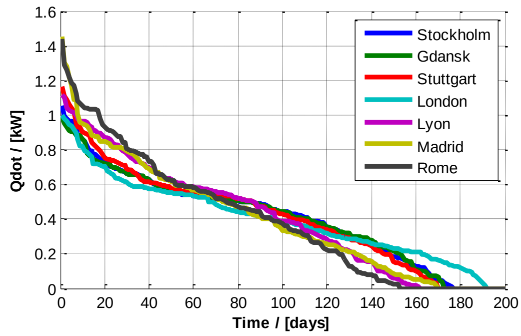


*Figure 11: Load duration curves of the building heating load in EnerPHit standard for different locations*

### SPF as a function of climate and building standard

Two seasonal performance factors (SPF) of the tested system are presented. The first $SPF_{sys}$ refers to the ratio of the heating supply and the total electrical consumption (Eq. (1)). The second one, $SPF_{HP}$, accounts only for the performance of the micro-heat pump (Eq. (2)):

$$SPF_{sys} = \frac{Q_{sys}}{W_{el\_sys}} \quad (1)$$

$$SPF_{HP} = \frac{Q_{HP}}{W_{el\_HP}} \quad (2)$$

Here $SPF_{sys}$ is seasonal performance factor of the system (-), $Q_{sys}$ heating supply of the system (kWh), $SPF_{HP}$ seasonal performance factor of the micro-heat pump (-), $Q_{HP}$ heating supply of heat pump (kWh) and $W_{el\_HP}$ electrical consumption of heat pump (kWh).

The heating demand is almost the same in all climates. The SPF can be used for the system comparison. In Figure 12 the $SPF_{HP}$ and $SPF_{sys}$ are presented. The performance of the micro-heat pump is hardly influenced by the different climatic conditions and energy standards. This happens since the influence of the ambient temperature on the COP is almost negligible (see Figure 7 bottom). The increase of ambient air temperature leads to higher exhaust air temperature (source temperature of the heat pump) but also to a higher power at the condenser resulting a higher supply air temperature (sink temperature of the heat pump). Thus, the benefit of higher source temperature is eliminated by the higher sink temperature of the heat pump (Eq. (3)).

$$\mathrm{COP} = \eta_{carnot} \frac{T_{snk}}{T_{snk} - T_{src}} \quad (3)$$

Here $\eta_{carnot}$ is the Carnot performance factor, $T_{src}$ the source and $T_{snk}$ the sink air temperature of the heat pump.

The system performance depends on both building standards and climatic conditions. In case of Passive House standard, the $SPF_{sys}$ is higher since the share of backup heater of electricity consumption is less (max share in PH standard is 4.9 % when in EnerPHit is 18.3 %). By varying the climatic conditions, both the shares of defroster of the MVHR and backup heater are changing influencing the $SPF_{sys}$. The higher $SPF_{sys}$ is observed for PH standard in climate of London (Figure 12), since there is almost no need for backup heater (see Figure 10) and no use of the defroster.

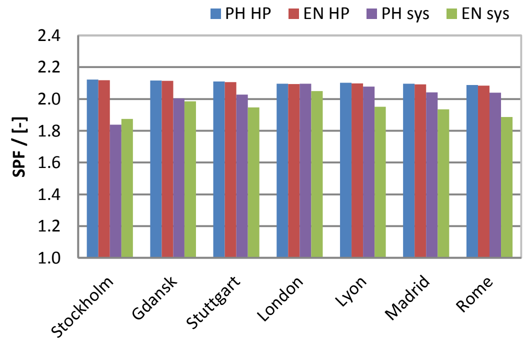


*Figure 12: SPF of the micro-heat pump (μHP) and of the system (sys) for different energy building standard and locations (climates).*

### Influence of the size of the heat pump power and of the control strategy on the performance

A set of dynamic simulations is performed to investigate the influence of the controller. At a first step sensitivity analysis is performed assuming constant compressor frequency. The on/off controller with hysteresis is used. The different RPM correspond to different heating capacity of the micro-heat pump (see Table 3).

*Table 3:*
*Heating capacity of micro-heat pump at 0 °C ambient temperature*

| RPM | $P_{HP}$ / [W] | COP |
|---|---|---|
| 2000 | 384 | 3.84 |
| 2500 | 453 | 3.33 |
| 3000 | 520 | 2.96 |
| 3500 | 584 | 2.68 |
| 4000 | 646 | 2.40 |
| 4500 | 710 | 2.11 |

In Figure 13 and Figure 14 the system $SPF_{sys}$ is plotted as a function of the RPM and having as parameter the climate for PH and EnerPHit standard, respectively. With the present boundary conditions the $SPF_{sys}$ is higher with RPM range is from 2000 to 3000 for PH and 3000 to 3500 for EnePHit standard. A heat pump with lower heating capacity than the maximum building heating load increases the system performance despite the higher share of backup heater.

The optimum RPM varying also with the climate, i.e. for PH standard, the highest SPF is observed for 2000 RPM in climate of London, 2500 RPM in Stuttgart and 3000 RPM in Lyon. In case of EnerPHit standard, the optimum RPM is 2500 in London, 3000 in Gdansk and 3500 in Rome.

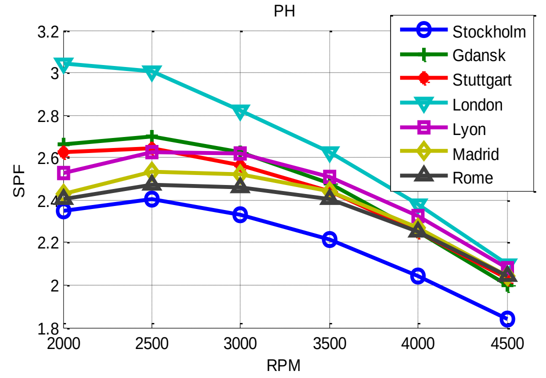


*Figure 13: $SPF_{sys}$ versus the frequency of the µHP compressor (RPM) for different locations in PH standard*

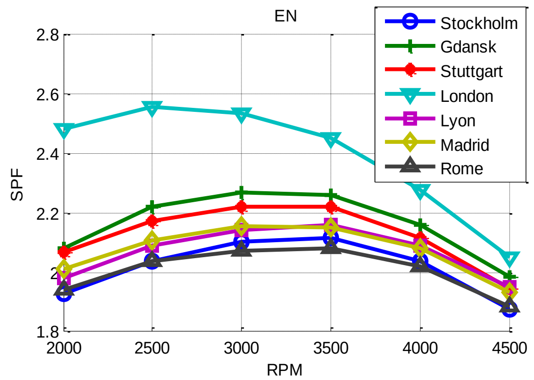


*Figure 14: $SPF_{sys}$ versus the frequency of the µHP compressor (RPM) for different locations in EnerPHit standard*

A simulation parametric study is performed also using a PI controller parameterized for the frequency controlled compressor with a RMP range of 2000 to 4500. In Figure 15 the total electrical consumption is presented using a PI controller or an on/off controller with constant RPM. The results show an improvement of system performance by using a PI controller. The benefit of a PI controller compared to the on/off controller with maximum frequency (4500 RPM) is about 15 %. Thus, the use of PI controller reduces the possibilities of improperly dimensioned heat pump with regard to the building load. The same results apply also for the other climates.

In case of a heat pump without frequency controlled compressor, it applies that the steeper is the building load duration curve at the peak load the less is the needed share of backup. Therefore, a heat pump without frequency controlled compressor designed for a lower heating capacity than the building load can lead to a better system's energy performance in combination with a backup heater.

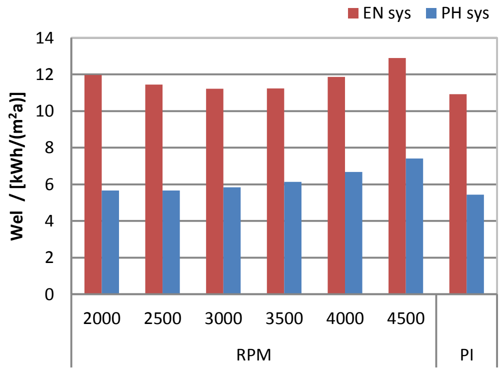


*Figure 15: Total electrical consumption using PI or on/off controller in climate of Stuttgart.*

Figure 16, Figure 17 and Figure 18 show for three locations, i.e. Stockholm, Lyon and Rome, respectively, the load duration curve of the building heating load and the load covered by the micro-heat pump. Results are presented for two control strategies: PI controller (continuous line) and on/off controller with constant compressor speed (dot line). For each location the optimum RPM is chosen (see Figure 13). Using a PI controller the backup heater is still needed for the peak loads. The maximum share of the backup heater is observed for climate of Rome, due to the highest heating load. In case of on/off controller the share of the backup heater increases significantly for all climates.

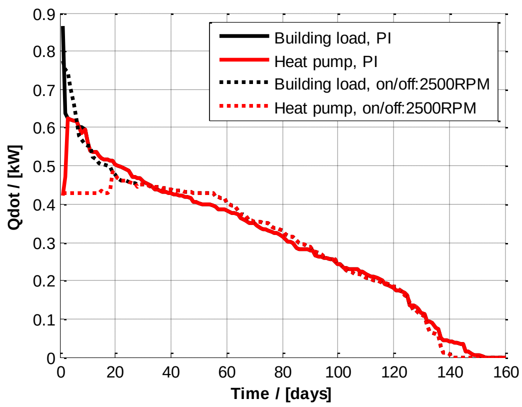


*Figure 16: Load duration curves of the building and load covered by the micro-heat pump using PI controller and on/off controller (constant 2500 RPM). The building is in PH standard for the climate of Stockholm.*

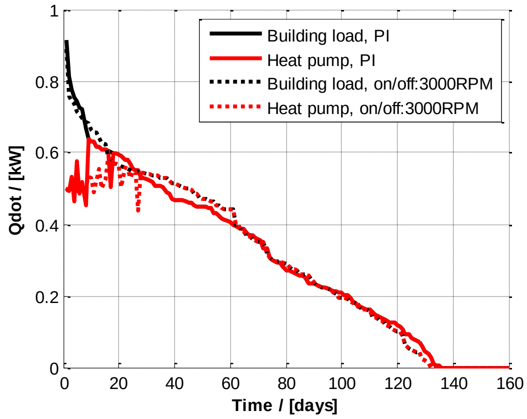


*Figure 17: Load duration curves of the building and load covered by the micro-heat pump using PI controller and on/off controller (constant 3000 RPM). The building is in PH standard for the climate of Lyon.*

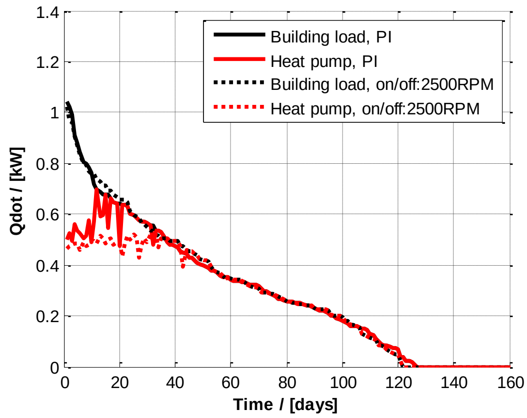


*Figure 18: Load duration curves of the building and load covered by the micro-heat pump using PI controller and on/off controller (constant 2500 RPM). The building is in PH standard for the climate of Rome.*

## CONCLUSIONS

The concept of a micro-heat pump in combination with mechanical ventilation with heat recovery is presented in this paper. Two prototypes were constructed and are currently measured in the laboratory of University of Innsbruck. In parallel, a physical vapour cycle and a performance map simulation heat pump model were developed. Both models will be optimized and validated using measurement results of the two prototypes.

A set of simulations is performed to investigate and optimize the energy performance of the system for different building standards in different climates. The feasibility of the concept is proven. Different control strategies are investigated. By comparing the performance of the system with an on/off controller with hysteresis and a speed controlled compressor, the importance of a well dimensioned heat pump has been shown. Additionally, the use of PI controller shows two main advantages: First, the system performance is improved (by a factor 1.15) and second, the risk of an improperly dimensioned heat pump is significantly reduced.

The µHP with MVHR represents a cost-effective compact heating system for buildings with very good energy performance such as Passive Houses or buildings renovated to EnerPHit standard. The integration of the system in a prefabricated façade enables minimized space use and reducing installation time and effort.

## ACKNOWLEDGEMENT

These results are part of the research and simulation work of the European project iNSPiRe funded under the 7th Framework Program (Proposal number: 314461, title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, duration: 01.10.2012 – 30.09.2016).

## REFERENCES

CoolProp2014, 2014. http://coolprop.sourceforge.net,

Gustafsson M., Dermentzis G., Myhren J.A., Bales C., Ochs F., Holmberg S., Feist W., 2014. Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation [Article submitted].

iNSPiRe, Proposal number: 314461, title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, WP 2, Deliverable 2.1 Report, 2014.

Mathworks, Inc. 2012. Matlab R2012a www.mathworks.com , 2012.

Ochs F., Dermentzis G., Siegele D., Feist W., Loose A., Drück H., 2014a Thermodynamic analysis of ground coupled heat pumps with solar thermal regeneration // 11th International Energy Agency Heat Pump Conference. Mondreal.

Ochs F., Dermentzis G., Siegele D., Feist W., 2014b. Feasibility of a Micro-heat Pump - Energy Performance Simulations, Energy Forum 28-29 October, Bressanone, Italy

PHI, Passive House Institute, http://passiv.de/downloads/03_Reqs_and_testing_procedures_ventilation_en.pdf

Siegele D., 2014. Master thesis - work in progress, Measurement and Simulation of the Performance of a Façade-integrated MVHR with Micro-heat Pump. University of Innsbruck.

Zeno B., Feist W. 2012. EnerPHit Planerhandbuch - Altbauten mit Passivhaus Komponenten fit für die Zukunft machen. - Darmstadt : Passivhaus Institut.

## 5.3 Publication C

**Title**

Innovative ventilation & heating system for Passive Houses – a European case study

**Authors**

Dermentzis, Georgios; Ochs, Fabian; Siegele, Dietmar; Feist, Wolfgang

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**Own contribution**

The presented work, the results, the discussion and the conclusions of this publication were performed by the first author. The significant contributions of the co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

# Innovative ventilation & heating system for Passive Houses – a European case study

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## 1 Motivation

The majority of existing building stock in Europe and worldwide is high energy consuming buildings. A renovation to EnerPHit or Passive House standard reduces significantly the heating load of the building. Hence, very small heating systems in the range of 1 kW can be used. Deep renovation solutions in combination with integrated HVAC (Heating, Ventilation, and Air Conditioning) systems are developed within the framework of the European project iNSPiRe. One approach is a small scaled exhaust-air heat pump in combination with mechanical ventilation with heat recovery (MVHR). The small size of the heat pump (space and power) gives the potential for cost reduction as well as minimization of space use (compactness).

## 2 Concept

Different heat pump concepts can be applied in Passive Houses. In Figure 1 two simple and cost-effective concepts are presented:

- a micro-heat pump combined with MVHR unit [Ochs et al., 2015] and
- an air-to-water heat pump directly connected to the panel radiators.

The concept of the micro-heat pump is developed within the European project iNSPiRe. The heat pump uses the exhaust air of the MVHR as source and provides heat to the supply air of the ventilation system (Figure 1a). Thus, one compact unit can be used for combined ventilation and heating or (optional) cooling (reverse operation of the HP). As the micro-heat pump is limited to the hygienic air rate (source and sink side), an air-to-water heat pump is potentially more efficient. However, compared to an air-to-water heat pump, the micro-heat pump can be more compact and therefore better integrated into a façade. Fresh outdoor air flows into the preheater (used for frost protection of the heat exchanger) and then into the heat exchanger of the MVHR unit, where it is heated with an energy recovery coefficient up to 95 %. It is then further heated by the heat pump up to maximum 52 °C in order to supply space heating. Principally, the micro-heat pump concept would work also for water based systems (radiator, floor heating, radiant ceiling). However, the exhaust air (source) to supply air (sink) heat pump has the highest potential to be micro.

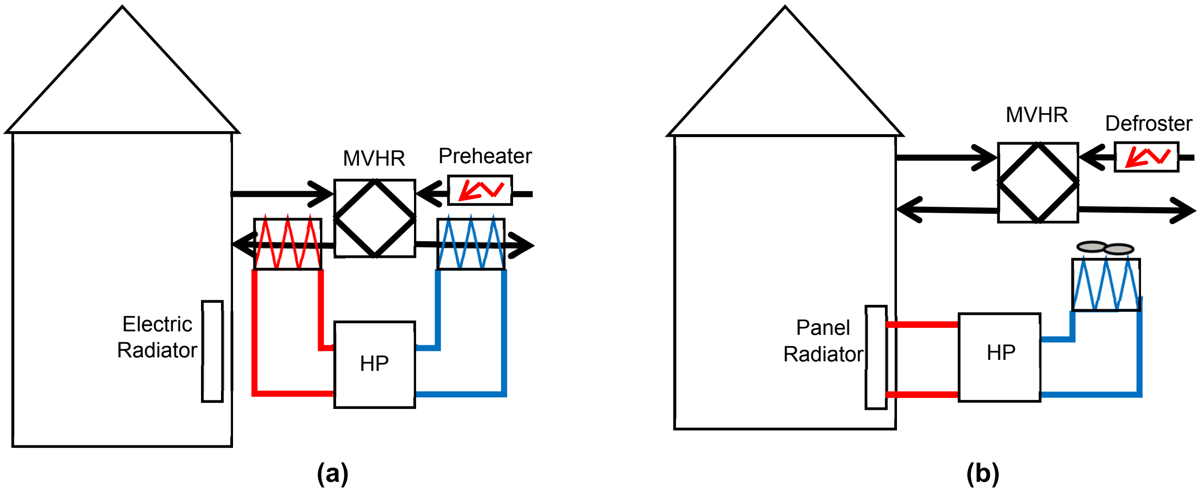



**Figure 1: (a) Concept of the micro-heat pump (µHP (b): Standard air-to-water heat pump with MVHR).**

# 3 Simulation models

Building and system simulations are performed to show the feasibility of the concept.

**Building model:** The building considered in this study is a semi-detached single family house (SFH), with a treated floor area of 78 m². The actual building is located in London, UK, and consists of two floors and an unheated attic, with an insulated ceiling between the top floor and the attic [Gustafsson, et al., 2014]. Climate data for seven different European locations are used. The chosen locations are the ones used in WP2 [iNSPiRe 2014] and represent continental and coastal climates as well as a range of average ambient temperature and relative humidity. For each climate, two renovation levels (i.e. U-values of roof, floor, walls and windows) are defined. EnerPHit standard (EN) and Passive House standard (PH) are used to define houses with heating demands of 25 kWh/(m²·a) and 15 kWh/(m²·a), respectively, assuming an air heat recovery efficiency of 85 % and disregarding cooling demand. The ventilation rate is taken to be 0.4 h-1 and the infiltration rate 0.1 h-1.

**Heat pump and MVHR model:** A simplified physical vapour cycle model for the heat pump in combination with a MVHR model was developed and presented in [Ochs et al., 2014]. The vapour cycle and the air heating/cooling are modelled in steady state to derive the thermodynamic states of the refrigerant and of the air. For the investigation of the dynamic system behavior, a heat pump model based on performance map data in combination with a MVHR model is developed in Matlab/Simulink [Dermentzis et al., 2014]. The heat pump model is based on 2D Look-up tables. Both the heating capacity and the coefficient of performance (COP) are calculated based on the ambient air temperature and the frequency of the compressor (revolutions per minutes – RPM). The thermal capacities of the evaporator and condenser are not yet included in the present model. Constant volume flow (75 m3/h) of dry air is assumed in the present simulation study. The MVHR model is based on the model described in [Ochs et al., 2014] and the influence of humid air is disregarded in this work. The model is validated against measurement data [Siegele, 2015]. A PI controller is used to control the heat pump. The process variable is the indoor air temperature and the set point is 20 °C. In the present study an auxiliary heater (electric radiator) of 1 kW is used as backup and it is controlled by an on/off differential controller with hysteresis. The set point is 19.75 °C with upper and lower dead band of 0.25 K.

**Validation:** The physical model is validated with measurement results presented in Figure 2. The measured and simulated coefficient of performance of the system (COPsys, micro-heat pump & MVHR) is displayed as a function of the ambient temperature with the speed of the compressor as parameter. The simulation model slightly overestimates the COPsys for lower ambient temperatures and underestimates in case of higher ambient temperatures. Overall, relative good agreement can be achieved.

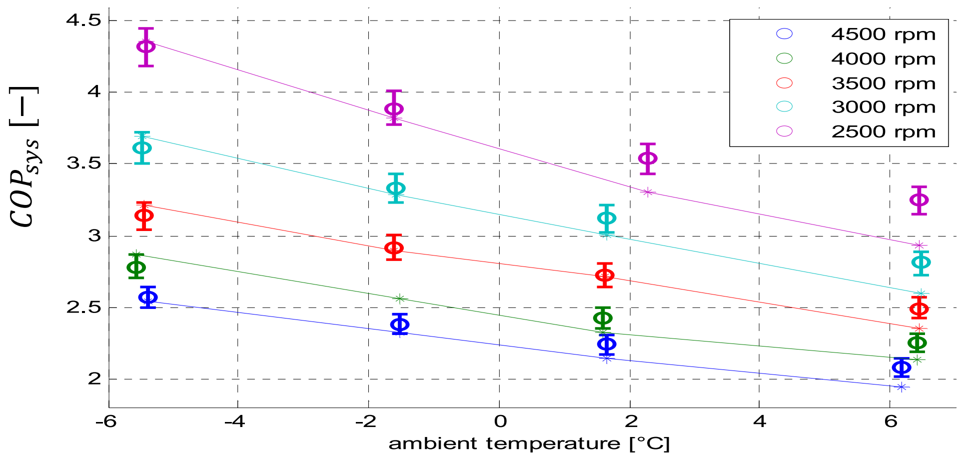



**Figure 2: Simulated and measured system COP as a function of the ambient temperature with parameter the compressor's speed [Siegele, 2015]**

Additionally, the results of the physical heat pump simulation model for an optimized version of the heat pump are compared to measured data of existing certified compact units (Figure 3). The compact units cover both heating and domestic hot water demand. From the certificate of compact units, the COP data only for heating are used for the comparison:

- Comparison of the measured COP (certificate of compact units) and simulated COP (physical model) shows that the simulation results are in the same order of magnitude as the existing compact units.
- The trends coming from the simulations are verified by the certified measured compact units.

The trend of COP as function of the ambient temperature coming from the simulation is same as the compact units of Genvex. The reason of the steep slope of the COP of the compact units from D&W and Nilan has still to be clarified.

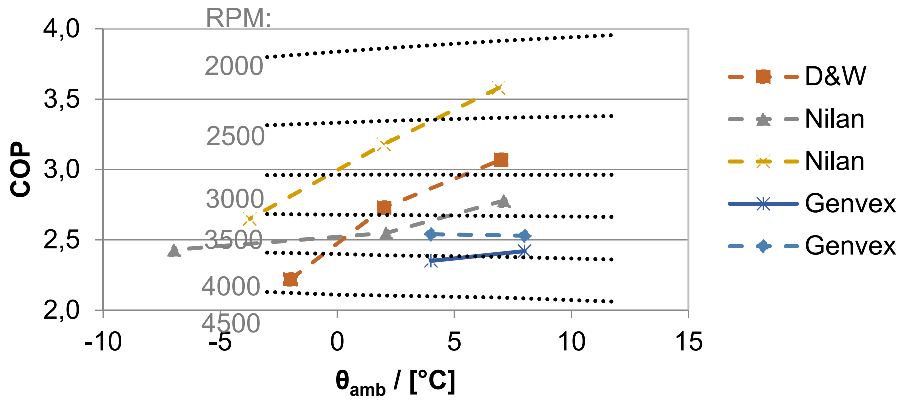



**Figure 3: Performance map data of the physical heat pump model in comparison to performance data of certified compact units (with fixed speed compressor)**

# 4 Parametric study - simulation results

A parametric study has been performed to prove and investigate the energy performance of the micro-heat pump concept. Both the climatic conditions and the building standards are varied. The goal of iNSPiRe project is to renovate a building in such a way to achieve 50 kWh/(m²a) primary energy demand including heating, cooling, domestic hot water (DHW), auxiliary energies and lighting. In the present study cooling is disregarded.

All energy consumed is electricity including heat pump's compressor, auxiliary heater, preheater and fans of MVHR. The total electrical consumption as well as the different shares are presented in Figure 4. The system performance depends on both building standards and climatic conditions. In case of Passive House standard, the electrical consumption is lower since the share of auxiliary heater is less. By varying the climatic conditions, both the shares of preheater of the MVHR and auxiliary heater are changing influencing the system performance. The lowest consumption is observed for PH standard in climate of London, since there is no need for preheater and low need for auxiliary heater.

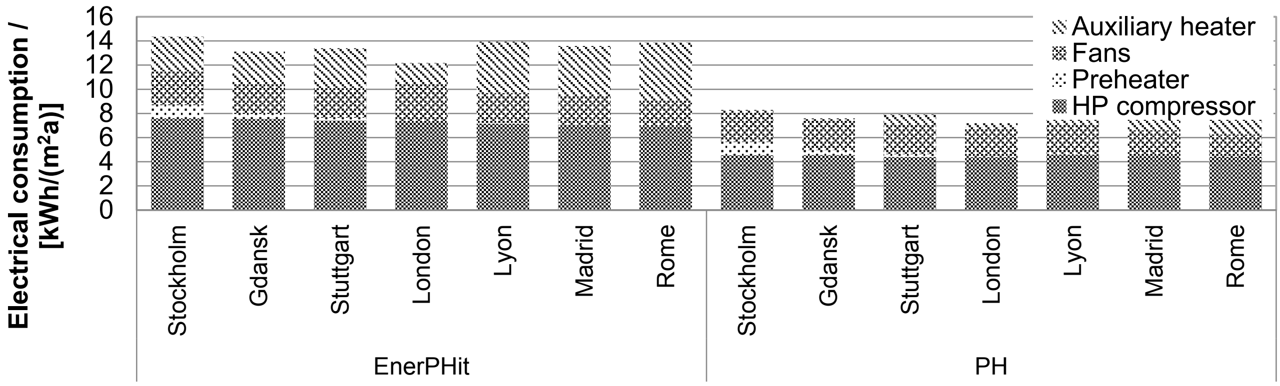
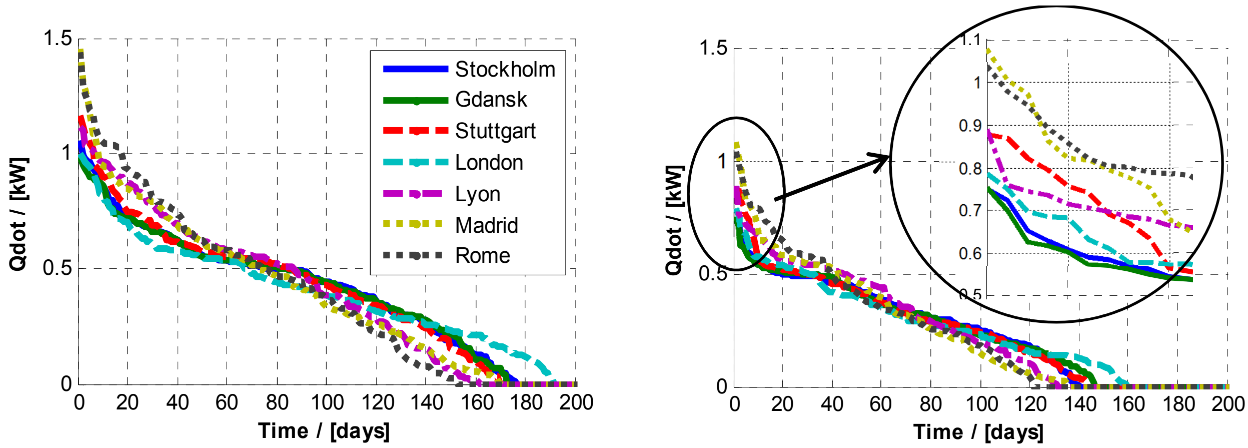



**Figure 4: Total system electric consumption for Passive House building standard in different locations (climates).**

In Figure 5 the load duration curves for both building standards are shown. Interestingly the highest heating loads are observed in warm climates (Madrid, Rome) and the lowest in cold climates (Stockholm, Gdansk). This explains why the share of auxiliary heater's consumption is higher in warm climates. The most homogenous load distribution is observed in climate of London for both standards.




a) EnerPHit b) PH

**Figure 5: Load duration curves for EnerPHit (a) and Passive House (b) building standard in different locations (climates).**

Using the micro-heat pump concept for heating and ventilation, two different systems are investigated for hot water preparation in the present study: an air-to-water heat pump (AWHP) and a gas boiler. The domestic hot water (DHW) demand is assumed to be of 20 kWh/(m$^2$a). Primary energy of 5 kWh/(m$^2$a) is used for lighting. For the AWHP a seasonal performance factor depending on the climate is used to calculate the final electrical consumption for DHW [iNSPiRe, 2015]. Primary energy factors of 2.4 and 1.2 are used for electricity and gas, respectively, for all climates.

The total primary energy demands for the two building standards, the seven climates and the two different DHW systems are presented in Table 1. The goal of iNSPiRe (50 kWh/(m$^2$a)) can be reached in PH standard for all climates and both solutions for DHW. In case of EnerPhit standard an additional photovoltaic (PV) system has to be installed to cover the additional primary energy.

| | | Primary energy (Heating, Ventilation, DHW, lighting) / [kWh/(m$^2$ a)] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Climate: | Stockholm | Gdansk | Stuttgart | London | Lyon | Madrid | Rome |
| EnerPHit | AWHP-DHW | 62.9 | 58.8 | 58.6 | 55.6 | 59.9 | 56.6 | 58.1 |
| | Gas-DHW | 63.5 | 60.5 | 61.2 | 58.2 | 62.5 | 61.6 | 62.3 |
| PH | AWHP-DHW | 48.3 | 45.6 | 45.4 | 43.6 | 45.1 | 42.3 | 43.0 |
| | Gas-DHW | 48.9 | 47.2 | 48.0 | 46.3 | 47.7 | 47.2 | 47.2 |

**Table 1: Primary energy including heating, ventilation, DHW and lighting for two building standards and two concepts for DHW preparation (air-to-water heat pump and gas boiler)**

# 5 Conclusions

The concept of a micro-heat pump in combination with mechanical ventilation with heat recovery is presented in this paper. It represents a cost-effective and compact system for heating, ventilation and optional cooling. Energy performance simulations are performed to investigate the feasibility of a concept in a single family house (SFH). The simulations results show that the micro-heat pump with MVHR is a concept which can be applied to buildings with very good energy performance such as EnerPHit and Passive Houses in various climates. The primary energy target of iNSPiRe (50 kWh/($m^2$a) for heating, domestic hot water and lighting) is achieved in Passive House standard for all climatic conditions and is feasible in EnerPHit standard with an additional PV system. The concept of the micro-heat pump can be also applied to a multi-family house (MFH) as a decentralized solution. Energy performance simulations of the micro-heat pump in a MFH are part of an ongoing work. Furthermore, the simulation results can serve as a basis for the extension of the heat pump or compact sheet in PHPP.

# 6 Acknowledgement – References

These results are part of the research and simulation work of the European project iNSPiRe funded under the 7th Framework Program (Proposal number: 314461, title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, duration: 01.10.2012 – 30.09.2016).

Dermentzis G., Ochs F., Siegele D., Feist W — A façade integrated Micro-Heat Pump – Energy performance simulations. BauSIM2014, Aachen, Germany, 2014

Gustafsson M., Dermentzis G., Myhren J.A., Bales C., Ochs F., Holmberg S., Feist W. — 2014. Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation. Energy and Buildings vol.82, 512–519, 2014.

Ochs F., Dermentzis G., Siegele D., Feist W — Retrofitting of multi-family houses with facade integrated micro-heat pump and MVHR, 19th International Passive House Conference, Leipzig, 2015.

Ochs F., Dermentzis G., Siegele D., Feist W — Feasibility of a Micro-heat Pump - Energy Performance Simulations, Energy Forum, Bressanone, Italy, 2014.

iNSPiRe. Proposal number: 314461 — Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, 2014:WP2, Deliverable 2.1 Report. 2015: Primary energy of HVAC systems, Zafh.net.

Siegele D — Measurement and Simulation of the Performance of a Façade-integrated MVHR with Micro Heat Pump, Master Thesis, University of Innsbruck, 2015.

## 5.4 Publication D

**Title**

A micro-heat pump combined with mechanical ventilation including heat recovery - simulation and in situ monitoring

**Authors**

Dermentzis, Georgios; Ochs, Fabian; Feist, Wolfgang

**Published in**

Proceedings of 12th IEA Heat Pump Conference, 15-18 May 2017, Rotterdam, Netherlands

http://hpc2017.org/wp-content/uploads/2017/05/O.1.5.1-A-micro-heat-pump-combined-with-mechanical-ventilation-including-heat-recovery.pdf

**Reference**

G. Dermentzis, F. Ochs, W. Feist, A micro-heat pump combined with mechanical ventilation including heat recovery - simulation and in situ monitoring, in: 12th IEA Heat Pump Conf., Rotterdam, 2017.

**Own contribution**

The presented work, the results, the discussion and the conclusions of this publication were performed by the first author. The significant contributions of the co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

# A micro-heat pump combined with mechanical ventilation including heat recovery - simulation and in situ monitoring

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**Abstract**

An innovative heating and ventilation system is developed within the European fp7 project iNSPiRe for the deep energy retrofit of residential buildings. A low capacity heat pump of about 700W is combined with mechanical ventilation including heat recovery. The evaporator of the heat pump is located in the exhaust air flow of the mechanical ventilation system and the condenser heats further the supply air. The whole system is meant to be cost-effective, compact and thus, suitable to be integrated into a prefabricated timber façade. Several functional models were already measured in the laboratory of university of Innsbruck (AT) and finally one is installed in a demonstration building in Ludwigsburg (D). The building is a multi-family house with four stories and one flat per story. Within the refurbishment the heat pump with the mechanical ventilation is installed in one flat and designed to cover the heating demand of it; an additional electric radiator is installed in bathroom for comfort reasons. A detailed monitoring system is installed in the demo building to investigate the performance and the dynamic behavior of the HVAC system as well as the comfort in the flat. A simulation model of the system and flat is developed in Matlab/Simulink for dynamic simulations. The model is calibrated and validated against the monitoring data and is used for simulation based analysis of the performance.


Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: micro-heat pump; façade integration; deep renovation; refurbishment of residential buildings; HVAC

## 1. Introduction

The majority of existing building stock in Europe and worldwide is poor energy performance buildings. Deep renovation solutions in combination with integrated heating, ventilation and air-conditioning systems (HVAC) are developed within the framework of the European project iNSPiRe [1]. Passive renovation measures are already known and used worldwide, e.g. EnerPHit standard [2]. The very low heating load of such buildings gives the opportunity to develop new compact and economic HVAC systems. The present study focuses on a system composed of a micro-heat pump (micro-HP) combined with a mechanical ventilation unit with heat recovery (MVHR), which is integrated into a timber frame prefabricated façade. The main advantages of the proposed system are the compactness (providing the possibility of integration into the façade) and cost reduction. A functional model including a monitoring system is installed within the refurbishment of a demonstration residential multi-family house in Ludwigsburg, Germany.

Analytical monitoring and simulation results for the building and the flat are presented in [3]. The present study focuses on the micro-HP. The HVAC system, the monitoring concept and the demonstration building are presented in section 2. Simulation models of the micro-HP and the MVHR are developed and further calibrated

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and validated against monitoring data (section 3). System and building annual simulations results are performed to investigate the performance of the HVAC system (section 4).

| Nomenclature | |
|---|---|
| $\vartheta_{amb}$ | Ambient air temperature |
| $\vartheta_{exh}$ | Exhaust air temperature |
| $\vartheta_{ext}$ | Extract air temperature |
| $\vartheta_{sup1}$ | Supply air temperature after the heat pump condenser |
| | |
| $\dot{m}$ | Air mass flow |
| $c_p$ | Heat capacity of air |
| $n_{MVHR}$ | Efficiency of the MVHR unit |
| $P_{fan}$ | Power consumption of the electric fans |
| $Q_{MVHR}$ | Heating energy supplied by the MVHR unit |
| $Q_{condenser}$ | Heating energy supplied by the micro-heat pump |
| $Q_{post\ heater}$ | Heating energy supplied by the post heater |
| $Q_{bath\ radiator}$ | Heating energy supplied by electric radiator in bath |
| $W_{el\_MVHR}$ | Electrical energy consumption of the MVHR unit |
| $W_{el\_compressor}$ | Electrical energy consumption of the micro-heat pump |
| $W_{el\_post\ heater}$ | Electrical energy consumption of the post heater |
| $W_{el\_bath\ radiator}$ | Electrical energy consumption of the electric radiator in bath |

## 2. HVAC and monitoring system on the demonstration building

The micro-HP combined with MVHR system addresses very good building standards (e.g. EnerPHit 25 kWh/(m² a) [2] or better), corresponding to a specific heat load in the range of 10 W/m². Hence, the heat power of the heat pump is about 700 W. An additional radiator in the bathroom is suggested for comfort reasons. Basically, the concept would work also for water (radiator, floor heating, radiant ceiling) and air based systems (supply air and principally also recirculated air). As source ambient air and/or exhaust air or brine are possible. The exhaust air-to-supply air has the highest potential to be micro and thus compact. The proposed system is designed for hygienic volume flow rates i.e. between 90 m³/h and 120 m³/h (based on 25-30 $m^3$/(h·person)).

Figure 1 shows the hydraulic scheme of the unit. The ambient air (1) will be heated with the electric heater (5) (frost protection of the heat exchanger) when the ambient temperature is below -5 °C. The filter for the ambient air (6) is situated in front of the heat exchanger (16). The ventilator for the supply air (8) is situated after the heat exchanger. The supply air will be further heated due to the losses of the frequency controlled compressor (10) and then by the condenser (13) of the micro-heat pump. An additional heater (15) will heat the supply air (3) up to (in maximum) 52 °C in case the heat pump cannot cover the entire heating load. The extract air (2) is filtered (7) before the heat exchanger. The extract/exhaust air ventilator (9) is situated in the air flow of the exhaust air (4) in front of the evaporator (11). The expansion valve (12) reduces (as usual) the pressure between condenser and evaporator. A defrost cycle is implemented using a hot gas defrost bypass valve (14) which is used to bypass the condenser, so the hots gas of the compressor flows directly into the evaporator and the heat melts the ice that formed during operation.

The demonstration building is a multi-family house of the company “Wohnungsbau Ludwigsburg GmbH” (WB-L) built in 1971 in Ludwigsburg (Germany). The building consists of four stories and four flats: one small in cellar (39.5 $m^2$), two identical in ground and first floor (99 $m^2$) and one in attic floor (61.4 $m^2$), see Figure 2 right.

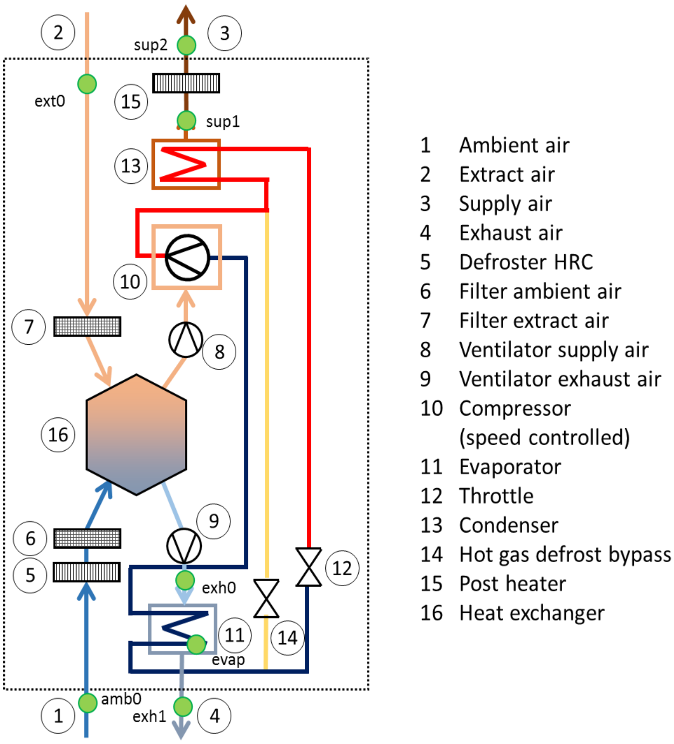


Fig. 1. Hydraulic scheme [3] of micro-HP and MVHR including the temperature sensors (green dots)

The building was renovated with prefabricated timber frame façade elements in passive house quality. The air-tightness was measured in 1.5/h via a blower door test, which does not meet the aimed target of 1/h but is still within the allowed range according to German energy standard (EnEV). All flats have a MVHR with a recovery efficiency in the range of 0.85. The flats in the ground floor and attic floor were occupied during the renovation, but the flats in the first floor and cellar were empty and were also refurbished inside. A central air-to-water heat pump (with a brine circuit) is used to cover space heating in all flats and for domestic hot water preparation. The central heating system is switched off in the flat in ground floor, where the micro-HP is installed (Figure 2 left). The floor plan and distribution ducts are shown in Figure 3. Since all extract air rooms are situated in the north, all extract air ducts are integrated into the prefabricated timber frame façade (the inlets are placed in the reveal of the windows). Thus only the supply air ducts are inside the flat minimizing the disturbance to the tenants during the renovation fostering the concept of a minimal disruptive renovation [4].

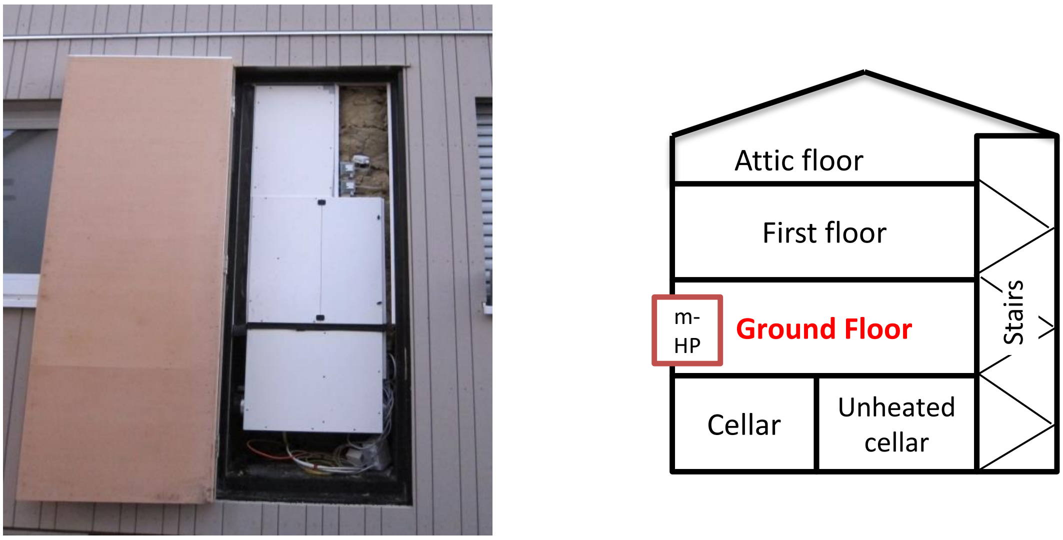


Fig. 2. Left: Outside view of the micro-HP and MVHR (company: Siko Energiesysteme) within the prefabricated timber frame façade (company: gumpp&maier). Right: simplified scheme of the demonstration building


Fig. 3. Floor plan of the renovated flat in ground floor with a simplified scheme of ducting for ventilation and heat distribution [5]

## *2.1. Monitoring system*

A monitoring system was installed with the micro-HP and the MVHR. The position of the temperature sensors are also shown in Figure 1. In total, eight temperature sensors (PT1000 with an accuracy of $\pm 0.15+(0.0002\cdot\vartheta)$)), one humidity sensor, two pressure difference sensors for measuring the volume flows, and three electricity meters (compressor, MVHR and post-heater) are used to monitor the dynamic behavior of the system. The measurement accuracy is similar to [6]. An additional temperature sensor is installed in the corridor of the flat (green dot in Figure 3) and is used for the control of the system.

The building is also separately monitored (comfort, heat and electricity consumption) before and after the renovation [3]. The flat in ground floor was renovated in December 2015, and the full monitoring started in

February 2016 until September 2016 (there might be an extension of one year more). Thus, within the project iNSPiRe, which ended in September 2016, data are not available for one whole winter.

## 3. Calibration and validation of the HVAC system

### *3.1. Simulation models*

The simulation models are developed in Matlab/Simulink [7] with the additional Carnot blockset [8]. The MVHR is modelled using as input the heat recovery efficiency according to [9], see eq. (1), to calculate the heat transfer between the two air flows. Then the temperature and humidity of exhaust and supply air flows are calculated based on enthalpy balance.

For the micro-heat pump a dynamic performance map model was calibrated against measured data from laboratory tests. The power of the micro-HP ($P_{m\text{-}HP}$) and COP are modeled as functions of ambient temperature (or exhaust air temperature of MVHR) and the compressor frequency - see Figure 4. The performance map data are steady state test points measured at the laboratory of University of Innsbruck [10] using a constant air volume flow of 120 $m^3$/h. For sake of simplicity, the slightly increased flow in the Demo case (around 10 $m^3$/h) is not considered in the performance map data. The dynamic behavior of the heat pump i.e. the time duration to reach the steady state condition after switching on or off, is modelled using a transfer function with different time constants for start and stop function. The time constants for on/off cycling are similar to those of the defrost switches.

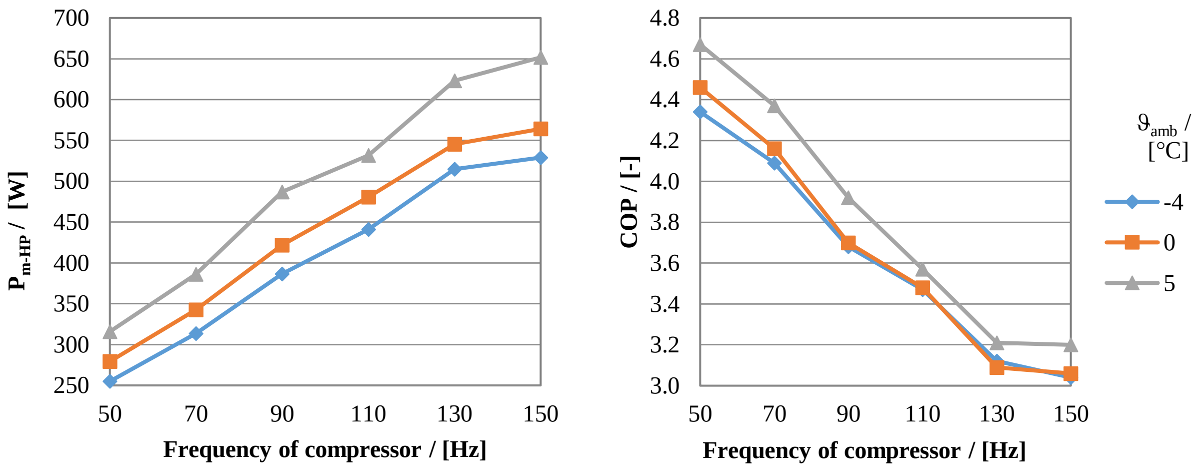


Fig. 4. Performance map of the power (left) and of the COP (right) of the heat pump depending on ambient air temperature and compressor frequency [10]

$$n_{MVHR} = \frac{\vartheta_{ext} - \vartheta_{exh} + \frac{P_{fan}}{\dot{m} \cdot cp}}{\vartheta_{ext} - \vartheta_{amb}} \quad (1)$$

A PI controller is implemented having as process variable the indoor temperature. The output is the required supply air temperature and then correspondingly the compressor speed and the power of the post-heater are calculated via a look-up table [10]. In the functional model, the controller of the defrost cycle is based on operation time and evaporator surface temperature (when the evaporator surface is below the set point for two hours, the defrost cycle starts for 15 minutes). Since the evaporator surface temperature is not calculated in the simulation model, the outlet exhaust air temperature of the evaporator is used. The value of 15 minutes is set as minimum operation time of the compressor.

### *3.2. Calibration*

Measured values of ambient and extract air temperature, relative humidity and mass flow are used as inputs for the simulation model with a time step of 30 seconds. Additionally, the measured signals of the controllers are directly given to the heat pump model i.e. the frequency of the compressor and the signal of the defrost cycle.

The electrical consumption of the fans and the controller has been calibrated to the measurement data and turned out to be significantly higher compared to the specifications of the MVHR data sheet due to higher pressure losses mainly because of the condenser and the evaporator.

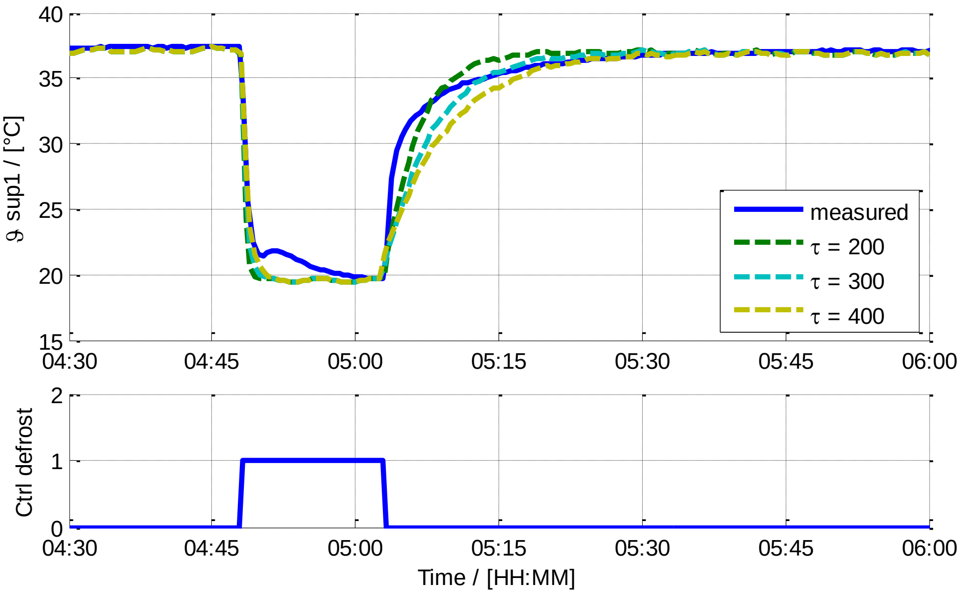


Fig. 5. Parametric study varying the time constants of the condenser (the time constant when condenser is cooled down is set to 10 times lower than the one in case of heating up)

The time constants used for heating and cooling phase of condenser during on/off operation are calibrated against the monitored data via a parametric study (Figure 5). The time constant, when condenser is cooled down, is set to 10 times lower than the one in case of when the condenser is heated up. The value of 300 sec is used further in simulations.

### *3.3. Validation*

Two parameters are important for the validation of the simulation model: the supplied power to the flat and the consumed electricity of the HVAC. Since the supplied power is not measured directly, the supplied air temperature is used for comparison of measurement and simulation. The measured temperature after the condenser ($\vartheta_{sup1}$) is used for the validation of the model.

The measured and simulated supply air temperature ($\vartheta_{sup1}$) in average values of 15 minutes is presented in Figure 6. A good agreement between simulation and measurement results can be observed both in low and high supply air temperature. The measured and simulated electrical consumption of the compressor are shown in Figure 7. The simulated electricity is slightly lower than the measured one in maximum operation (ca. 15 W) and quite similar in low operation.

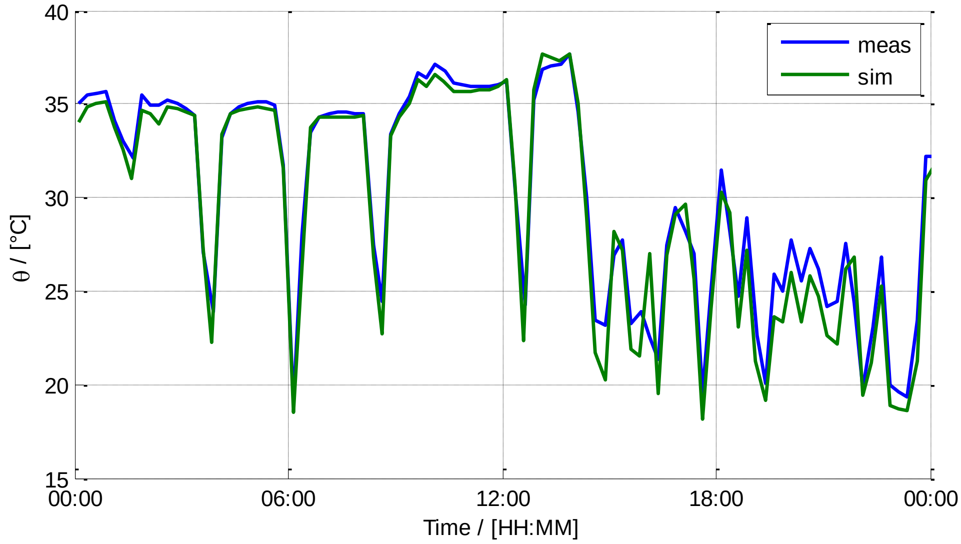


Fig. 6: Comparison of simulated and measured air temperature after the condenser ($\vartheta_{sup1}$) for one day in February. Results in average values of 15 minutes.

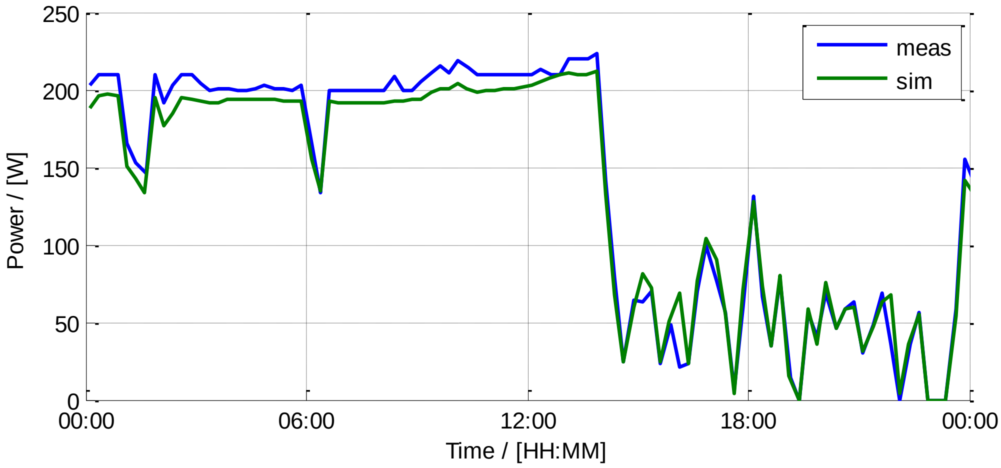


Fig. 7: Comparison of simulated and measured electrical consumption of the compressor for one day in February. Results in average values of 15 minutes

As mentioned in the previous section, the two flats below and above the investigated flat were renovated and unoccupied during the monitoring period. Therefore, the transmission losses from the monitored ground floor flat to the other two flats were relatively high leading to relative high heating demand compared to thermal losses to the ambient only. As a consequence, the micro-HP was most of time in operation and often with maximum compressor speed and also at higher ambient temperature than would be normally expected. As a further consequence, also the post-heater was almost continuously in operation. Therefore, the monitoring data can be used to calibrate the micro-HP model but the results do not represent normal operation.

## 4. Simulation study

Annual building and system simulations are performed to investigate the performance of the micro-HP in annual operation under several boundary conditions by varying a) the set point temperature of the flat and its neighboring flats and b) the minimum operation time of the micro-HP.

*4.1. Boundary conditions*

A six-zone two star building model of the refurbished ground floor flat is used [5] for the annual simulations. The six thermal zones are presented in Figure 3. Another 6-zone model of the whole renovated building is used to calculate the temperature of the neighboring flats as well as the unheated zones (cellar and staircase) [3]. These temperatures are used as boundary conditions in the simulation model of the ground floor flat. An occupancy (with three persons) and electric profile based on [11] is used, while the distribution to each thermal zone is presented in [5]. The climatic data of Stuttgart (WP2, iNSPiRe [1]) is used. The post-heater is assumed to be located in corridor instead of the north children room (remark: this corresponds to the real situation after autumn 2016). An additional electric radiator is modelled in bathroom, which is required for comfort reasons (this is also the situation in the real building). Its set point temperature is assumed to be same as the one of the flat here, but it could be set differently.

*4.2. Results and discussion*

The seasonal performance factor (SPF) is calculated for three different balance boundaries as shown in equations (2), (3) and (4):

$$SPF_{m-HP} = \frac{Q_{condenser}}{W_{el\_compressor}} \tag{2}$$

$$SPF_{sys} = \frac{Q_{condenser}+Q_{post\,heater}+Q_{bath\,radiator}}{W_{el\_compressor}+W_{el\_post\,heater}+W_{el\_bath\,radiator}} \tag{3}$$

$$SPF_{tot} = \frac{Q_{MVHR}+Q_{condenser}+Q_{post\,heater}+Q_{bath\,radiator}}{W_{el\_MVHR}+W_{el\_compressor}+W_{el\_post\,heater}+W_{el\_bath\,radiator}} \tag{4}$$

Remark: the $Q_{MVHR}$ and $W_{el\_MVHR}$ are calculated for the heating period assuming that measured temperature is lower than the set point plus 2 K.

*4.2.1. Parametric study: varying the set point temperature*

The set point temperature of the ground floor flat and of its neighbor flats (in cellar and first floor) is varied from 20 to 22°C. The corresponding set point temperatures and the results are shown in Table 1. The sum of the supplied energy by the micro-HP, the post-heater and the electric radiator in bathroom is considered as heating demand of the flat, while the MVHR is considered a "passive component" in the energy balance (such as in PHPP [12]).

Table 1. Varied parameters: set point temperatures. Results: heating demand and SPF of the micro-HP ($SPF_{m-HP}$) and of the system with ($SPF_{tot}$) and without MVHR ($SPF_{sys}$) for the simulated cases

| | Parameters | | | Results | | |
|---|---|---|---|---|---|---|
| Case | $\vartheta_{set}$ of ground floor flat / [°C] | $\vartheta_{set}$ of neighbour flats / [°C] | HD / [kWh/m2a] | $SPF_{m-HP}$ | $SPF_{sys}$ | $SPF_{tot}$ |
| A (ref) | 20 | 20 | 8.5 | 3.6 | 2.11 | 4.0 |
| B | 21 | 21 | 12.1 | 3.5 | 2.14 | 3.8 |
| C | 22 | 22 | 16.4 | 3.4 | 2.12 | 3.6 |
| D | 21 | 20 | 20.7 | 3.2 | 2.11 | 3.3 |
| E | 22 | 20 | 38.1 | 3.1 | 1.77 | 2.6 |

In reference case A, the heating demand is 8.5 kWh/(m$^2$·a) and the $SPF_{tot}$ is relative high with a value of 4. In case C $\vartheta_{set}$ 22°C the heating demand is 16.4 kWh/(m$^2$·a) quite increased compared to cases A and B but still the micro-HP can cover the heating demand (post-heater almost not operated see Figure 9). In extreme case E the heating demand is quite high (38 kWh/(m$^2$·a)) and the HVAC is at the limit to cover the whole demand. The share of direct electricity increases to 36% from 27% in case A.

Although, the SPF of the micro-HP is decreasing with increasing heating demand - since the micro-HP operates in high frequency (and thus low COP see Figure 4) - , it is always in a relative high values between 3.1 and 3.6. The cumulative distribution function of the frequency of the compressor for all simulated cases is presented in Figure 8. In the first three cases the compressor operates in full speed less than 22%, resulting to relative high SPF. The SPF of the system has a value a bit higher than 2 (except case E), which is acceptable since in combination with the low heating demand the resulting electrical consumption is not high e.g. in case C it is 765 kWh/a. The $SPF_{tot}$ is increased compared to the $SPF_{sys}$, due to the high efficiency of the MVHR, and follows the same trend as the $SPF_{m\text{-}HP}$. The minimum value of 2.6 is shown in case E.

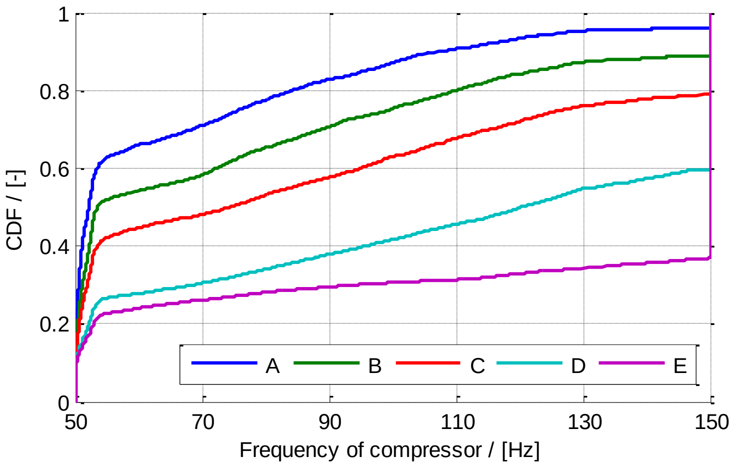


Fig.8. Sorted frequency of the compressor for the simulated cases A to E

The load duration curve of the investigated flat, which is the sum of the supplied power to the flat (by micro-HP, post-heater and electric radiator) for case C is shown in Figure 9. The maximum supplied power to the flat in daily average is almost 900 W. The post-heater operates for a short period (five days), while the electric radiator operates often with a share of 24% to the total supplied heat.

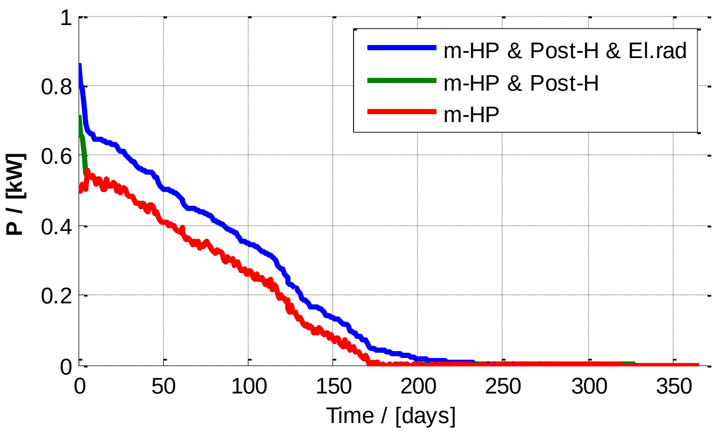


Fig. 9. Sorted daily supplied power to the flat (load duration curve) by micro-HP, post-heater and electric radiator

In general, the micro-HP delivers comfort conditions all over the year with an $SPF_{m\text{-}HP}$ of 3.1 even for the case with the highest heating demand. However, the operation time of the post-heater is significant for the system performance. In case of higher heating demand, another heat pump with higher thermal capacity would be recommended.

### *4.3. Parametric study: varying the minimum operation time of the micro-HP*

The minimum operation time of the compressor is varied from 15 min to 90 minutes in order to show its influence on the performance of the micro-HP. An increased operation in low frequency would lead to improved performance due to higher COP in low frequency. The simulation results for the reference case A are presented in Table 2. Although, the $SPF_{m\text{-}HP}$ is slightly increased with higher operation time (the supplied energy to the flat is also slightly increased), the electric consumption remains almost the same. Thus, there is no significant benefit to increase the minimum operation time.

Table 2. Electrical consumption and SPF of the micro-HP for different minimum operation time of the compressor

| Minimum operation time / [min] | Wel_comp / [kWh/a] | $SPF_{m\text{-}HP}$ |
|---|---|---|
| 15 | 273 | 3.43 |
| 30 | 272 | 3.48 |
| 60 | 271 | 3.57 |
| 90 | 271 | 3.60 |

## 5. Conclusions

The concept of a micro-heat pump (micro-HP) combined with mechanical ventilation with heat recovery (MVHR) unit is presented. A functional model of the system integrated into a prefabricated timber frame façade was developed within the EU-project iNSPiRe [1] and was installed in one flat during the refurbishment of a multi-family house in Ludwigsburg (D).

The micro-HP combined with MVHR system is proposed in combination with deep refurbishment of buildings to very good energy standard such as EnerPHit or Passive House. The integration of the system into a prefabricated façade has many advantages i.e. minimized use of space, reduction of installation time and effort. The low heating capacity of the heat pump, the prefabrication and the combination of m-HP with the MVHR have the potential to be an economically attractive solution.

The system was monitored in detail for several weeks. The monitoring data are used to calibrate and validate the simulation models, which are developed in Matlab/Simulink [7] using the Carnot Blockset [8]. Since there are no available data for a whole heating period, annual dynamic building and system simulations were performed to investigate the performance of the HVAC system. Two parametric simulation studies are performed a) varying the set point temperatures of the investigated flat and its neighboring flats and b) varying the minimum operation time of the micro-HP. The results show good performance with a total SPF of 2.6 in the worst case and 4 in the best case. The SPF of the micro-HP varies between 3.1 and 3.6. The influence of minimum operation time of the compressor is negligible on the performance of the system.

## Acknowledgements

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## References

[1] "iNSPiRe Proposal number: 314461, title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, duration: 01.10.2012 – 30.09.2016," [Online]. Available: http://inspirefp7.eu/..

[2] Passive House Institute, “EnerPHit certification criteria,” [Online]. Available: http://www.passiv.de/downloads/03_building_criteria_en.pdf. [Accessed 10 2016].
[3] F. Ochs, G. Dermentzis, D. Siegele, S. Hernandez and A. Sief, “D3.3. Report on Ventilation and Active Heating/Cooling Devices integrated in the Façade – Part A,” iNSPiRe, 2014.
[4] F. Ochs, D. Siegele, G. Dermentzis and W. Feist, “Prefabricated Timber Frame Façade with Integrated Active Components for Minimal Invasive Renovations,” Energy Procedia, vol. 78, pp. 61-66, November 2015.
[5] E. Leonardi, “Micro-Heat Pump for a Renovated Multi Family House – Simulation Based Analysis of the Performance and Thermal Comfort,” Master Thesis, 2015.
[6] D.Siegele, “Measurement and Simulation of the Performance of a Façade-integrated MVHR with Micro Heat Pump”, Master Thesis, 2015
[7]. “Matlab Simulink,” Mathworks, 2013a. [Online]
[8] B. Hafner, “CARNOT 5.3,” 2012. [Online].
[9] Passive House Institute, “Requirements and testing procedures for energetic and acoustical assessment of Passive House ventilation systems for Certification as “Passive House suitable component, 9/2009. [Online]. Available: http://www.passiv.de/downloads/03_Reqs_and_testing_procedures_ventilation_en.pdf. [Accessed 10 2016].
[10] M. Magni, “Hardware-in-the-loop experiments for heat pump controller optimization,” Master Thesis, Innsbruck, 2015.
[11] “IEA SHC Task 44 Solar and heat pumps”.
[12] “Passive House Planning Package (PHPP),” Passive House Institute (PHI), [Online]. Available: http://passiv.de/en/04_phpp/04_phpp.htm.

## 5.5 Publication E

**Title**

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**Authors**

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**Own contribution**

The presented work, the results, the discussion and the conclusions of this publication were performed by the first author. The significant contributions of the co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

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# Renovation with an innovative compact heating and ventilation system integrated into the façade – An in-situ monitoring case study

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ABSTRACT

The very low heating load of deep renovated buildings following standards such as EnerPHit, and the limited space in renovation create the need for compact heating systems. An innovative heating and ventilation system - consisting of an exhaust air to supply air heat pump combined with a heat recovery ventilation unit, both integrated into a prefabricated timber frame façade - was developed and installed in a flat during the renovation of a multi-family house in Ludwigsburg, Germany. The system and the flat were monitored for the complete heating season 2016/2017. This paper presents: (a) an analysis of the monitoring data, (b) the development and validation of the models of the system and the flat, and (c) the results of the dynamic simulations that were performed for further system optimisation.

Inside the flat, good thermal comfort and indoor air quality conditions were achieved. The monitored SPF of the system was 2.8. Simulation results showed that with the optimised system and control, there can be an electricity savings of 25%.

The developed system has the potential to be cost-effective due to prefabrication and low heating capacity. It represents a compact solution with moderate energy performance, appropriate for minimally disruptive renovations.



## 1. Introduction

The building sector plays an important role in achieving the set target of fossil energy and $CO_2$ emissions reduction. In the European Union, the building sector share of energy consumption is 40% [1]. This is justified considering the fact that old, poor performing buildings dominate the existing building stock. For this reason, energy renovation has a high potential for energy savings. Within the framework of the European project iNSPiRe [2], energy renovation kits were developed aiming to simplify the renovation procedure while reducing costs, e.g. by prefabrication and façade integration of the heating, ventilation and air-conditioning (HVAC) system.

Passive renovation measures in buildings, such as the EnerPHit standard [3], are already well-known and established worldwide. The very low heating load of these buildings, in the range of 1 kW or even lower, poses an ideal scenario to apply very compact and cost efficient HVAC systems. The advantage of heat pumps compared to other technologies, such as gas boilers, is that they can be arbitrarily scaled down (in terms of heating power and size). Such compact heat pumps offer a high potential for a cost-effective plug-and-play-solution appropriate for deep renovations. Gustafsson et al. [4] compared the energy performance of three heat pump systems for a renovated single-family house through dynamic simulations. In the case of a building with low heating demand, a heat pump combined with HRV performed more efficiently than an exhaust ventilation system with either exhaust or ambient air-to-water heat pump and ventilation radiators. Kelly and Cockroft [5] compared a domestic air source heat pump to a gas boiler for terraced dwellings in Scotland resulting in 12% less carbon emissions, but 10% higher operating costs. In an experiment, Esen et al. [6] measured a solar-assisted ground source heat pump reaching a system COP of 2.88 using a horizontal ground heat exchanger.

Central heating systems are often not preferred in renovations of multi-family houses (MFH) [7] due to difficulties in reaching an agreement between the flat owners, and space limitations for the installation of ducts and pipes in common spaces. “Compact heat pump units” [8], which combine heating (optional cooling), ventilation, and hot water preparation, have been proposed as a decentralised solution. However, the available space inside the flats of MFHs could remain an issue. This space limitation can be solved through the development of new façade-integrated systems. In par-

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**Nomenclature**

| | |
|---|---|
| BA | Bathroom |
| CDF | Cumulative distribution function |
| CHN | Children room with north orientation |
| CHS | Children room with south orientation |
| CO | Corridor |
| COP | Coefficient of performance |
| $\dot{C}$ | Capacitance (mass flow times specific heat capacity), W/K |
| $c_p$ | Specific heat capacity of air, J/(kg·K) |
| GF | Ground floor |
| HD | Heating demand |
| HRV | Heat recovery ventilation |
| HVAC | Heating ventilation and air-conditioning |
| HX | Heat exchanger |
| IAQ | Indoor air quality |
| KI | Kitchen |
| LI | Living room |
| $\dot{m}$ | Mass flow, kg/s |
| MFH | Multi-family house |
| micro-HP | Micro-heat pump |
| P | Power, W |
| PI | Proportional-integral |
| Q | Thermal energy (heat), kWh |
| $\dot{Q}$ | Thermal power, W |
| RMSE | root mean square error |
| SPF | Seasonal performance factor |
| $W_{el}$ | Electricity, kWh |

*Subscripts*

| | |
|---|---|
| amb | Ambient air |
| exh0 | Exhaust air after the HRV (see Fig. 1b) |
| exh1 | Exhaust air after the evaporator (see Fig. 1b) |
| ext | Extract air |
| evap | evaporator |
| sup | Supply air |
| sup1 | Supply air after the condenser (see Fig. 1b) |
| sup2 | Supply air after the post-heater (see Fig. 1b) |
| min | minimum |
| sys | System composed of micro-HP, post-heater and electric radiator |
| tot | Total system composed of micro-HP, post-heater, HRV and electric radiator |

*Greek symbols*

| | |
|---|---|
| $\eta$ | Heat recovery efficiency |
| $\vartheta$ | Temperature, °C |

ticular, the combination of a heat pump with a ventilation heat recovery unit results in a highly efficient system. For example, Fucci et al. [9] measured such a system finding a COP of 9.5 at 0 °C. However, the high measured volume flow rate of 535 $m^3$/h makes the system unsuitable for a single flat. By simulating an air-to-air heat pump with and without heat recovery, Mortada et al. [10] concluded that the system performance increases significantly with heat recovery.

The present study focuses on an innovative HVAC system that consists of a so called micro-heat pump (micro-HP) and a mechanical ventilation unit with heat recovery (HRV). The objective of the paper is to prove the feasibility of the system, investigate its performance, and further optimise it. To the best of our knowledge, this is the first time that such a compact HVAC system has been integrated into a prefabricated façade. This system represents a decentralised solution (one unit per flat) for the renovation of MFHs aiming to minimise the space requirement inside the flat and to reduce investment costs through prefabrication and low heating capacity. A functional model of this system was installed in one flat, during the renovation of a MFH. A complete monitoring system was also installed to collect information on the performance of the HVAC system and on the comfort level inside the flat. The novelty of this paper lies in the collection and analysis of the monitoring data of the considered system for a complete heating period, combined with dynamic simulations for further system optimisation.

The structure of the paper is as follows. In Section 2, the core concept and the implemented methodology are described. Section 3 is divided into two parts. In the first part, the monitoring results from the first heating season (2016/2017) are discussed in detail. In the second part, the monitoring results are used to validate the simulation models; these validated models are then used to perform dynamic simulations for further system optimisation. Section 4 discusses the most important outcomes of this work, while Section 5 concludes the paper.

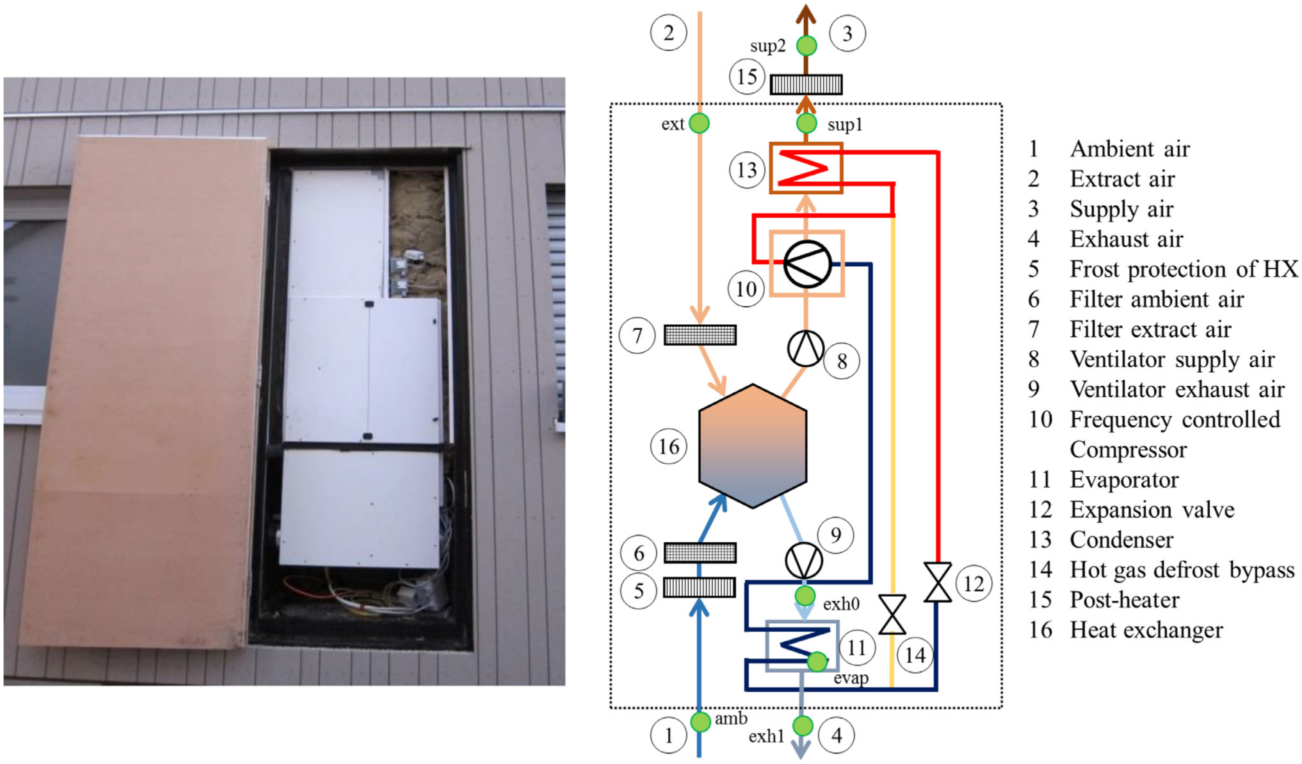
## 2. Concept and methodology

### *2.1. HVAC system*

A micro-HP combined with an HRV unit was developed [11] within the framework of the European project iNSPiRe [2]. As seen in Fig. 1, the evaporator of the micro-HP is located in the exhaust air flow after the heat recovery exchanger, using the remaining enthalpy of the exhaust air. On the sink side, the condenser further heats up the supply air.

Even though the concept could be also compatible with radiators or floor heating, air heating was preferred as a distribution system since it represents a more compact and cost-effective solution (the ventilation supply ducts will be installed anyhow to improve IAQ). In an investigation of heating distribution systems for passive houses [12], it was found that air heating has the potential of 50% less investment costs compared to radiators and 60% compared to floor heating. Compared to radiators, which are controlled in each room with a thermostatic valve, air heating might lead to minor temperature difference among the different rooms. However, this should not be a concern in realistic scenarios. In-situ measured data have shown that already simple supply air cooling can be beneficial compared to split units in humid climates [13].

The functional model was designed for hygienic volume flow rates, i.e. between 90 $m^3$/h and 120 $m^3$/h (based on 30 $m^3$/h per person according to DIN 1946–6 [14]). An additional electric post-heater was placed in the central supply air duct to cover the peak building load. An electric radiator convector is recommended in the bathroom for comfort reasons. A commercially available ventilation unit (Pichler LG180) with a heat recovery efficiency of 85% (according to [15]) was selected, including a polymer membrane heat exchanger (HX) and a pre-heater for frost protection of the HX (position 5 in Fig. 1). A hermetic rotary compressor with a displacement of 5.72 $cm^3$ was placed in the supply air side, which allows recovering the thermal losses. In addition, the frequency control compressor aims to maximise the use of the remaining enthalpy of the exhaust air and improve the energy performance of the heat pump [16] (mainly due to high COP in low frequencies). Refrigerant R134a was used as it is common for such a low capacity compressors and the availability of compressors for alternative refrigerants is poor. The nominal power of the evaporator and condenser was 530 W and 740 W, respectively. A hot gas bypass was also installed (see Fig. 1) for defrosting the evaporator. The control of the defrost cycle was based on operation time and evaporator surface temperature; when the exhaust air temperature is below the set point for two hours, the defrost cycle operates for a period of 15 min.




(a) (b)

**Fig. 1.** (a): Outside view of the micro-HP and HRV (company: Siko Energiesysteme) integrated into the prefabricated timber frame façade (company: Gumpp&Maier) in the demo building of "Wohnungsbau Ludwigsburg GmbH" (WB-L) [18]. (b): Hydraulic scheme [19–21] of the micro-HP and HRV, including temperature sensors of monitoring system (green dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During the design phase, the façade integration strategy affected the required compactness of the system. The main challenge was to fit all components into a casing with a depth of only 0.26 m. It was found favourable to place the HVAC system between two of the windows inside the timber façade (Fig. 3b) instead of placing it below a window. Hence, a vertical casing was developed, limiting the width to 0.65 m, which is the typical modular dimension for structural elements, and the height to2.3 m (height of the flat). The final dimensions of the casing were 205 cm × 65 cm × 26 cm. During the design phase, the aspects of building physics such as reducing thermal bridges, avoiding mould growth, and minimising acoustic impact were solved. Furthermore, access and maintenance issues as well as the release of condensate were also considered in detail [17]. In a future development, an even more compact design could be achieved e.g. by using a fine wire cooper heat exchanger.

The proposed system is designed for minimally disruptive renovation of a flat, and thus, has an advantage compared to conventional systems when there are space limitations, mainly for two reasons: (a) a hydronic or air emission and distribution system is not required, and (b) its compact design and the façade integration eliminate the space requirement inside the flat.

### 2.2. Demonstration building – flat with the micro-heat pump

The MFH, selected as demonstration building (Fig. 2), was built in 1971 in Ludwigsburg (Germany). It consists of four stories and four flats (Fig. 3a): a small flat on the cellar (39.5 m$^2$), two identical flats, one on the ground floor and one on the first floor (99 m$^2$), and one on the attic (61.4 m$^2$). The building was renovated with prefabricated timber frame façade elements up to the Passive House standard. The 1.5 1/h measured air-tightness did not meet the aimed target of 1 1/h, but was still within the allowed range according to the German energy standard (EnEV). A central air-to-water heat pump (with a brine circuit) was installed to cover space heating and domestic hot water.

The micro-HP was installed in the north façade of the flat on ground floor (GF) (Fig. 3b) and the central heating system was deactivated for this flat. Moreover, the ambient, exhaust, and extract air ducts were integrated into the prefabricated timber frame façade (the air inlets for the air extraction were placed in the reveal of the windows). Thus, only the supply air ducts were placed inside the flat, minimising the disturbance to the tenants and fostering the concept of a minimal disruptive renovation [17]. The floor plan with the ventilation ducts and the HVAC system are presented in Fig. 3b.

### 2.3. Monitoring concept

Fourteen comfort sensors (measuring temperature, humidity and $CO_2$) were installed in the building: five in the cellar (three in the flat and two in the common areas), five in the GF (blue dots in Fig. 3b) and four in the attic flat. Three of the four sensors from the attic were moved to the first floor during the renovation, because a separate monitoring system was installed in the attic. The comfort sensors were calibrated onsite, with respect to temperature and humidity, for a period of one month using calibrated comfort loggers. The electricity consumption of each flat (excluding HVAC systems) and the heat delivered for space heating and domestic hot water to each flat were measured separately. A weather station was placed in the outside yard to measure ambient temperature, relative humidity, and global and diffuse radiation. The mon-


**Fig. 2.** Outside view of the demonstration building in Ludwigsburg (Germany) before (a) and after (b) renovation; the building owner is "Wohnungsbau Ludwigsburg GmbH" (WB-L) [21].

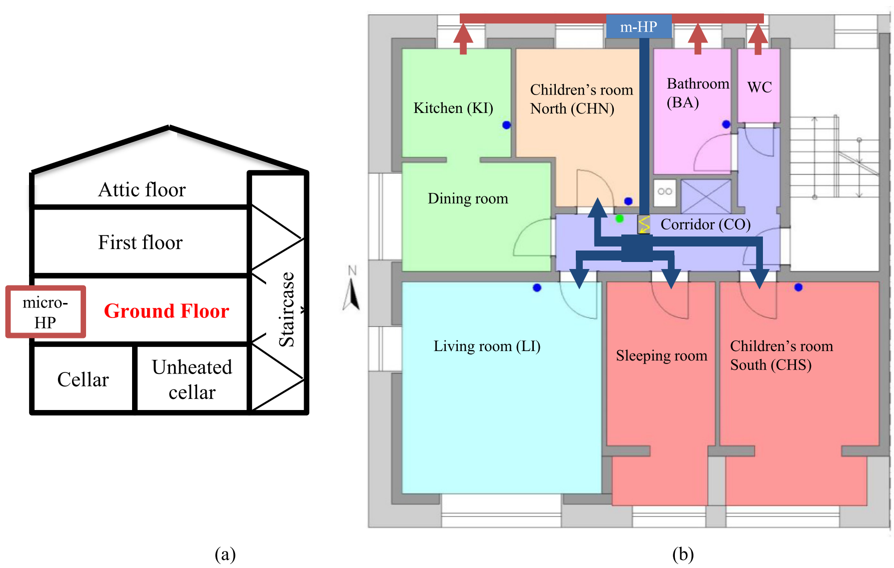



**Fig. 3.** Simplified scheme of the demonstration building (a) and floor plan of the flat on the ground floor with a simplified scheme of ducting for ventilation and heat distribution (b) [23].

itoring system was designed by the companies CARTIF and EURAC (more details can be found in [22]).

A separate monitoring system was installed for the micro-HP and the HRV unit. Eight temperature sensors, one humidity sensor, two pressure difference sensors with orifice plates for measuring the volume flows, and three electricity meters were used to monitor the dynamic behaviour of the system. The position of the temperature sensors is shown in Fig. 1b. An additional temperature sensor, which was used in the control system of the micro-HP, was installed in the corridor of the flat (green dot in Fig. 3b).

The temperature sensors used were Pt1000 1/3 DIN B with an uncertainty of ± 0.15 °C in the relevant measured values. The accuracy of the measurement acquisition equipment was not determined. However, this is not critical for the determination of the heating power, since the temperature difference was used. The temperature difference measurement had an uncertainty of ± 0.30 K. For the measurement of the humidity of the extract air, standard sensors for an HVAC system were used. The measurement error within the calculation of the mass flow was neglected. The extract and supply air volume flows, which were measured by orifice plates and differential pressure sensors, were adapted to the in-situ measured values. The in-situ volume flows were measured with a flow finder (Wöhler CFM 600 uncertainty ± 3%), which was calibrated by the producer beforehand. The in-situ calibration led to an estimated overall uncertainty for the volume flow measurement of ± 6%. Furthermore, the electric consumption was measured with an accuracy of ± 1%, leading to a maximum overall uncertainty for the power consumption of the compressor of ± 3 W. The overall uncertainty of the power measurement on the air side for the characteristic used volume flow of 130 m³/h can be determined at ± 49 W or ± 7%.

The building was being monitored even before the refurbishment for the winter 2014/2015 [20]. The flat on the GF was renovated in December 2015, and the full monitoring started in February 2016. This study includes the monitoring data analysis from the first complete heating season 2016/2017.

Due to technical problems in the monitoring system of the micro-HP, there were two periods (07/12 - 27/12, 26/01 - 31/01)

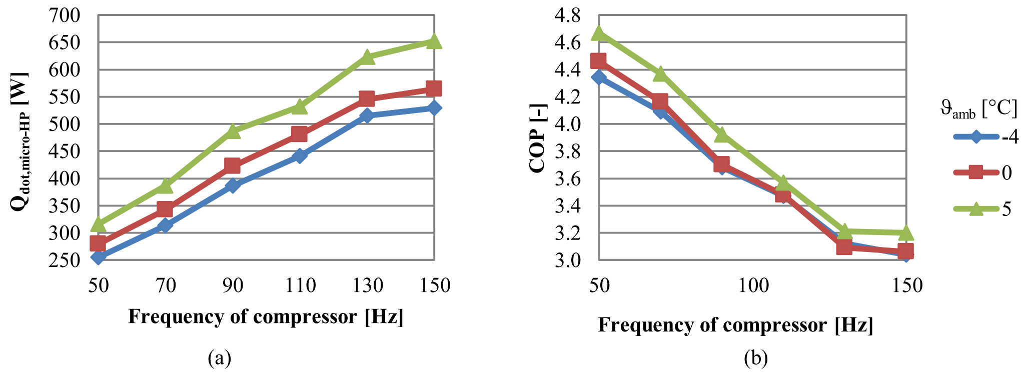



**Fig. 4.** Performance map of the thermal power of micro-HP (a) and the COP (b) depending on compressor frequency and ambient air temperature [19,28].

with only the electricity data available. For these periods, the heat supplied by the heat pump and the HRV was simulated and calibrated to the measured electricity consumption (see Section 3.2). In addition, the operation time of the electrical radiator in the bathroom was negligible during the monitoring period.

### 2.4. Simulation models

For the dynamic building and system simulations, Matlab/Simulink [24] with the additional CARNOT toolbox [25] was used. Below, the developed simulation model is described for each of the components.

**HRV:** The heat recovery efficiency $\eta_{HRV}$ from the certificate [15] - see Eq. (1), was used to calculate the temperature effectiveness $\eta_{\vartheta_{exh}}$ (see Eq. (2)) assuming dry air and balanced volume flow. The heat flux transferred in the HX $\dot{Q}_{HX}$ was calculated using Eq. (3). The total thermal power of the HRV $\dot{Q}_{HRV}$ also includes the power of one fan (see Eq. (4)), since one of the two fans was located in the supply air after the HX (Fig. 1). The enthalpy of exhaust air after the second fan $h_{exh0}$ was calculated with the enthalpy balance (Eq. (5)). As a next step, the temperature and the condensate mass flow were estimated depending on the enthalpy and absolute humidity.

$$\eta_{HRV} = \frac{\vartheta_{ext} - \vartheta_{exh} + \frac{P_{fan}}{\dot{m} \cdot c_p}}{\vartheta_{ext} - \vartheta_{amb}} \tag{1}$$

$$\eta_{\vartheta_{exh}} = \frac{\vartheta_{ext} - \vartheta_{exh}}{\vartheta_{ext} - \vartheta_{amb}} \tag{2}$$

$$\dot{Q}_{HX} = \eta_{\vartheta_{exh}} \cdot \dot{C}_{min} \cdot (\vartheta_{ext} - \vartheta_{amb}) \tag{3}$$

$$\dot{Q}_{HRV} = \dot{Q}_{HX} + \frac{P_{fan}/2}{\dot{C}_{sup}} \tag{4}$$

$$h_{exh0} = h_{ext} - \frac{\dot{Q}_{HX}}{\dot{m}_{ext}} + \frac{P_{fan}/2}{\dot{m}_{ext}} \tag{5}$$

**Micro-HP:** Blervaque et al. [26] compared four simulation models of air-to-air heat pumps with variable-speed compressor to experimental data, proposing the dynamic empirical or the simplified physical model for simulations. In this study, a performance map model (see Fig. 4) was used including the dynamic behaviour of the condenser (see Fig. 5). This behaviour, i.e. the time duration to reach the steady state condition after switching on or off, was modelled using a transfer function with different time constants for the start and stop functions. The time constants for on/off cycling are similar to those of the defrosting period. Salzmann [27] proposed an improved controller for the micro-HP that could increase the run-time for lower frequencies and reduce the duration of the defrost cycle to 10 min instead of 15 min on average. The heating capacity of the micro-HP ($Q_{micro-HP}$) and the coefficient of performance (COP) were modelled as a function of the exhaust air temperature of the HRV, the absolute humidity and the frequency of the compressor. The performance map data were based on the steady state test points from laboratory measurements using dry extract air (see [19,28] and Fig. 4).

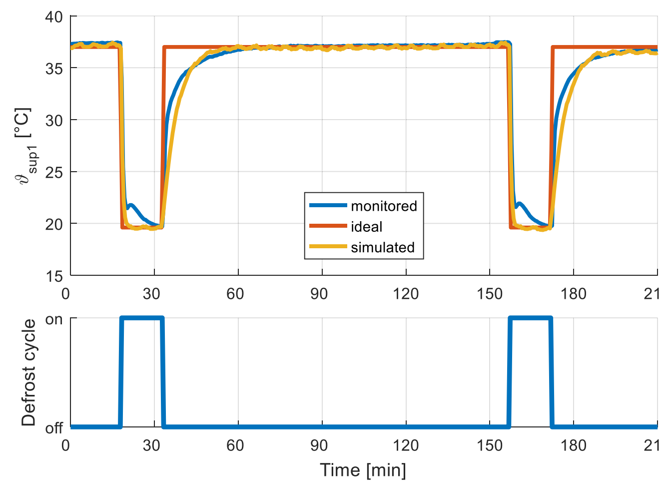



**Fig. 5.** Air temperature after the condenser ($\vartheta_{sup1}$) during and after the defrost cycle operation versus time.

**Remark.** The micro-heat pump installed in the demo building featured minor modifications compared to the one measured in the laboratory, such as a slightly larger evaporator.

A proportional-integral (PI) controller was implemented having as process variable the corridor temperature. The output of the PI controller is the required supply air temperature; based on the output, the compressor speed and the power of the post-heater are calculated accordingly via a look-up table. As for the controller of the defrost cycle, the outlet exhaust air temperature of the evaporator was used in the simulation model. The minimum heat pump operation time was set to 15 min.

**Building:** Several building simulation models with variable degrees of detail were developed for the demonstration building [20]. A calibration and validation for the flat on the GF before the renovation had already been performed [23]. In the present study, the six-zone model of the renovated flat in the GF (Fig. 3) was used [23]. It is a two star model with one node for radiative temperature and one for convective temperature as proposed by Feist [29].

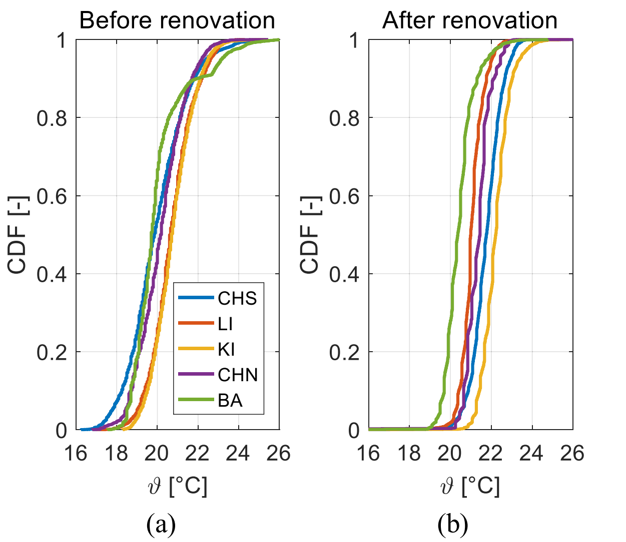



**Fig. 6.** Cumulative distribution function (CDF) of indoor temperatures of the monitored rooms before (a) and after (b) renovation. Hourly average values from 15/11/2016 to 31/03/2017.

## 3. Evaluation results

### *3.1. Monitoring data analysis*

#### *3.1.1. Thermal comfort and IAQ*

The indoor temperatures and the $CO_2$ concentration of the monitored rooms in the GF flat were compared before and after renovation for the same period of the year (middle of November until end of March).

Fig. 6 shows the cumulative distribution function (CDF) of the indoor monitored temperatures before and after renovation. The indoor temperatures were increased on average by almost 1 K after the renovation. In addition, the temperature difference between the rooms after the renovation is higher. This is due to the fact that the temperature of each room was controlled individually (using thermostatic valves with radiators) before the renovation, while the heating system was controlled by a single temperature sensor (located in the corridor) after the renovation.

Fig. 7 (a, b) highlights the significant improvement of the IAQ after the renovation. The highest $CO_2$ concentration is observed in room CHS; in particular, the concentration exceeds 1000 ppm 77% of the time before renovation compared to only 44% after renovation. A concentration higher than 1000 ppm indicates low IAQ (according to [30]). Fig. 7 (c, d) shows the $CO_2$ concentration after renovation both when the mechanical ventilation was in operation (Fig. 7c) and when not (Fig. 7d - instead of HRV, window ventilation took place). The mechanical ventilation was switched off by the occupants for 37% of the heating period, leading to significantly low IAQ. During the time when the mechanical ventilation was in operation, the $CO_2$ concentration in all rooms was lower than 1000 ppm only 5% of the time - expect in the LI room, which was 30%.

#### *3.1.2. System performance*

The sum of the heat supplied to the flat in the GF by the micro-HP, the post-heater and the electric radiator in bathroom was considered as heating demand (HD), while the HRV was considered a “passive component” in the energy balance, such as in PHPP [31]. The use of HRV reduced the HD to less than half i.e. from 26.8 kWh/(m$^2$·yr) to 11.7 kWh/(m$^2$·yr). However, it was higher than expected. For example, the HD of the identical flat in first floor was almost five times less with a value of 2.1 kWh/(m$^2$·yr). The main reason for this difference was the high transmission losses to the adjacent flats and the common spaces, due to the high indoor temperature of the flat on the GF. Fig. 8 demonstrates the average monitored temperatures of the neighbouring flats (top and bottom) and the unheated spaces in the cellar. The temperature of the GF was 2.3 K higher than the one of the flat in cellar, 3.2 K higher than the unheated cellar, and 0.6 K higher than the one of the flat on first floor. The aforementioned differences resulted in high transmission losses from the flat on the GF to the adjacent spaces. It is also noted that the flat in cellar was not occupied for a month between February and March.

Due to the high transmission losses to the adjacent flats and thus, the high HD, the contribution of the post-heater was higher than expected with a share of 30%. Fig. 9 demonstrates the percentage of electricity consumed by each component and underlines the need for optimisation in some components such as the pre-heater, the fans, and the size of the heat pump. The pre-heater had high power and the control strategy was not optimal. Therefore, when it was in operation, the whole HRV unit was overheated leading to poor performance of the heat recovery. The consumed electricity of the fans was 0.75 Wh/m$^3$ instead of 0.40 Wh/m$^3$ (according to the certificate [15] for standard operation of the HRV unit). One reason for the high specific fan consumption was the presence of the evaporator and the condenser in the air flows (presenting further pressure resistances). The specific fan power was also measured in the laboratory with and without the presence of the micro-HP resulting in 0.45 Wh/m$^3$ and 0.40 Wh/m$^3$ (same as the value in the certificate), respectively [19]. This increase of 0.05 Wh/m$^3$ in the fan electricity (‘HP fans’ in Fig. 9) was included in the calculation of SPF of the heat pump. The remaining difference can be explained by the increased pressure losses due to the small diameter of the ducts used because of the limited available space in the renovated flat. Finally, the volume flow of the supply air decreased by 4% per month due to dust accumulation in the filters.

For the performance evaluation of the micro-HP, the heat pump system, the HRV and the total HVAC, four SPFs were defined according to the following equations and illustrated in Fig. 10.

$$SPF_{micro-HP} = \frac{Q_{condenser}}{W_{el,compressor}} \quad (6)$$

$$SPF_{sys} = \frac{Q_{condenser} + Q_{postheater} + Q_{Radiator}}{W_{el,compressor} + W_{el,postheater} + W_{el,Radiator}} \quad (7)$$

$$SPF_{HRV} = \frac{Q_{HRV} + Q_{pre-heater}}{W_{fan} + W_{pre-heater}} \quad (8)$$

$$SPF_{tot} = \frac{Q_{HRV} + Q_{condenser} + Q_{postheater} + Q_{Radiator}}{W_{el,HRV} + W_{el,compressor} + W_{el,postheater} + W_{el,Radiator}} \quad (9)$$

$SPF_{sys}$ is 1.7 and is reduced with respect to $SPF_{micro\text{-}HP}$ (2.5) due to post-heating. As $SPF_{HRV}$ reaches the value of 5.2, a $SPF_{tot}$ of 2.8 can be achieved. The monthly $SPF_{micro\text{-}HP}$ reached the highest value of 3.2 in March and the lowest value of 2.2 in January.

### *3.2. Simulation assisted monitoring analysis*

#### *3.2.1. Calibration and validation of the models*

##### *3.2.1.1. HVAC system.*

*Boundary conditions and calibrated parameters.* For the validation of the micro-HP and the HRV unit, monitoring data with a time step of 30 s were used as inputs to simulation. The inputs were the ambient and extract air temperature, the relative humidity and the air mass flows of ambient and extract air. As a first step, the measured signals of the controller were directly provided to the heat pump model, i.e. the frequency of the compressor and

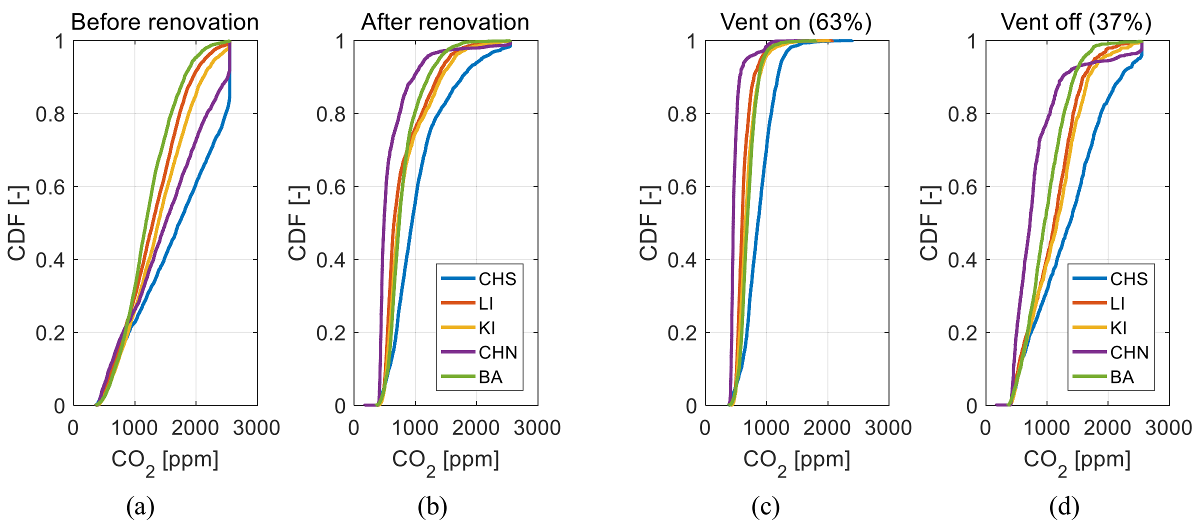



**Fig. 7.** Cumulative distribution function of $CO_2$ concentration of the monitored rooms before (a) and after (b) renovation, and only after renovation when the mechanical ventilation was in operation 'Vent on' (c) and when not 'Vent off' (d). Hourly average values from 15/11/2016 to 31/3/2017.

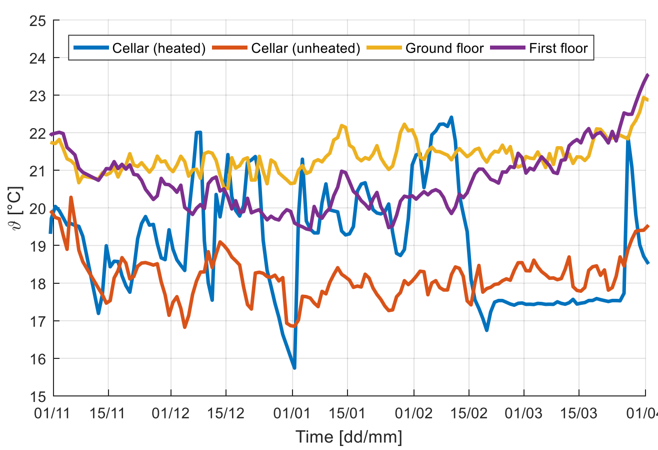



**Fig. 8.** Average indoor temperature of the flats in cellar, ground floor and first floor, as well as of the unheated spaces in cellar in daily resolution.

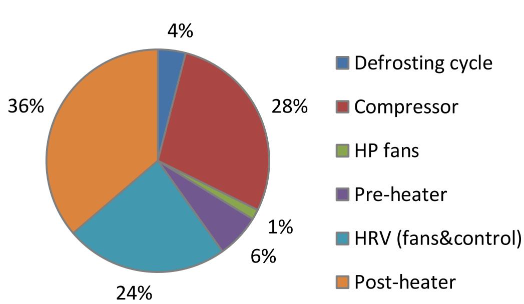



**Fig. 9.** Percentage of the consumed electricity by each component for the heating period 2016/17. The total measured electricity for the HVAC was 960 kWh.

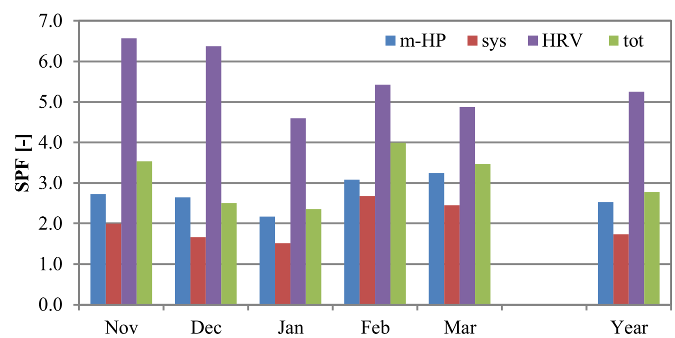



**Fig. 10.** Monthly and annual (heating season) SPFs of the HRV, the micro-HP, the heat pump system and the total HVAC (acc. to Eq. (6)-(9)).

the control signal of the defrost cycle, in order to compare the performance map and the dynamic behaviour. As a second step, the controller was included in the simulation model receiving the monitored temperatures (set point and corridor) as inputs.

The performance map data were adapted to the monitoring data (Fig. 11). To account for humidity, a linear correlation was found between the heating capacity (and correspondingly the electric power), the exhaust air temperature, and absolute humidity for the maximum frequency. The heating capacity and the electric power were reduced according to the frequency similarly to the measured test points in the laboratory (see Fig. 4).

The time constants, used for the heating up and the cooling down phases of the condenser during on/off operation, as well as the electrical consumption of the fans and the controller were also calibrated against the monitored data [18].

*Results of the validation.* For the validation of the simulation model, the most important parameters are the supplied power to the flat and the consumed electricity. Since the supplied power was not measured directly, the supplied air temperature after the condenser ($\vartheta_{sup1}$) was used for comparison. It was found that the temperature sensor after the post-heater ($\vartheta_{sup2}$) was installed in an inappropriate way and could not be used for the analysis. Thus, the measured electrical consumption of the post-heater was used to calculate the $\vartheta_{sup2}$ in the simulation model.

The supply air temperature ($\vartheta_{sup1}$) and the electricity of the compressor from monitoring data and simulations are shown in Fig. 12. The temperature difference is relatively low and rarely exceeds 1 K, (see Fig. 12 top). The simulated electricity is slightly higher than the measured one with a maximum of 10 W.

In addition, the heat supplied by the micro-heat pump and the electricity of the compressor were calculated for the heating period (excluding periods with measurement gaps). The simulated results were 5% and 4% higher than the monitored ones, respectively. As a further step, the PI controller was included in the simulation model using the simulated corridor temperature as control variable. In this case, the simulated supplied heat was 9% higher and

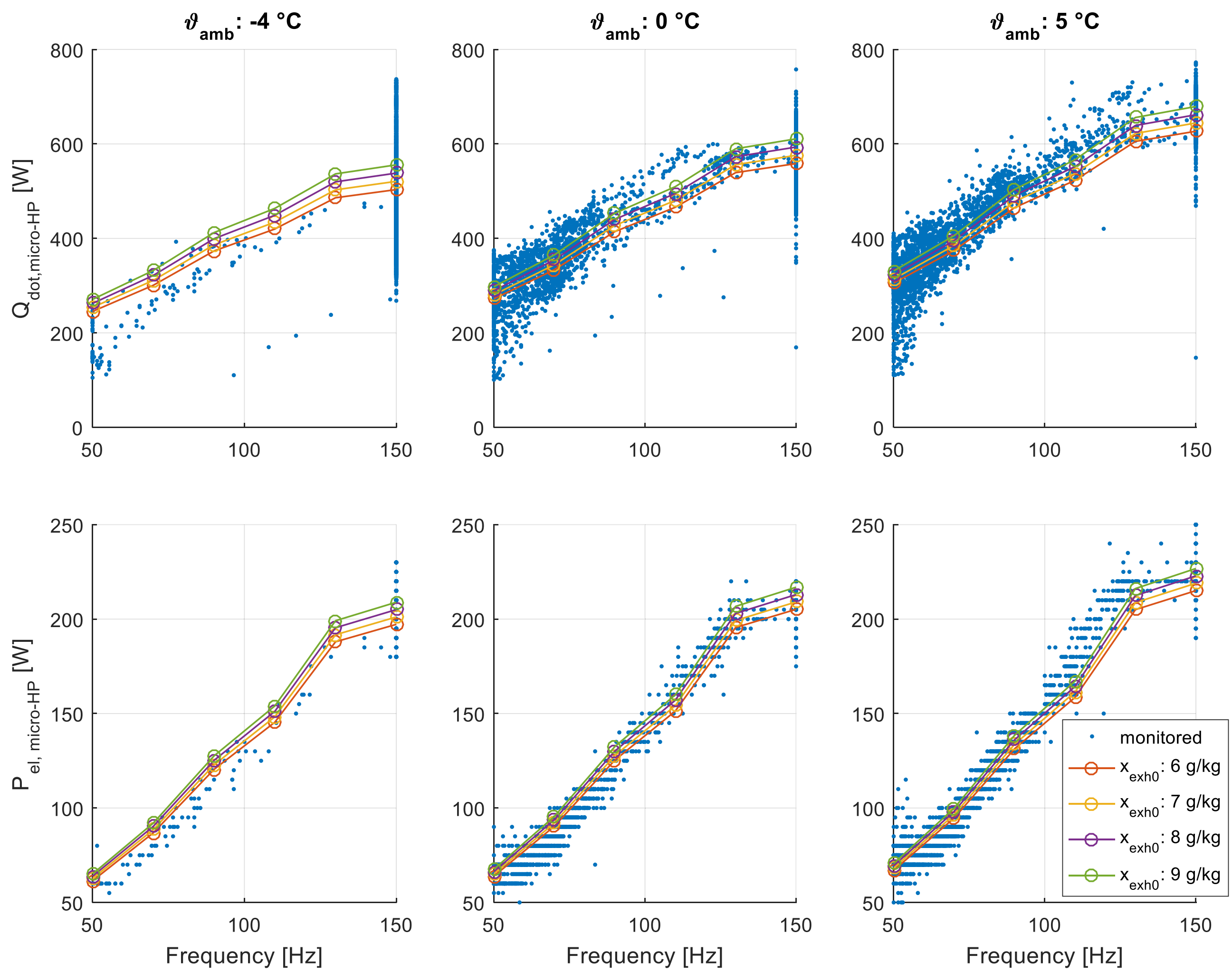



**Fig. 11.** Performance map data, and monitored thermal and electric power of the micro-HP, versus the frequency of the compressor, with varying parameters of the absolute humidity (exh0) for three ambient temperatures (−4, 0 and 5 °C).

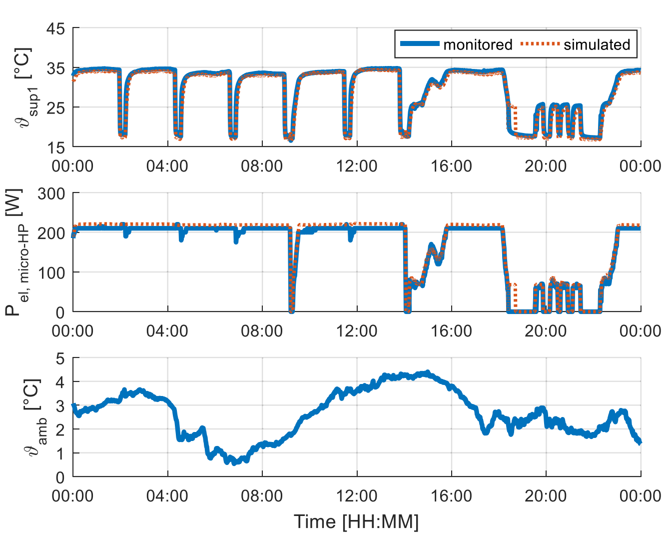



**Fig. 12.** Comparison of simulated and monitored air temperature after the condenser ($\vartheta_{sup1}$), and electrical consumption of the compressor for one day (28/12/2016) using one minute resolution.

the consumed electricity was 6% higher compared to the measured ones.

*3.2.1.2. Building model of the flat.*

*Simulation model and boundary conditions.* The building model of the flat was calibrated and validated using the monitoring data. The monitored temperature of the heated cellar, the unheated cellar and the first floor were used as boundary conditions (Fig. 8). The stratification effect in the staircase was confirmed by additional in-situ measurements in spring 2016. Therefore, the temperature of the staircase was set equal to the corridor of the unheated cellar plus an offset of 0.4 K. The electrical consumption of the flat, the supply temperature ($\vartheta_{sup1}$), and the electricity of the post-heater were also used as inputs to the simulation. The air mass flows were distributed to each zone based on the measured onsite values of the supply and extract air flow of each zone with the flow finder. The electricity consumption (for lighting and appliances) was distributed to each thermal zone using a calibrated factor. In addition, a profile for the occupancy (considering three residents) was used based on the one before the renovation [23].

As an output, the simulated operative temperature of each zone was compared to the monitored one. An initial period of one week was used in the simulations, due to the thermal mass of the building.

*Calibration and validation of the building model.* For the calibration of the model, several parameters were varied, such as infiltration rate (including window opening), U-value of the internal walls, solar shadings, and the ratio for the distribution of electricity to each zone. One cold week with low solar gains in January was

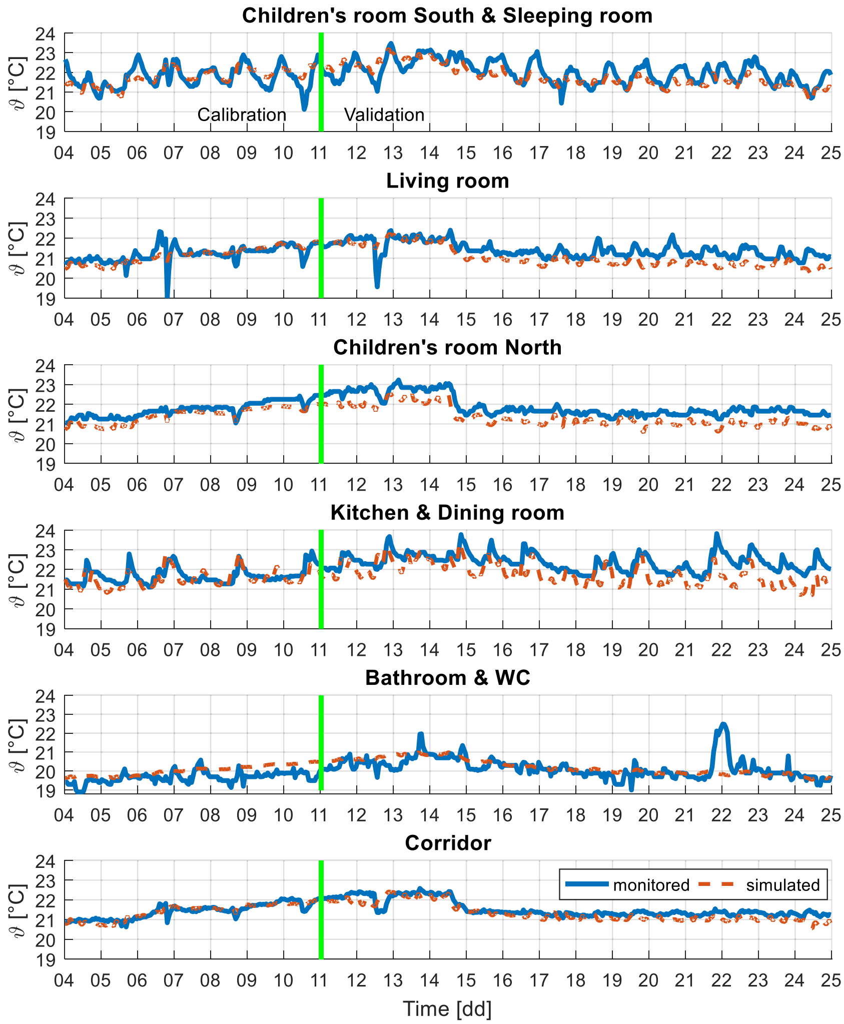



**Fig. 13.** Comparison between simulated (operative) and measured temperature of each thermal zone using hourly resolution. Calibration period: 04/01 until 11/01. Validation period: 11/01 until 25/01.

selected as a calibration period. The root mean square error (RMSE) of the measured and simulated temperatures was used as the comparing measure. Using the calibrated model, the simulations were performed for an additional two weeks in January, which was the validation period.

Fig. 13 shows the results of the calibration. The temperature difference is within the range of ± 1 K (except some extreme peaks). The average RMSE of all zones is 0.35 K with a maximum value of 0.46 K in the bathroom and 0.16 K in the corridor. As for the validation period in all zones, the long-term trends were well predicted and there was a good agreement in the dynamic behaviour, again with the exception of occasional peaks, which were caused by occasional situations, such as cooking or a window opening. In the majority of the zones, the simulated temperature tends to be slightly lower than the monitored one.

*3.2.2. Dynamic building and system simulations*

Dynamic simulations were performed using the validated HVAC and building model aiming to (a) optimise the system, (b) fill the gaps in the monitoring data (see Section 2.3), and (c) normalise the HD regarding the specific user behaviour with respect to the set point temperature and ventilation operation (on/off operation of the HVAC system plus window ventilation).

The boundary conditions remained identical to those described in the previous subsection with the exceptions that the HRV unit was set to continuous operation and the set point temperature to 21 °C (close to the average monitored one). The simulated period was from 11/2016 until 03/2017. The simulated cases were the following:

- Reference case with a HD of 15.4 kWh/(m$^2$·yr)
- Operation the electric radiator in the bathroom
- Use of an ideal controller for the pre-heater
- Use optimised ventilators in the HRV unit
- Use of an optimised defrost operation cycle (i.e. reduced operation time)
- Elimination of the heating up time of the condenser
- Comparative study varying the heating capacity of the heat pump.

When the electric radiator in the bathroom was set in operation, the total electric consumption was increased by 9%. In the bathroom, usually the temperature is set to 1 or 2 K higher than the other rooms due to comfort reasons (clothing factor in the bathroom - temperature of 24 °C according to [32] for the design of heat load). In this study, the set point temperature was set equal to the one of the flat, but different assumptions could be used, such as a higher set point temperature or operation of the radiator in maximum power for some hours during the day.

As a first optimisation step, an ideal PI controller (instead of an on/off hysteresis) of the pre-heater was modelled, in order to reach

**Table 1**
Influence of scaling the heating capacity of the micro-HP on HD and SPF.

| Simulated cases | Scaling up factor | $Q_{micro-HP}$ ($\vartheta_{amb}$: 0°C, freq: 150, $x_{exh0}$: 9g/kg) [W] | HD [kWh/(m²·yr)] | $SPF_{micro-HP}$ | $SPF_{sys}$ | $SPF_{tot}$ |
|---|---|---|---|---|---|---|
| A (ref) | 1 | 589 | 15.4 | 2.2 | 1.8 | 3.2 |
| B | 1.5 | 884 | 15.5 | 2.1 | 2.0 | 3.4 |
| C | 2 | 1178 | 15.9 | 2.0 | 2.0 | 3.4 |

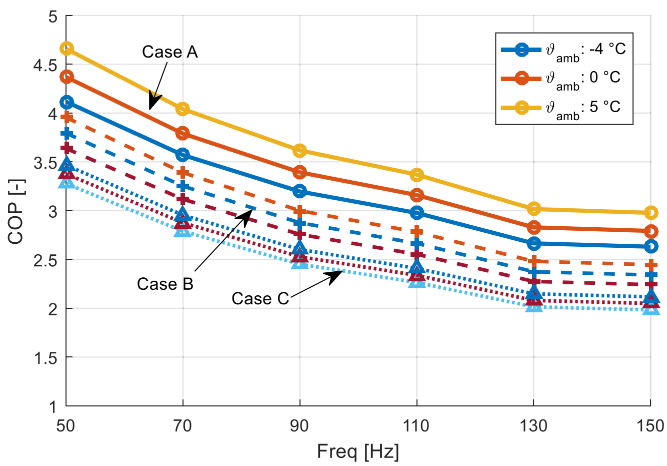



**Fig. 14.** COP for three sizes (heating capacity) of the micro-HP (cases A, B and C, see Table 1) versus frequency of compressor having as parameter the ambient temperature with an absolute humidity of 7 g/kg in the exhaust air.

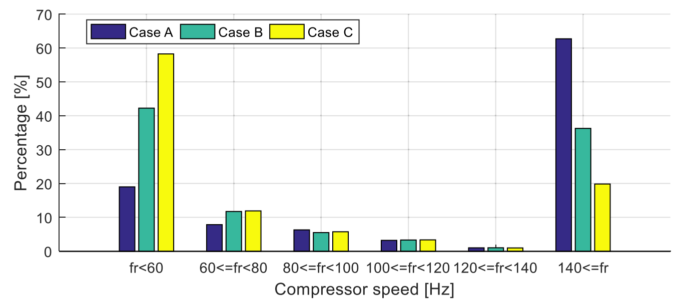



**Fig. 15.** Frequency plot of the compressor speed for the cases A, B and C, see Table 1.

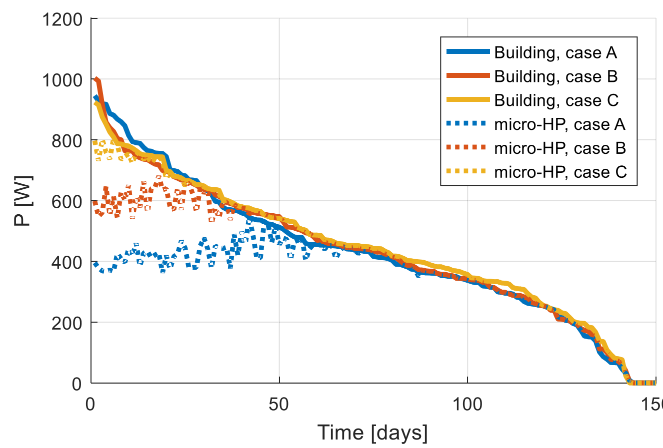



**Fig. 16.** Load duration curves of the flat and the micro-HP for the cases A, B and C.

the required set point temperature of the HRV inlet temperature of −5 °C, when the ambient temperature was lower. In this way, 5% savings was achieved in the total electricity and 17% savings in the consumption of the HRV unit. As a second step, the specific fan consumption of the certificate was used resulting to 12% less electricity.

For the optimisation of the system, the duration of the cycle was set to 10 min instead of 15 min assuming an optimised controller for the defrost cycle as proposed by Salzmann [27]. The simulation results showed a reduction in total electricity by 5%, mainly because of the 10% less contribution of the post-heater.

As shown in Fig. 5, the required time to reach the steady state condition after the defrost cycle is around 30 min. Theoretically, this time could be eliminated (see ideal case in Fig. 5). Simulation with this ideal case showed 3% less electricity consumption.

A comparative study with three simulation cases was performed to investigate the influence of the heating capacity of the micro-HP on the system performance. The reference heating capacity, used in case A, was scaled up by a factor of 1.5 in case B and 2 in case C (Table 1). The COP for each test point of the performance map was recalculated keeping the Carnot performance factor equal to the reference performance map. Fig. 14 depicts the COP of the three sets of performance map data. The COP decreases as the heat pump is scaled up if the volume flow remains constant (hygienic air flow), since the temperature difference between the source and the sink sides increases.

Table 1 summarises the results of these three simulated cases. The HD was almost identical for cases A and B with a value of 15.4 kWh/(m²·yr), and increased slightly in case C (15.9 kWh/(m²·yr)). The scaling up of the heat pump led to a reduction in the $SPF_{micro-HP}$ from 2.2 to 2.0, but to an increase in the $SPF_{sys}$ from 1.8 to 2.0 and the $SPF_{tot}$ from 3.2 to 3.4. Fig. 15 demonstrates the frequency ranges during the operation time of the compressor. The compressor was operating mainly on the lowest or highest speed in all three cases. This is an indication that the tuning of the PI controller was not optimal. By scaling up the heat pump, the contribution of post-heater to space heating was significantly reduced from 21% (case A) to 7% (case B) and 1% (case C) – see also Fig. 16. The savings in terms of consumed electricity for heating were 9% in cases B and C. By comparing case C with case B, the energy savings due to less post-heating were almost compensated by the lower COP of the heat pump (Fig. 14) leading to almost equal $SPF_{sys}$ and $SPF_{tot}$ with a value of 2.0 and 3.4, respectively. Fig. 16 presents the load duration curves of the flat, as well as the heating power of the micro-HP sorted correspondingly (excluding post-heating) for the three cases, highlighting the effect of reduced post-heating when scaling up the micro-HP.

## 4. Discussion

Thermal comfort conditions were achieved in all rooms except the bathroom, which could be improved with the operation of the electric radiator. Simulation results showed that the electric radiator in the bathroom would increase the electricity consumption by 8%. The limited complaints by the occupants mainly referred to the temperature of the dining room, even though the temperature in the kitchen, which was adjacent to the dining room, was higher than the other rooms. Furthermore, the response of the control system was considered slow. In particular, the occupants could not immediately feel the temperature difference after changing the set point temperature (more than a couple of days were needed). This can be explained by the high thermal mass of the building and the low capacity of the HVAC system. Comparing the thermal comfort before and after the renovation, the average indoor temperature was increased by 1 K (with the same occupants). The temperature difference between the rooms was increased by 0.8 K including the bathroom or 0.2 K when excluding it. There was no indication that the occupants realised the increase.

The IAQ was strongly improved after the renovation, even though the occupants tended to switch off the ventilation system very often, even during the heating season. Surprisingly, the ventilation was out of operation for 33% of the heating season. The average $CO_2$ concentration of the monitored rooms after the renovation was below 1000 ppm for 77% of the time, significantly increased from 21% before the renovation. The $CO_2$ concentration was significantly lower when the HRV unit was in operation; for example, the lowest IAQ was observed in the room CHS with a $CO_2$ concentration higher than 1000 ppm for 33% of the time reduced from 80%.

The energy performance of the HVAC system was lower than expected. The monitored $SPF_{micro\text{-}HP}$ was 2.5, while $SPF_{tot}$ was 2.8. The HD this year was relatively high due to the unusually low ambient temperature in January (down to −12 °C) and lower indoor temperature of the neighbouring flats. For example, the identical flat above had 82% less heating demand, and the flat below was not occupied for one month. The resulting high transmission losses (and the corresponding HD) led to reduced energy performance due to the high contribution of the post-heater. A simulation study using normalised boundary conditions demonstrated improved performance by significantly lower operation time of the post-heater, resulting in a maximum $SPF_{tot}$ value of 4.0 [18].

The HRV reduced the HD by 56% (from 26.8 kWh/(m$^2$·yr) to 11.7 kWh/(m$^2$·yr)), while savings could be even higher, if the unit was operating the whole heating period. However, the consumed electricity of the unit (fans) was relatively high, equal to one third of the total electricity consumption. The electricity consumption of the fans was higher than the one specified in their certificate [15] due to higher pressure losses. These high-pressure losses are due to the presence in the ducts of the evaporator, the condenser, the post-heater, the silencers, and the orifice plates (used for volume flow measurement equipment). In addition, the relatively small diameter of ducts, and the type of inlets and outlets might also increase the pressure losses. One approach to reduce the fan power would be to decrease the volume flow from 130 m$^3$/h to 110 m$^3$/h, which is still acceptable according to standards [14]. Moreover, since the monitored volume flow of the supply air was reduced by 4% per month, it is recommended to change the air filters based on the measured volume flow or the pressure difference. As Dodoo el al. [33] proposed that for a ventilation heat recovery decision, the electricity consumption, the air tightness of the building, and the type of heating system all constitute important issues. Similarly, Mortada et al. [10] concluded that the fans of an air-to-air heat pump have a remarkable impact on the COP of the system.

The developed simulation models of the HVAC and the flat are in agreement with the monitoring data. The electricity consumption of the compressor was slightly overestimated at 10 W. The modelled performance map of the micro-HP is dependent on three variables (compressor speed, air source temperature and humidity) for a given volume flow. This was not critical in this case study, since the flow remained constant (expect the reduction over the time due to dust in the filters). The building model of the flat was validated using the monitoring data. The temperatures of the six thermal zones were in accordance to the monitored ones with a difference less than ± 1 K with exception of some extreme peaks e.g. due to cooking or showering.

Dynamic simulations were performed to optimise the energy performance of the system. The optimum operation of the fans along with the use of the PI controller for the pre-heater would lead to an $SPF_{HRV}$ of 11.6 instead of 5.2 (monitored). By scaling up the micro-HP with a factor of 1.5 or 2, the $SPF_{tot}$ increased from 3.2 to 3.4. Interestingly, there is almost no difference in all $SPF_{sys}$ and $SPF_{tot}$ for cases B and C. Since hygienic constant volume flow was used, the COP was decreased as the heat pump scaled up. Even though the $SPF_{micro\text{-}HP}$ was reduced (2.0 from 2.2), the $SPF_{tot}$ increased due to the reduced operation of the post-heater. Scaling up the heat pump has the further advantage of minimised possibilities for an under-dimensioned heating system. Moreover, an improved controller for the defrost cycle would increase the $SPF_{micro\text{-}HP}$ from 2.2 to 2.4. Finally, considering all these improvements resulted in 25% electricity savings.

The compressor was operating mainly either on maximum or minimum speed, indicating that the PI controller was not optimally tuned. The use of a variable-speed compressor may increase the performance up to 15% compared to a constant speed compressor [16] and make the system more robust with respect to a non-optimised heat pump size for the building (too high heating power) or special events such as unexpected user behaviour [34]. In order to achieve this improvement, appropriate tuning of the PI controller is crucial [34] and further research is required, e.g. self-learning control.

The proposed system could operate also sufficiently in different climate conditions with the requirement of complying with EnerPHit or an even better building standard such as Passive House. The climate insignificantly influences the COP of the micro-HP, because the source and sink inlet temperatures are dampened, due to the heat recovery, compared to the ambient temperature and thus, the temperature difference between evaporator and condenser slightly varies. However, the HRV strongly improves the system performance when the climate gets colder. In contrast, the electricity share of the pre-heater increases when the ambient temperature drops below −5 °C, leading to a decrease in performance. In a simulation comparative study including seven European climates and two building standards (EnerPHit and Passive House), a micro-HP combined with HRV consumed less electricity (up to 38%) compared to an air source heat pump in all cases [4]. The difference in energy consumption between the two systems increased with the improved building energy standard (Passive House) and colder climates. For example, the micro-HP system required 2% and 24% less electricity than the air source heat pump in Rome and in Stockholm, respectively.

The monitored system performance was compared to those from other monitoring studies about heat pumps found in literature. Esen et al. [35] measured an SPF of 2.2 (average COP of 2.82) for a ground source heat pump system with a horizontal heat exchanger in 2 m depth. Miara et al. [36] monitored several heat pumps for 10 years. The SPF for air-source heat pumps in existing building varied between 2.1 and 3.3 with an average value of 2.6. In the present study, the monitored $SPF_{sys}$ was lower with a value of 1.7 due to high operation time of the post-heater (the $SPF_{micro\text{-}HP}$ was 2.5), but when the HRV performance is included, the $SPF_{tot}$ had a value of 2.8.

From an economic point of view, the proposed system has a potential for cost reduction compared to conventional systems for three main reasons:

a) No further cost is required for the equipment and the installation of the heat emission and distribution system, since the ducting is required anyway for the distribution of the hygienic air flow;

b) Lower heating capacity and size compare to conventional heat pumps;

c) The prefabrication reduces the onsite working time.

The main reason for façade integration is the limited available space in MFHs, which also has an economic benefit that is however difficult to monetarize.

To summarise, the monitoring data analysis of the first complete heating season proved the feasibility of the concept, and the dynamic simulations showed possible further improvements. The results could be applied directly in praxis by manufacturers, in order to produce and bring such promising, compact and cost-effective heating and ventilation systems into the market of building renovation.

## 5. Conclusions

Monitoring and simulation results of a micro-heat pump (micro-HP) combined with a heat recovery ventilation (HRV) unit integrated into a prefabricated timber frame façade system, developed within the EU-project iNSPiRe [2], has been presented in this study. A functional model of this system was installed in one flat during the renovation of a demonstration building. Both the flat and the HVAC system were monitored for a complete heating season.

The analysis of the monitoring data showed a significant improvement in the indoor air quality (IAQ) after renovation, especially during the operation of the ventilation system. The average IAQ of all rooms was poor ($CO_2$ concentration higher than 1000 ppm) in only 2% of time after the renovation when the HRV was operating. The corresponding value before the renovation was 79%. Thus, continuous operation of the HRV during the heating season is recommended. The relatively high heating demand (HD) of the monitored year led to the high share of 30% for the post-heater and an acceptable SPF of the system equal to 2.8 (the SPF of the micro-HP was 2.5). Combining the relatively low indoor temperature of the neighbouring flats with the fact that all measurements were collected during a very cold winter, higher performance should be expected in the coming years. In addition, the use of HRV significantly reduced the HD by 56%.

An extensive simulation study, using the validated building and HVAC system models, showed potential for optimisation by: a) reducing the fan consumption, which was almost one fourth of the total consumed electricity - resulting in 12% electricity savings, b) increasing the heating capacity of the heat pump e.g. with a factor of 2 - resulting in 7% electricity savings, c) implementing a proportional-integral (PI) controller for the pre-heater – resulting in 5% electricity savings, and d) using a better controller for the defrost cycle – resulting in 5% electricity savings. By implementing all the aforementioned proposals, the electricity consumption can be reduced by 25%.

The aim of the developed system is to save space and reduce costs - i.e. with prefabrication, façade integration, and low heating power of the heat pump - while at the same time achieving a sufficient energy performance. It is appropriate for minimally disruptive renovations according to energy efficient building standards, i.e. EnerPHit [3], representing a compact heating and ventilation system.

Further research will focus on increasing the supply air volume flow by using recirculated air, investigating the heat distribution inside the flat, and further improving the control strategy in order to increase the performance and guarantee robust operation.

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## References

[1] Directive 2010/31/EU, Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings. The European Parliament and the Council of the European Union., Off. J. Eur. Union. L153 (2010) 13–35. doi:10.3000/17252555.L_2010.153.eng.

[2] iNSPiRe, European Commission 7th Framework Programme project. Grant agreement no. 314461; Title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems; Duration: 2012-10-01–2016-09-30, (n.d.).

[3] B. Zeno, W. Feist, EnerPHit Planerhandbuch - Altbauten Mit Passivhaus Komponenten Fit Für Die Zukunft machen, 2012 http://www.passiv.de/de/03_zertifizierung/02_zertifizierung_gebaeude/04_enerphit/04_enerphit-planer-hb.htm.

[4] M. Gustafsson, G. Dermentzis, J.A. Myhren, C. Bales, F. Ochs, S. Holmberg, et al., Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation, Energy Build 82 (2014) 512–519, doi:10.1016/j.enbuild.2014.07.059.

[5] N.J. Kelly, J. Cockroft, Analysis of retrofit air source heat pump performance: results from detailed simulations and comparison to field trial data, Energy Build 43 (2011) 239–245, doi:10.1016/j.enbuild.2010.09.018.

[6] H. Esen, M. Esen, O. Ozsolak, Modelling and experimental performance analysis of solar-assisted ground source heat pump system, J. Exp. Theor. Artif. Intell 29 (2017) 1–17, doi:10.1080/0952813X.2015.1056242.

[7] Sinfonia, European Commission 7th Framework Programme project. Grant agreement no. 609019; Title: SINFONIA - Smart INitiative of cities Fully cOmmitted to iNvest in Advanced large-scaled energy solutions, (n.d.). http://sinfonia-smartcities.eu/ (accessed July 8, 2017).

[8] Passipedia, Compact HVAC systems, (n.d.). https://passipedia.org/planning/building_services/compact_hvac_systems (accessed July 8, 2017).

[9] F. Fucci, C. Perone, G. La Fianza, L. Brunetti, F. Giametta, P. Catalano, Study of a prototype of an advanced mechanical ventilation system with heat recovery integrated by heat pump, Energy Build 133 (2016) 111–121, doi:10.1016/j.enbuild.2016.09.038.

[10] S. Mortada, A. Zoughaib, C. Arzano-Daurelle, D. Clodic, Energy efficiency of air-to-air mini heat pump, in: Int. Refrig. Air Cond. Conf., 2010, p. Paper 1078. http://docs.lib.purdue.edu/iracc/1078/.

[11] F. Ochs, G. Dermentzis, D. Siegele, S. Hernandez, A. Sief, EU project iNSPiRe D3.3. Report on Ventilation and Active Heating/Cooling Devices integrated in the Façade – Part A, 2014.

[12] G. Rojas, R. Pfluger, W. Feist, Comfort and affordability with air heating – a comparison of radiators and floor heaters, in: 19th Int. Passiv. House Conf., Passive House Institute, 2015, pp. 125–130.

[13] M. Mori, Measured data of supply air cooling in Ibaraki PH-solution for hot & humid climates, in: 21th Int. Passiv. House Conf., Vienna, Austria, Passive House Institute, 2017, pp. 313–318.

[14] DIN, DIN 1946-6. Raumlufttechnik-Part-6: Ventilation and air conditioning - General requirements, requirements for measuring, performance and labeling, delivery/acceptance (certification) and maintenance, 2009.

[15] Passive House Institute, Requirements and Testing Procedures For Energetic and Acoustical Assessment of Passive House Ventilation Systems For Certification As " Passive House Suitable Component, 2009 http://www.passiv.de/downloads/03_Reqs_and_testing_procedures_ventilation_en.pdf.

[16] G. Dermentzis, F. Ochs, D. Siegele, W. Feist, A façade integrated micro-heat pump - energy performance simulations, BauSIM 2014, IBPSA, 2014 http://www.ibpsa.org/proceedings/bausimPapers/2014/p1159_final.pdf.

[17] F. Ochs, D. Siegele, G. Dermentzis, W. Feist, Prefabricated timber frame façade with integrated active components for minimal invasive renovations, Energy Procedia 78 (2015) 61–66, doi:10.1016/j.egypro.2015.11.115.

[18] G. Dermentzis, F. Ochs, W. Feist, A micro-heat pump combined with mechanical ventilation including heat recovery - simulation and in situ monitoring, 12th IEA Heat Pump Conf., Rotterdam, 2017.

[19] D. Siegele, Measurement and Simulation of the Performance of a Façade-integrated MVHR with Micro Heat Pump Master Thesis, 2015.

[20] F. Ochs, D. Siegele, A. Ksiezyk, E. Leonardi, G. Dermentzis, D5.6a - Report on Data Reduction Procedure for Systems Monitored in Real Conditions. Case study Ludwigsburg. EC FP7 project iNSPiRe Grant agreement no. 314461, 2016. http://inspirefp7.eu/wp-content/uploads/2017/01/WP6_D5.6a_P1_20160930_Data_Reduction_Procedure_for_Systems_Monitored.pdf.

[21] F. Ochs, G. Dermentzis, D. Siegele, Façade integrated mvhr and heat pump, 12th Conf. Adv. Build. Ski. 2-3 Oct. 2017, 2017.
[22] A. Corredera, A. Macia, R. Sanz, F. Velez, R. Fedrizzi, R&D Team- GIT, D5.1 - Report on the Adopted ICT Solutions. EC FP7 project iNSPiRe Grant agreement no. 314461, 2013. http://inspirefp7.eu/wp-content/uploads/2013/01/WP5_D5-1_20131215_PP2_Report-on-the-Adopted-ICT-Solutions.pdf.
[23] E. Leonardi, Micro-Heat Pump for a Renovated Multi Family House – Simulation Based Analysis of the Performance and Thermal Comfort Master Thesis, 2015.
[24] MathWorks, Matlab 2013a, (n.d.). https://de.mathworks.com/products/matlab.html (accessed April 18, 2017).
[25] B. Hafner, Carnot toolbox, (2012). https://fh-aachen.sciebo.de/index.php/s/0hxub0iIJrui3ED.
[26] H. Blervaque, P. Stabat, S. Filfli, M. Schumann, D. Marchio, Variable-speed air-to-air heat pump modelling approaches for building energy simulation and comparison with experimental data, J. Build. Perform. Simul 9 (2015) 210–225, doi:10.1080/19401493.2015.1030862.
[27] A. Salzmann, Dynamic Analysis of the Performance and the De-icing Behaviour of a Micro-Heat Pump. Master Thesis, n.d.
[28] M. Magni, Hardware-in-the-loop experiments for heat pump controller optimization Master Thesis, 2015.
[29] W. Feist, Thermische Gebäudesimulation: Kritische Prüfung Unterschiedlicher Modellansätze, in: C.F. Müller (Ed.), 1994.
[30] Euopean Standard, EN 13779: Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems, 2007.
[31] W. Feist, PHPP - passive house planning package, (1998). http://passiv.de/en/04_phpp/04_phpp.htm (accessed April 18, 2017).
[32] EN, EN 12831-1: Heating systems and water based cooling systems in buildings - Method for calculation of the design heat load - Part 1: Space heating load., 2014.
[33] A. Dodoo, L. Gustavsson, R. Sathre, Primary energy implications of ventilation heat recovery in residential buildings, Energy Build 43 (2011) 1566–1572, doi:10.1016/j.enbuild.2011.02.019.
[34] D. Siegele, F. Ochs, W. Feist, Prüfung von Kompaktgeräten mit drehzahlgeregelten Kompressoren und Enthalpieübertragern (Testing of compact devices with speed-controlled compressors), in: 21th Int. Passiv. House Conf. 2017, Passive House Institute, Vienna, Austria, 2107: pp. 651–656.
[35] H. Esen, M. Inalli, M. Esen, Technoeconomic appraisal of a ground source heat pump system for a heating season in eastern Turkey, Energy Convers. Manag 47 (2006) 1281–1297, doi:10.1016/j.enconman.2005.06.024.
[36] M. Miara, D. Günther, R. Langner, S. Helmling, J. Wapler, 10 years of heat pumps monitoring in Germany. Outcomes of several monitoring campaigns. From low-energy houses to un-retrofitted single-family dwellings, 12th IEA Heat Pump Conf., 2017.

## 5.6 Publication F

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**Own contribution**
The simulation work was performed with co-operation and supervision by the first and third author, while most of the text was written by the second author. The significant contributions of the co-authors (as well as the first author) were in reviewing, supervising and participating in the scientific discussions about this article.

# Evaluation of a versatile energy auditing tool

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## ABSTRACT

Energy auditing can be an important contribution for identification and assessment of energy conservation measures (ECMs) in buildings. Numerous tools and software have been developed, with varying degree of precision and complexity and different areas of use.

This paper evaluates PHPP as a versatile, easy-to-use energy auditing tool and gives examples of how it has been compared to a dynamic simulation tool, within the EU-project iNSPiRe. PHPP is a monthly balance energy calculation tool based on EN13790. It is intended for assisting the design of Passive Houses and energy renovation projects and as guidance in the choice of appropriate ECMs.

PHPP was compared against the transient simulation software TRNSYS for a single family house and a multi-family house. It should be mentioned that dynamic building simulations might strongly depend on the model assumptions and simplifications compared to reality, such as ideal heating or real heat emission system. Setting common boundary conditions for both PHPP and TRNSYS, the ideal heating and cooling loads and demands were compared on monthly and annual basis for seven European locations and buildings with different floor area, S/V ratio, U-values and glazed area of the external walls.

The results show that PHPP can be used to assess the heating demand of single-zone buildings and the reduction of heating demand with ECMs with good precision. The estimation of cooling demand is also acceptable if an appropriate shading factor is applied in PHPP. In general, PHPP intentionally overestimates heating and cooling loads, to be on the safe side for system sizing. Overall, the agreement with TRNSYS is better in cases with higher quality of the envelope as in cold climates and for good energy standards. As an energy auditing tool intended for pre-design it is a good, versatile and easy-to-use alternative to more complex simulation tools.

## KEYWORDS

Energy auditing tool, energy conservation, building simulation, PHPP, TRNSYS

## INTRODUCTION

Accounting for 40% of the total energy use in Europe, the building sector is very important in the work towards more efficient use of energy and resources (EC, 2008, EC, 2010). As a part in that work, energy auditing can be an effective way to identify and assess energy conservation measures (ECMs) in buildings. While the extent of an energy audit can vary, it typically includes data collection and review, system survey and measurements, observation and review of operating practices and data analysis (Krarti, 2010). An energy audit is normally done using one of the many available computer software or calculation tools. A comprehensive review of existing software for energy auditing, certification, calculation and simulation was done within the iNSPiRe project (Gustafsson et al., 2015), identifying more than 200 tools with varying scopes and levels of detail. A lot of the tools in the survey had limitations in terms of area of use, restricted modification rights, high level of knowledge required or not being available in English.

PHPP was developed by Passive House Institute in Germany as an easy-to-use planning tool for energy efficient buildings, intended for architects and planning experts (PHl, 1998). Heating and cooling demand is calculated according to EN ISO 13790 (ISO, 2008) as a monthly energy balance. Heating load is calculated using an approach considering two days (one cold and sunny and one milder but overcast) (Bisanz, 1999) and a similar method is used also for cooling load (Schneiders, 2012). Both are estimated with a safety margin for designing purposes without taking building dynamics into account. Other features include calculation of heating and cooling load, active components (heat pumps, boilers, air heat recovery, solar thermal, PV), passive components (opaque, transparent, frame, thermal bridge), shading, ground losses and DHW losses (distribution/storage). Being a monthly balance calculation tool, PHPP has some limitation compared to dynamic simulation tools, as complex control of systems is not possible. Furthermore, the building, regardless of size, is modelled as a single zone.

Many features and components of PHPP have been validated in previous studies, including the solar thermal (Siegele et al., 2015) and heat pump (Dermentzis et al., 2014) applications. Gustafsson, Dermentzis et al. (Gustafsson et al., 2014) compared the heating demand of low-energy and passive single family houses in PHPP and TRNSYS for seven European climates. Ochs, Dermentzis et al. (Ochs et al., 2013) performed a parametric study with 44 renovation variants of a multi-family house with four apartments and compared heating demands and heat loads to TRNSYS and MATLAB/Simulink results. For larger buildings and for cooling, however, there is more work to be done.

In this paper, PHPP is assessed as an energy auditing tool for single- and multi-family houses through comparison against TRNSYS 17 (Klein et al., 2011). The study focuses on calculation of heating and cooling demand, heating and cooling load, heat losses and heat gains. Buildings of different energy standard, from typical levels of existing buildings down to a heating demand of 25 kWh/(m²·a), were included, and climate data for seven European locations were used.

## METHOD

Calculation results from PHPP were compared against results for a full year simulation with TRNSYS 17, a dynamic simulation tool for buildings and energy systems (Klein et al., 2011). Identical boundary conditions and building models, a 97 m² single family house (designed by EURAC (Birchall et al., 2014)) and a multi-family house (designed by UIBK (Birchall et al., 2014)) of 1950 m², were defined and implemented in PHPP and in TRNSYS. Both houses were modelled as single-zone buildings in TRNSYS, which is always the case in PHPP. The comparison included heating and cooling loads and demands, heat losses and heat gains, and was done for seven European locations, defined in the iNSPiRe project to represent regions with similar numbers of heating and cooling degree days (Birchall et al., 2014). The locations used were: Stockholm, Sweden; Gdansk, Poland; London, UK; Stuttgart, Germany; Lyon, France; Madrid, Spain; and Rome, Italy. The houses were modelled in their existing state (denoted “EX”), with construction data for typical buildings from the period 1945-1970 in the respective climate (Birchall et al., 2014), and with ECMs applied to achieve annual heating demand levels of 45 kWh/(m²·a) (denoted “45”) and 25 kWh/(m²·a) (denoted “25”), respectively. The ECMs included mechanical ventilation with heat recovery (MVHR), new windows and insulation in walls, roof and ground floor layers, and were defined to achieve the chosen heating demand in PHPP. For the single family house, a comparison was done between using the convective and the operative temperature for controlling the heating and cooling in TRNSYS, while for the multi-family house the operative temperature was used throughout. PHPP does not distinguish between convective and operative temperature. Boundary conditions regarding shading, ventilation and internal gains were based on IEA/SHC Task 44 (IEA, 2012) and are described in detail in iNSPiRe project reports (Birchall et al., 2014, Gustafsson et al., 2015).

The reader should keep in mind that results of dynamic building simulations might strongly depend on the model assumptions and simplifications, such as ideal heating or real heat emission system, heat emission to convective or radiative node, control with respect to radiative or operative temperature, sky model, zoning or ground coupling etc. Also the choice of the physical model (e.g. star-node or 2-star, transfer function or R-C-wall) might influence the results.

## RESULTS

### Single family house

Figure 1 shows the heating demand for all variations of the single family house as simulated with TRNSYS and calculated with PHPP, as well as the absolute difference between TRNSYS and PHPP. For the renovated cases the deviations are below 5 kWh/($m^2 \cdot a$), except for the “45” house in the warmest climates of Madrid and Rome. For Rome “45” there was a different behavior in TRNSYS with respect to ground losses. For the existing cases the absolute deviations are generally higher, but in relative numbers they are below 7%. The difference between using convective or operative temperature for heating control in TRNSYS is negligible for the renovated cases, while for the existing cases the heating demand is considerably higher if the operative temperature is used.

When it comes to the maximum daily heating load, the deviations are also small in absolute terms – 6 W/$m^2$ or less for the renovated cases. For the non-renovated houses in Gdansk, London and Stuttgart, the agreement is also very good. PHPP calculations give slightly higher heating loads than TRNSYS for all cases apart from STO_EX (5.5 W/$m^2$ higher or 9%).

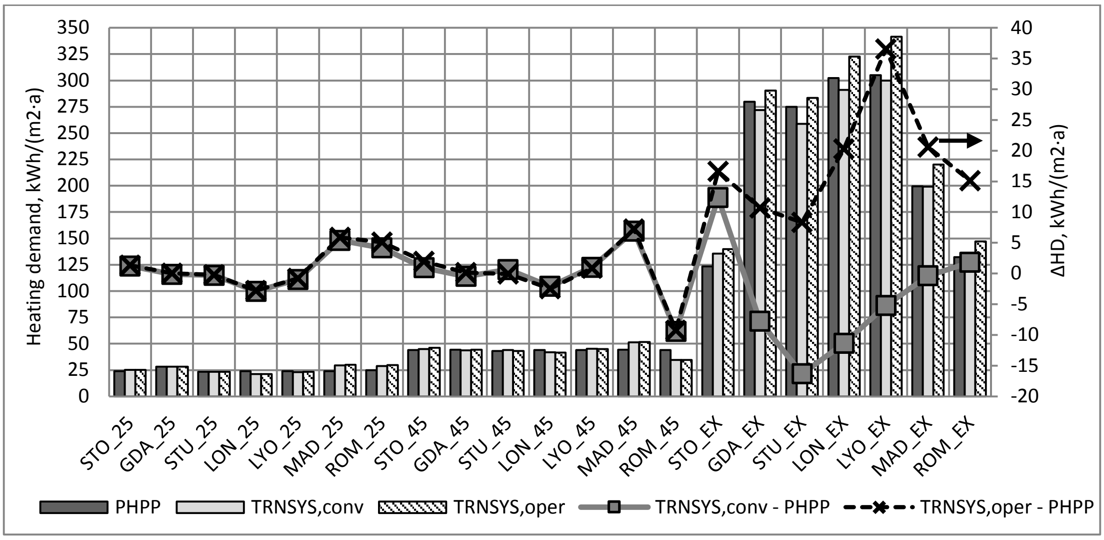


Figure 1. Heating demand (left axis) and absolute deviation (right axis) between TRNSYS (convective/operative temperature control) and PHPP for the single family house model for all climates and renovation levels.

Figure 2 shows the results from TRNSYS and PHPP for the cooling demand of the single family house, with absolute deviation between TRNSYS and PHPP. For the climates of Lyon, Madrid and Rome, which have the highest cooling demands, the relative deviations are within ±27%. The absolute deviations for these climates are below 4.3 kWh/(m²·a), except for ROM_45 with 6 kWh/(m²·a), where there was the same issue with the ground losses as for the heating comparison. Generally, the agreement is acceptable, although not as good as for the heating demand. The difference between using convective or operative temperature in TRNSYS was noteworthy only for the warmer climates, although still not larger than 1 – 8 kWh/(m²·a).

The cooling loads are, similar to the heating loads, higher in PHPP than in TRNSYS (equal for LYO_25 and ROM_45). The agreement for the cooling loads is better for renovated buildings, with deviations below 5 W/m$^2$ for all cases, while for the existing cases the deviations are above 10 W/m$^2$ for Lyon, Madrid and Rome.

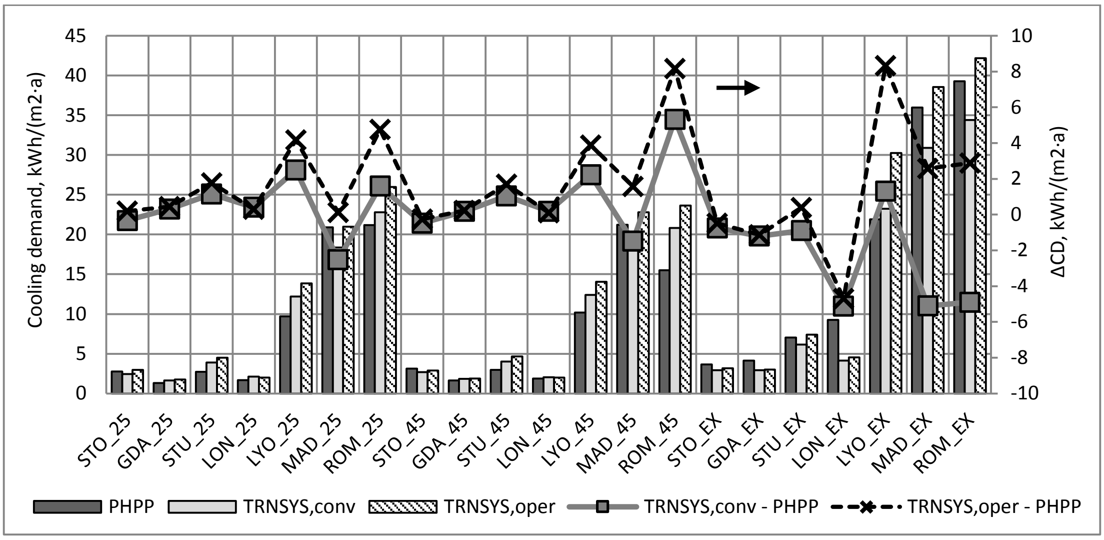


Figure 2. Cooling demand (left axis) and absolute deviation (right axis) between TRNSYS (convective/operative temperature control) and PHPP for the single family house model for all climates and renovation levels.

**Multi-family house**

Results for the heating demand of the multi-family house are shown in Figure 3, with absolute deviation between TRNSYS and PHPP. Contrary to what is seen for the single family house, PHPP produces slightly lower results than TRNSYS for all cases. The agreement is good though, within 1 – 6 kWh/(m²·a) for almost all renovated cases in the colder climates: Stockholm, Gdansk, Stuttgart, London and even Lyon. For non-renovated cases and warmer climates the absolute deviations are larger, although not so high in relative terms.

The heating loads are in most cases higher in PHPP than in TRNSYS, around 1 – 5 W/m$^2$, with exception for the existing buildings in Gdansk, Stuttgart, London, Lyon and Madrid and the 45 kWh/(m²·a) house in Gdansk and Madrid, where TRNSYS gives 1 – 4 W/m$^2$ higher results.

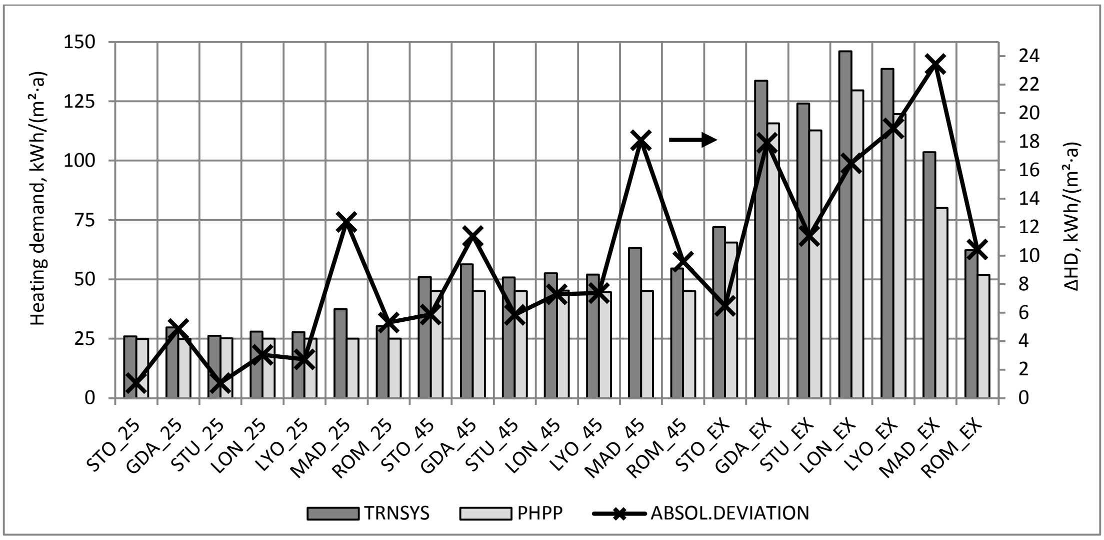


Figure 3. Heating demand (left axis) and absolute deviation (right axis) in TRNSYS and PHPP for the multi-family house model for all climates and renovation levels.

Figure 4 shows the cooling demand for all variations of the multi-family house in TRNSYS and PHPP, with absolute deviations between the two tools. TRNSYS gives slightly higher results than PHPP, 1 – 8 kWh/(m²·a), for all cases except Lyon. The agreement is equally good for renovated and existing houses.

The cooling loads of the multi-family house are higher in PHPP than in TRNSYS for all cases, with a difference of 1 – 7 W/m$^2$.

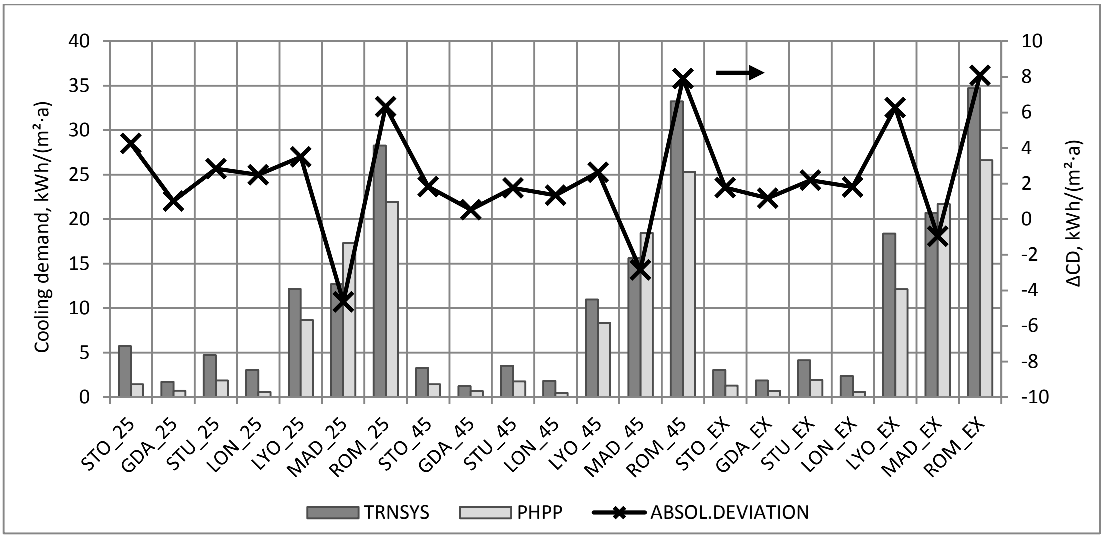

Figure 4. Cooling demand (left axis) and absolute deviation (right axis) in TRNSYS and PHPP for the multi-family house model for all climates and renovation levels.

**DISCUSSION**

In general, the agreement between PHPP and TRNSYS is good. The comparison is a bit better for heating than for cooling. It is also better for houses with good quality of the building envelope, i.e. better for renovated buildings than existing and better in cold climates than in warm climates. It should be noted that for the colder climates of Stockholm, Gdansk, Stuttgart and London, the cooling demand is too small to make a meaningful comparison. Heating and cooling loads are in most cases estimated to be higher in PHPP than in TRNSYS. This overestimation, however, is intentional, to be on the safe side for system design.

In PHPP, the internal temperature was assumed to be 20 °C in the winter season and 25 °C and in summer season; no transition season exists in PHPP. Thus, in cases where there are periods with cooling demand and heating demand at the same time there is a disagreement between the internal temperature of TRNSYS and PHPP, resulting in the deviations of the transmission and ventilation losses. The influence on the total heating and cooling demand is, however, negligible.

For the multi-family houses, heating demands were higher in TRNSYS than in PHPP. This happened mainly for two reasons: 1) The set point temperature in TRNSYS was controlled according to the operative instead of convective. As a consequence, the convective temperature will often be higher than 20 °C, thus increasing the heating demand; 2) In PHPP, unlike TRNSYS, there is a fully separated algorithm for heating and cooling calculations. The parameters controlling shading and bypass of MVHR should therefore work only in non-heating period, while in TRNSYS these two parameters may influence also the heating period.

## CONCLUSIONS

This paper evaluates PHPP as an energy auditing tool for residential buildings by comparing calculations of heating and cooling demands and loads to the dynamic simulation tool TRNSYS. The comparison includes renovated and existing single- and multi-family houses in seven European climates.

The investigations show that PHPP can be used to assess the heating demand of residential buildings and the reduction of heating demand with energy conservation measures. The prediction of the cooling demand is also acceptable. Generally, the results are better in cases of good energy standards and with higher quality of the envelope (e.g. as in cold compared to warm climates). The predictability is more difficult for lower envelope qualities due to the increasing influence of the boundary conditions. However, setting the boundary conditions correctly in a simulation requires more information, which might not be available in many cases, thereby be based on assumptions as well.

As an energy auditing tool intended for pre-design, PHPP is an easy-to-use, versatile and accurate alternative to more complex simulation tools. In addition to what was shown here, it is also possible to perform parametric studies, including comparison of economics of different energy conservation measures.

## ACKNOWLEDGEMENT

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## REFERENCES

Birchall, S., C. Dipasquale, R. Fedrizzi, A. Bellini, M. D'Antoni, C. Bales, M. Gustafsson, F. Ochs and G. Dermentzis (2014). D2.1c Simulation Results of Reference Buildings. iNSPiRe FP7 project, grant agreement no. 314461.

Birchall, S., I. Wallis, D. Churcher, S. Pezzutto, R. Fedrizzi and E. Causse (2014). Survey on the energy needs and architectural features of the EU building stock, EC FP7 project iNSPiRe.

Bisanz, C. (1999). Heizlastauslegung im Niedrigenergie- und Passivhaus. Darmstadt, 1st Edition.

Dermentzis, G., F. Ochs and W. Feist (2014). Heat pumps in Passive Houses – PHPP application. 18th iPHC. Aachen.

EC (2008). Energy efficiency: delivering the 20% target, European Commission**:** 3.

EC (2010). Directive 2010/31/EU on the energy performance of buildings. Official Journal of the European Union, European Commission**:** 13-35.

Gustafsson, M., G. Dermentzis, J. A. Myhren, C. Bales, F. Ochs, S. Holmberg and W. Feist (2014). "Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation." Energy and Buildings **82**: 512-519.

Gustafsson, M., F. Ochs, S. Birchall, G. Dermentzis, C. Bales and R. Fedrizzi (2015). Report on Auditing tool for assessment of building needs, EC FP7 project iNSPiRe, Grant no. 314461.

Gustafsson, M., F. Ochs, S. Birchall, G. Dermentzis, C. Bales, R. Fedrizzi and T. Calabrese (2015). D2.2 Report on Auditing tool for assessment of building needs. iNSPiRe FP7 project, grant agreement no. 314461.

IEA (2012). The Reference Framework for System Simulation of the IEA SHC Task 44 / HPP Annex 38 - Part B: Buildings and Space Heat Load.
ISO (2008). ISO 13790 - Energy performance of buildings - Calculation of energy use for space heating and cooling.
Klein, S. A., A. Beckman, W. Mitchell and A. Duffie (2011). TRNSYS 17 - A TRansient SYstems Simulation program, Solar Energy Laboratory, University of Wisconsin, Madison.
Krarti, M. (2010). Energy audit of building systems: an engineering approach, CRC Press, 2nd Edition.
Ochs, F., G. Dermentzis, D. Siegele, A. Konz and W. Feist (2013). Use of Building Simulation Tools for Renovation Strategies - a renovation case study. Energy forum. Bressanone.
PHl. (1998). "PHPP - The energy balance and passive house planning tool." Retrieved 2015-09-15, from http://passiv.de/en/04_phpp/04_phpp.htm.
Schneiders, J. (2012). Planungstools für den Sommerfall im Nichtwohngebäude. Sommerverhalten von Nichtwohngebäuden im Passivhausstandard – Projekterfahrungen und neue Erkenntnisse, Passive House Institute.
Siegele, D., F. Ochs and W. Feist (2015). Validierung der Algorithmen für die solare Warmwasserbereitung und Heizung in PHPP. 19. Internationale Passivhaustagung 2015. Leipzig.

## 5.7 Publication G

**Title**
Heat pumps in Passive Houses – PHPP application

**Authors**
Dermentzis, Georgios; Ochs, Fabian; Feist, Wolfgang

**Published in**
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**Reference**
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**Own contribution**
The presented work, the results, the discussion and the conclusions of this publication were performed by the first author. The significant contributions of the co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

# Heat pumps in Passive Houses – PHPP application

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## 1 Introduction

The number of heat pump applications in buildings according to Passive House and EnerPHit standard increases rapidly. A PH-designer can use PHPP (heat pump sheet) in order to calculate and optimize the electrical consumption and the seasonal performance factor (SPF) of a heat pump system. In this study the heat pump tool is presented as well as application examples. Results are cross-validated against simulation.

Heat pumps have significant advantages compared to other heating systems, especially in Passive Houses with the extremely low building heating load: heat pumps can be scaled down to very small heating capacities (some 1000 W and even lower). This is hardly possible or available in case of other technologies such as gas or pellet boilers. The heating capacity reduction can lead to cost reduction and compact solutions. Moreover, heat pumps can cover both heating and cooling demand (reversible heat pumps). Heat pumps run in most cases on electricity, the dominant primary energy produced by renewable energy sources. The electric grid is available almost everywhere - at least, if the application does not draw too much current (what may happen with less efficient homes), this will provide a simple method for heating and cooling. In buildings according to EnerPHit standard, where air heating is usually not feasible, air or ground sourced heat pumps are increasingly used. Compact units (i.e. air sourced heat pump combined to mechanical ventilation with heat recovery used for hot water and heating with air distribution) are widely used in Passive Houses. However, heat pumps with different sources (e.g. ground heat exchanger) or sinks (e.g. floor heating) can be used in order to increase system efficiency or can be applied as central systems in multifamily houses. Furthermore, the use of heat pumps in Passive Houses leads to a low residual electric energy demand. Renewable energy sources (e.g. PV or/and wind) can cover a significant share of this demand and therefor a Nearly Zero Energy Building (NZEB) can easily be achieved.

## 2 Heat pump tool in PHPP

### 2.1 Options and handling

The annual electrical consumption as well as the Seasonal Performance Factor (SPF) of a heat pump system is calculated for different heat pump configurations. Various options are available such as different sources (air, ground water, ground heat exchanger), functionalities (space heating, domestic hot water or both), distribution systems (air heating, radiators, floor heating), storage options and control strategies (figure 1).

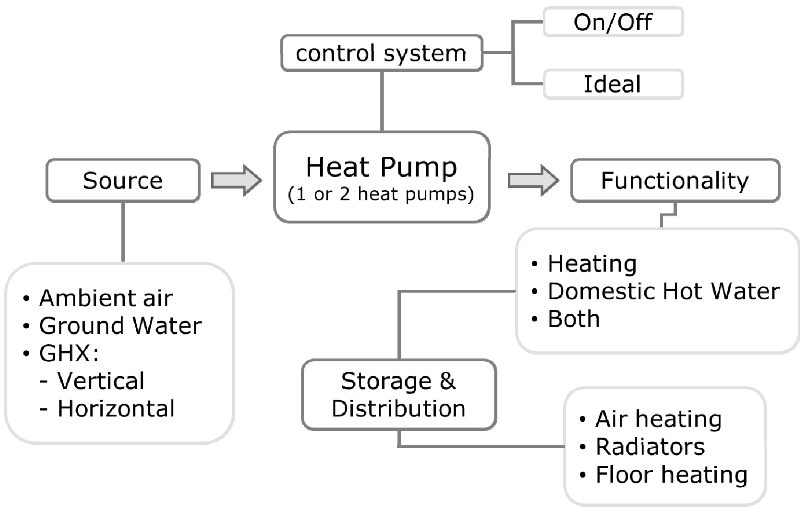


**Figure 1: Heat pump tool options**

Input data for the heat pump are measured test points of heating capacity and coefficient of performance (COP) corresponding to different source and sink temperatures. Input data may be found at heat pump test centers such as Test Center WPZ [WPZ 2013] and also at the manufacturer's datasheets based on [EN 14511].

## 2.2 Methodology

The algorithm of the heat pump tool in PHPP is based on the already existing compact unit sheet [Pfluger 2007], which uses heating demand and heating load of PHPP as inputs for the calculation. More bins are implemented in the new algorithm in order to improve the accuracy (figure 2). The annual electrical energy consumption of the system ($W_{el}$) is calculated as follows:

$$W_{el} = \sum \frac{Q_{hp}(bin)}{COP(bin)} + W_{dir} \qquad (1)$$

The energy supplied by the heat pump ($Q_{hp}$) depends on the heating capacity of the heat pump and on the heating load of the building. If the two lines intercept, the created triangle corresponds to the direct electricity ($W_{dir}$) (figure 2).

**Control strategies:** Two control strategies are available. The first is the common 'on/off' (the sink temperature is constant over the heating period). The second is the 'ideal' which yields the minimum possible electrical consumption. This corresponds to the appropriate sink temperature [Dermentzis 2012].

**Heating capacity of the heat pump ($P_{hp}$):** The heating capacity depends on the source temperature and the sink temperature of the heat pump. The correlation between these three quantities is defined by linear approximation using the following equation.

$$P_{hp} = a_1 \cdot \theta_{src} + a_2 \cdot \theta_{snk} + a_3 \qquad (2)$$

**Coefficient of performance (COP):** The COP significantly depends on source and sink temperature of the heat pump, too. This can be taken into account using Carnot efficiency together with a Carnot performance factor (Ψind):

$$\mathrm{COP} = \eta_{ind} \cdot \frac{\theta_{\mathrm{snk}} + 273.15}{\theta_{\mathrm{snk}} - \theta_{\mathrm{src}}} \tag{3}$$

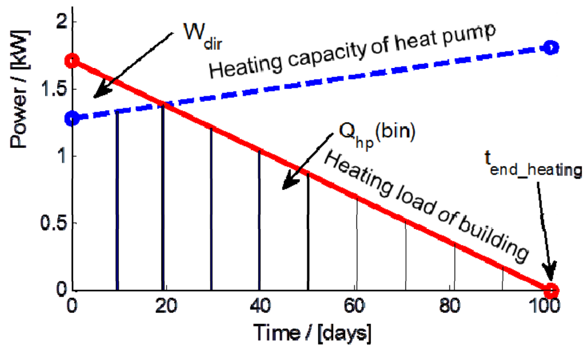


**Figure 2: Load duration curve and heating capacity of the heat pump in heating period.**

# 3 Validation and parametric study

The tool was validated using as case-study the reference building SFH15 of IEA Task44 A38 [IEA 2013]. A heat pump was used for covering both heating and domestic hot water demand in [Dermentzis 2013]. The focus in the present study is to calculate the air sourced heat pump performance for heating considering different heating demands (EnerPHit and PH) in different climates. A parametric analysis has been performed and the final electrical consumption is calculated using the heat pump sheet of PHPP. Results are cross-validated by dynamic simulations using the Carnot blockset in Matlab/Simulink [Matlab]. The detailed building model of Carnot blockset is used for the validation [Ochs 2013].

The existing building is a semi-detached single family house (78 m$^2$) with two storeys in England [iNSPiRe]. This study is carried out on six different European climates. The climate data are produced in meteonorm [Meteonorm] for both models. The building is renovated in one case to achieve EnerPHit standard and in another case to Passive House standard in all climates. Triple-glassed windows, infiltration rate n50 = 1 h-1 and mechanical ventilation with heat recovery of 85% are implemented in PHPP as reference renovation. External insulation is added in order to achieve a heating demand of 25 kWh/(m$^2$ a) or 15 kWh/(m$^2$ a) in each climate, respectively (table 1). Thermal bridges are disregarded in this PHPP calculation and external wall dimensions are used. In this study the focus is the validation of the heat pump algorithm in the calculation of electrical consumption. Therefore, the dynamic building model was modified in order to obtain identical heating demand in PHPP and Carnot. In [Ochs 2013] it was already shown that correct consideration of thermal bridges leads to quite good agreement of heating demand between PHPP and dynamic simulation (Matlab/Simulink blockset Carnot). Since internal wall dimensions are used in the Carnot model, a linear thermal loss coefficient Ψ is used in order to obtain the heating demand of 25 kWh/(m$^2$ a) or 15 kWh/(m$^2$ a), respectively in each climate.

| | EnerPhit | | | Passive House | | |
|---|---|---|---|---|---|---|
| Climate | U-value / [W/(m$^2$K)] | Heating Demand / [kWh/(m$^2$a)] | Heating Load / [W/m$^2$] | U-value / [W/(m$^2$K)] | Heating Demand / [kWh/(m$^2$a)] | Heating Load / [W/m$^2$] |
| Stockholm | 0.16 | 25.4 | 16.2 | 0.08 | 15.0 | 12.4 |
| Gdansk | 0.18 | 25.0 | 15.2 | 0.11 | 15.1 | 11.8 |
| Stuttgart | 0.25 | 24.9 | 16.4 | 0.17 | 15.1 | 12.7 |
| London | 0.28 | 24.7 | 14.0 | 0.20 | 14.9 | 10.9 |
| Madrid | 0.46 | 25.1 | 17.2 | 0.34 | 14.6 | 12.9 |
| Rome | 0.55 | 24.8 | 17.6 | 0.42 | 15.2 | 13.4 |

**Table 1: Renovated status of a semi-detached family house at EnerPHit and Passive House standard.**

The standard air-to-water heat pump of PHPP is used to cover the heating demand. The nominal power of the heat pump is scaled to 2.5 kW for EnerPHit and 1.5 kW for Passive House standard, respectively. The heat pump is directly connected to the distribution system (radiators) of the heating without storage.

## 3.1 Results

In figures 3 and 4 the electrical consumption of the air sourced heat pump is presented for EnerPHit and Passive house standard, respectively for the six climates. Three cases are presented. The first case corresponds to PHPP results using ‘on/off’ as control strategy (‘PHPP’), the second using the ‘ideal’ control strategy (‘PHPP_ideal’) and the third the results of the dynamic simulations of Carnot using a control according to zone temperature with hysteresis of 19.75 °C to 20.25 °C. Source and sink temperatures play an important role in heat pumps efficiency. The design distribution (sink) temperature used in PHPP is 45 °C and 40 °C for EnerPHit and Passive House standard, respectively. Three conclusions can be made from the results in figures 3 and 4. First, the electrical consumption (Wel) decreases with the increasing air source temperature for different climates. Second, ‘PHPP_ideal’ shows the upper limit of the positive improvement of system performance (in this study about 13 %) by improving the control strategy. Third, the heat pump tool delivers results with good accuracy (simulation results are between ‘PHPP’ and ‘PHPP_ideal’).

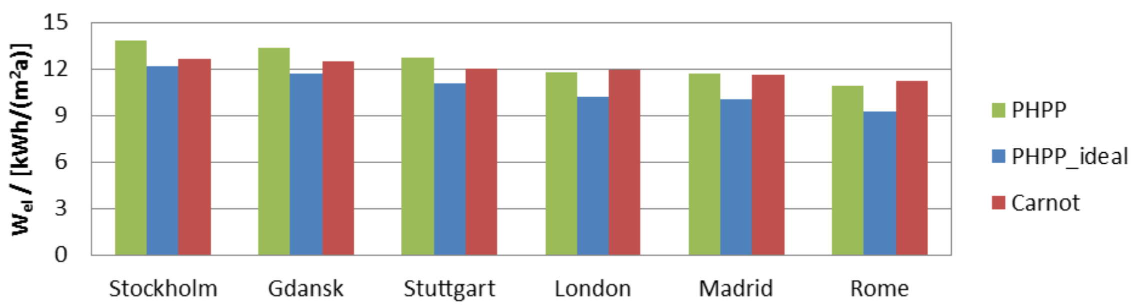


**Figure 3: Electrical consumption of an air-to-water heat pump in a semi-detached family house at EnerPHit standard.**

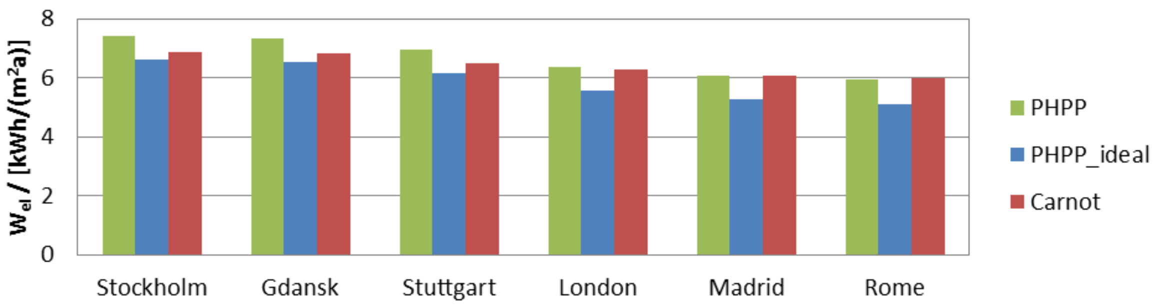


**Figure 4: Electrical consumption of an air-to-water heat pump in a semi-detached family house at Passive House standard.**

Since the heat pump is directly connected to the radiators (no storage), the design and the actual working distribution (sink) temperature of the heat pump differs slightly. E.g. in a system with design distribution temperature 40 °C the working temperature may vary from 35 °C to 45 °C. A parametric study (figure 5) has been performed using the heat pump tool in PHPP. The aim is to show the influence of design distribution temperature (sink temperature of heat pump) and source temperature (climate) on the seasonal performance factor (SPF) of the heat pump system. In figure 5, for radiators with a design distribution temperature of 40 °C which may correspond to working temperature of 35 °C to 45 °C, the SPF e.g. in Stuttgart climate varies from 2.44 to 1.97, respectively.

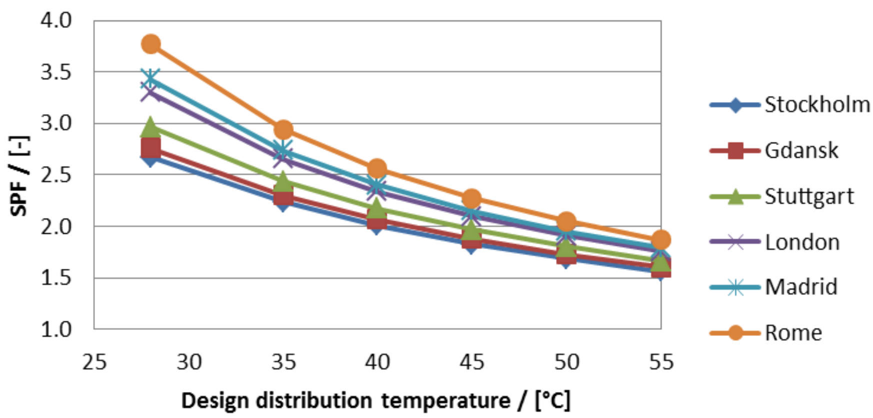


**Figure 5: Electrical consumption of an air-to-water heat pump in a semi-detached family house at Passive House standard.**

The SPF strongly increases by reducing the design distribution temperature e.g. by having a floor heating system at 28 °C design distribution temperature (which is reasonable in a Passive House) instead of 55 °C with small radiators.

# 4 Conclusions

The heat pump tool in PHPP gives the opportunity to PH designers and planners to calculate the final electrical consumption and the primary energy demand of a Passive House with a heat pump easily and accurately. A parametric study in representative European climates shows good agreement between PHPP and dynamic simulation results.

Heat pumps represent an energy and cost effective solution for buildings according to EnerPHit and Passive House standards. In this parametric study, for Passive House standard even a heat pump with a capacity of just 1 kW is sufficient to cover the whole heating demand in all climates except Stockholm. The benefits of such a small system are the cost reduction and compact solution (less needed space). Investigation of such a heat pump (1 kW) is in progress within the fp7 European project iNSPiRe. The way to achieve Nearly Zero Energy Building (NZEB) is the minimization of residual energy demand. Using a heat pump in a building according to Passive House standard, the residual electric energy demand becomes extremely low and therefore, NZEB can be realized.

### *Acknowledgement - References*

**Acknowledgement:** European project iNSPiRe / Framework Program 7 (Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems, duration: 01.10.2012 – 30.09.2016).

[Dermentzis 2012] Dermentzis G., Ochs F., Feist W., Calculation of primary energy and seasonal performance factor of heat pump in a Passive House, PHI, internal document, Dec. 2012

[Dermentzis 2013] Dermentzis G., Ochs F., Feist W., Models of Sub-Components and Validation for IEA SHC Task 44/ HPP Annex 38, Part C: Heat Pump Models, A7: Calculation of primary energy and seasonal performance factor of heat pumps in Passive Houses

[EN 14511] EN 14511 Part 1-4, Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling, EU

[IEA 2013] http://www.iea-shc.org/task44/, Models of Sub-Components and Validation for IEA SHC Task 44/ HPP Annex 38, Part C: Heat Pump Models and Part B: Buildings and Space Heat Load

[iNSPiRe] WP2, http://inspirefp7.eu/

[Matlab] Matlab simulink Carnot blockset, http://www.mathworks.com/

[Meteonorm] Meteonorm 6.1.0.20, Global meteorological database for engineers, planners and education, Meteotest, Bern, Switzerland, 2009

[Ochs 2013] Ochs F., Dermentzis G., Siegele D., Konz. A., Use of Building Simulation Tools for Advancing Renovation Strategies - a renovation case study, Nov. 2013

[Pfluger 2007] Rainer Pfluger, Berechnung des Primärenergiekennwertes und der Jahresarbeitszahl aus den Messwerten der Laborprüfung für die Zertifizierung von Passivhaus-Kompaktgeräten, PHI, internal document, Jan. 2007

[WPZ 2013] Wärmepumpen-Testzentrum WPZ, http://institute.ntb.ch/ies/competences/heat-pump-test-center-wpz.html?L=1

## 5.8 Publication H

**Title**

An overview of energy district tools in Europe and the importance of an equivalent heating reference temperature for district simulations

**Authors**

Dermentzis, Georgios; Schnieders, Juergen; Pfluger, Rainer; Pfeifer, Domink; Feist, Wolfgang; Ochs, Fabian

**Published in**

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**Reference**

G. Dermentzis, J. Schnieders, R. Pfluger, D. Pfeifer, W. Feist, F. Ochs, An overview of energy district tools in Europe and the importance of an equivalent heating reference temperature for district simulations, Bauphysik. 39 (2017) 316–329. doi:10.1002/bapi.201710036.

**Own contribution**

The first author performed the overview of district tools and wrote this paper with the significant contribution of the second author, who performed the simulation work and wrote the part for the simulation study. The first author coordinated and organised the article. The significant contributions of the rest co-authors were in reviewing, supervising and participating in the scientific discussions about this article.

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# An overview of energy district tools in Europe and the importance of an equivalent heating reference temperature for district simulations

The international building sector plays an important role on energy policy and reduction of $CO_2$ emissions. The focus of energy conservation has started from building level and nowadays expands to district, city, region or national level. In this study, an overview, performed within the European project Sinfonia for preparation of a new district tool with focus on energy conservation, will be presented about existing district tools. Several aspects of the tools were included in the overview, such as focus, aim, analytical approach, methodology, geographical coverage, required input data, commercial/freeware, source code, language, tool status, organization/project developing the tool, and web link. The main components of energy district tools such as 3D geographical data, data for building features and properties, and simulation methods were also addressed.
Additionally, the issue of appropriate boundary conditions on urban energy analysis, such as user behaviour, will be discussed. A simulation study of a dwelling in various energy standards including different occupant scenarios was performed, and as a result, a formula was developed to estimate an equivalent heating reference temperature as a function of building envelope, living area, and outdoor temperature. Thus, the estimated equivalent heating reference temperature can be used as input in district energy simulations, instead of a constant set point value independent of the building.
The present study can serve as a basis for new or further development of tools trying to cover the gap and the limits of the existing ones.

**Überblick über Distrikt-Tools in Europa für Energiebedarfsberechnungen – Vergleichsanalyse und Bedeutung einer äquivalenten Heizungsreferenztemperatur für die Simulation.** *Der internationale Bausektor spielt eine Schlüsselrolle in der Energiepolitik für die Reduzierung der CO2-Emissionen. Waren die Energieeinsparmaßnahmen im Baubereich anfänglich noch auf Einzelgebäuden beschränkt, so hat sich der Fokus der Energieeinsparung heute auf Stadtquartiere, ganze Städten und Regionen bis auf nationale Ebene erweitert. In dieser Studie wird ein Überblick über heute bereits verfügbare Software-Tools zur Energie-Simulation auf Distrikt-Ebene vorgestellt, der im Rahmen des europäischen Projekts Sinfonia zur Vorbereitung eines neuen Distrikt-Tools mit Schwerpunkt Energieeinsparung durchgeführt wird. Mehrere Aspekte der Tools wurden in dieser Arbeit berücksichtigt, wie z.B. Fokus, Ziel, analytischer Ansatz, Methodik, geografische Abdeckung, erforderliche Eingabedaten, kommerzielle Tools bzw. Freeware, Verfügbarkeit des Quellcodes, Sprache, Status, Zugehörigkeit und Webseite. Die Hauptteile der District-Tools wie geographische 3D Daten, Daten für Gebäudeeigenschaften sowie Simulationsmethoden wurden ebenfalls adressiert.*
*Darüber hinaus wird der Einfluss der Randbedingungen, wie z.B. das Nutzerverhalten, für die städtische Energieanalyse diskutiert. Eine Simulationsstudie einer Wohnung in verschiedenen Energiestandards, einschließlich verschiedener Einsatzszenarien wurde durchgeführt und als Ergebnis eine Gleichung hergeleitet, um eine äquivalente Heizungsreferenztemperatur als Funktion der Gebäudehülle, des Wohnbereichs und der Außentemperatur zu bestimmen. Somit kann die berechnete äquivalente Heizreferenztemperatur als Eingabe für die Simulation von Stadtquartieren anstatt einer vom Gebäude unabhängigen konstanten Temperatur verwendet werden.*
*Diese Studie kann als Grundlage für die Neu- oder Weiterentwicklung von Simulationstools verwendet werden mit dem Ziel, die Lücken der bestehenden Tools zu schließen.*

## 1 Introduction

Nowadays, the idea of energy conservation at district, city or region level is increasing popularity. Especially for the energy policy and the urban design, the reduction of the energy demand at this level plays a very important role. Therefore, various district tools were developed focusing on energy and economical aspects.

In literature, studies about energy tools in district or higher level are available. An analytical study about reviewing of decision support tools for district refurbishment was done by [1]. A comparison of different tools (used mainly in Austria) for energy planning from building to region level has been published [2]. Ten energy mapping visuals with various applications in USA were reviewed by [3]. A detailed energy analysis, including baseline and future scenarios for Ontario communities (Canada), was presented by [4].

In this study, an overview of energy performance tools at district or higher level was carried out with focus on Europe. The motivation was to review the existing energy district tools with respect to several aspects such as the focus of the tool (demand, consumption side), use (forecast or status quo – baseline), open source code or not, organizations developing the tool, calculation method and architecture of the tool. Additionally, the important issue of appropriate use of boundary conditions is addressed. A simulation study is performed, resulting in a recommendation for an equivalent heating reference temperature, which should be used in energy district tools.

## 2 Main components of energy district tools

### 2.1 General structure

Energy district tools often are composed of four main parts (see Figure 1):
– Geographical and geometrical data e.g. building volume and area, interference between buildings, building position on a map, etc.
– Building features and physic properties e.g. U-values, air change rate, building type, user behaviour/profile, etc. and technical systems
– Simulation or calculation method
– Post processing- results analysis

Modern geographical and geometrical geo-datasets are usually based on defined 3D-format models. The building features (building type and age) combined with statistical physical properties (U-values) are the basic-information for the simulation or calculation process. Most of this information usually depends on data availability in the investigated area. Common calculation methods of the energy demand are often based on monthly average energy balance, but as the computational power is increasing, dynamic simulation will become possible. In the post-processing analysis, the results can be presented and plotted on a 3D geo-data map.

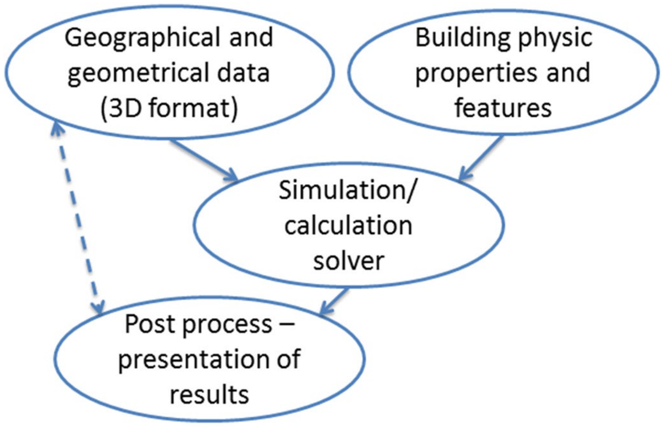


*Fig. 1. Main components of energy district tools.*
*Bild 1. Hauptteile der Distrikt-Tools*

### 2.2 3D data format

Many 3D data formats already exist and serve as basis for the geographical and geometrical data for energy district simulation tools. A summary of the available 3D data formats can be found in [5]. City Geography Markup Language (CityGML [6]) is an open data format model used for single buildings or to create a 3D-city model. Five building levels of detail (LoD) are available, starting with LoD0, simple building foot print, up to LoD4, a detailed architecture building model (LoD4) plus indoor view [5]. As CityGML is a common used open standard, several research institutes cooperate to develop the Energy Application Domain Extension (ADE) [7], which is an extension of CityGML, created to combine the energy features of buildings with the geographical and geometrical data. Keyhole Markup Language (KML) is another option that is used also in Globus Google Earth [5]. Industry Foundation Classes (IFC) is also an open standard for the description of building model e.g. wall, windows and doors and can be coupled with many 2-D architecture software such as AutoCAD [5]. Green Building XML similar to IFC with more focus to energy building simulation e.g. it includes weather data and radiation model [5]. Finally, the 3D City Information Model (3DCIM) is used in the commercial software ArcGIS and CityEngine [5] for 3D Cities from Esri [8].

Some examples of available 3D models were listed in [5]. For example, in Germany around 51 million buildings have been already available in level LoD1 (2015), and in addition the number of buildings in level LoD2 increases rapidly (database of both detail levels are updated once per year) [5]-(p.41). Free available data exist for the city of Berlin [9] (3D model of exists in LoD2 and some attractions buildings already in LoD3 und LoD4 [5]- (p.46)) and for the city of Hamburg [10] (3D models in LoD1 level [5]-(p.47)). Since 3D models are not always available, another option is to use the building polygons and the building height to represent a LOD1 in CityGML, an example can be found in [11].

### 2.3 Building stock analysis

In general, there are two analytical approaches (bottom up, top down) to analyse the energy demand of city district. If detailed information are available (e.g. U-values, building type, building geometry, etc.), it is possible to calculate or simulate the energy demand based on a bottom up approach. This implies that the calculations are performed on sub-system-level (dwelling, building), and then aggregated to total-system-level (building, block, district) to get the overall result, as it was done for Innsbruck in [11]. The top down approach disaggregates information from a total system level into different sublevels. Both approaches have to be verified due to the various assumptions. The selection of these approaches depends on the data availability in the investigation area.

Several studies are available concerning the analysis of the building stock.

Gas consumption measured data of Basel (Switzerland) at city and district level were gathered and analysed [12]. Additionally, information about the buildings was also gathered such as “building-category, construction year, footprint, number of floors, number of apartments and persons per building” and type of heating system and hot water supply. As authors mention, the organization of all data to one database was a challenging, high effort and time consuming procedure. Detailed analysis performed in two districts resulted that the volume and gross floor area were proven to be the variables with the better correlation to energy consumption. Furthermore, a correlation was found between compactness and building age.

Within the Intelligent Energy Project TABULA (and its follow up project EPISCOPE) [13], a web-tool [14] was created trying to cover the residential building stock of 13 European countries. Building classes were created depending on the country/region, the construction age and the building type (e.g. single-family houses, terraced houses, etc.). A representative building is available for each class which might be either real or virtual. Additionally different building properties, heating systems, and typical energy consumption can be chosen for each class.

Within a project at TU Munich a web application of energy rating of buildings was developed [5]-(p.132). The heating demand of the energy certification as well as construction information (e.g. U-values) can be saved for each building. Afterwards, using the Spread-sheet-Web application of Google the data can be saved in KML database and then visualized in 2D and 3D.

European building stock energy statistics were gathered and published within the European Project iNSPiRe [15]. The database was structured in several categories such as seven climate regions (depending on Heating Degree Days), countries of each region, building type (residential and office) and type of energy used (heating, lighting, electricity and DHW). Both specific demand and consumption for each category were presented.

Often cities have districts with heritage protected buildings and 'old towns'. These buildings should be taken under consideration in a specific way at district tools such as in GemEB [16], which distinguishes the buildings into historic and not historic. Refurbishment of heritage protected districts was the main topic of the European project EFFESUS including a detailed analysis of European building stock [17].

### 2.4 Simulation methods

The heating demand of a city or district can be estimated using various ways. A simplified approach is to use average value for specific heating demand (kWh/(m$^2$ yr) depending on the building age and building type. Another approach is to use the 3D City models and the available consumption data e.g. from gas or district heating. In this approach, the different buildings have to be categorized according to building type (single-family house, multi-family house, etc.), area, volume, age type, etc. A more enhanced solution is the coupling of geographical information system (GIS) data with a monthly energy balance calculation method based on ISO 13790 [18]. More sophisticated is the use of energy simulation programs, leading to an increase on required input data (often in specific format) and computational effort. Domestic hot water demand can be calculated based on standards, which are summarised in [5]-(p.62), and the profiles can be created with specific software like DHWcalc and SimDeum as mentioned in [5]-(p.63).

## 3 Tools overview

### 3.1 List of tools

In this study, a survey was performed, which was structured according to [19]. An overview list of 11 tools is presented in the following Tables 1 and 2, using information from the developers.

District energy tools vary strongly with respect to several aspects such as focus, outcome, structure and applied methodology. All 11 tools (see Tables 1 and 2) focus on demand side, and three of them focus also on supply side. The majority of the tools (eight) is based on GIS. The bottom-up approach is used in eight tools, while the top-down approach in two tools. Monthly energy calculations are included in five tools, dynamic simulations in four tools and more simplified approaches in two tools. Renewable energies are considered in five out of 11 models. Interestingly, eight tools are freeware (with three of them offering commercial version for more options – one is free for academics), while only two are fully commercial. With respect to the code, three tools are open source, one partly and six not open source. English is the main used language, implemented in seven tools (German is offered also as an option in one of them); while in the rest tools, national language is preferred (three tools are in German and one in French). Finally, three tools are under development, and eight are finalized (five of them with ongoing updates).

### 3.2 Input data

The input data for district tools vary depending on the focus and structure of the tool. Usually, building features and geographical data (e.g. volume, floor area, etc.) are needed. Data availability can be an issue both is case of non-public or open public data. In addition the incorporation of the input data (either with an accurate or simplified way) into the simulation model possibly with specific format can be challenging. Thus, the required detail of input data is a compromise between collection effort and required accuracy of the results.

A big advantage of some tools is the default values that can be modified by the user. In D-ECA, a building database is included from the countries participating to the IEA ECBCS Annex 51 [20], and in "Hotmaps toolbox", default open data base is going to be provided for the 28 European Union member states. Similarly, predefined values for the building properties are used in UMI [32] and Invert/EE-Lab includes a database on disaggregated building stock data for all countries of EU-28 [developer information – Lukas Kranzl]. In some cases, non-public data are available e.g. input data for Invert/EE-Lab can be found in [33].

An issue to overcome with respect to input data can be the data protection law, which may differ for each country. For example in EneRAlp model, the basic information of all energy-related databases (geographic information and building feature data) are collected, combined and linked, in accordance with the Austrian data protection law [11].

Often the building sector is classified according to the building type (e.g. single-, multi-family house, office, schools etc.) and to the construction age. The heating supply system is categorized to district or building level. Algorithms are developed to create automatically the available inputs in the required format for the simulation tool. For example, a tool in Python was developed to automatically calculate the thermal resistances and heat capacities for the simulation model based on construction year, floor height, number of floors and net floor area [34]. Thus, an automatic tool chain retrieves the data from GIS and automatically calculates the inputs for the building model leading to a parameterization and simulation of the building models with minimized effort. Similar approach is used in TEASER [35]. In CitySim a Graphical User Interface is used to help the user to derive the 3D geographical model as well as the energy features of the buildings [22].

*Table 1. Energy district tools (using information from the developers)*
*Tabelle 1. Distrikt-Tools für Energiebedarfsberechnungen (Daten wurden von den Entwicklern geliefert)*

| Properties/ Tool-Name | Citycalc | CitySim | MODER District Energy Concept Adviser (MODER D-ECA) | EEP | EneRAlp Tool | Gem-EB |
|---|---|---|---|---|---|---|
| Focus on supply or demand side | Demand side | Demand side | Both | Demand side | Demand side | Demand side |
| General and specific purposes of energy models | Energy demand of buildings and quarters for early design stages based on Austrian calculation method for energy performance certificates | Thermal and electrical demand of buildings, with provision of photovoltaics and solar thermal | Comparison of results of delivered energy, primary energy, $CO_2$ emissions, renewable energy ratio, investment costs and energy costs for different variants of building envelope quality, building services systems and central energy supply systems. | Establishing of current energy use and $CO_2$ emissions produced by buildings, traffic and industrial processes, and prediction of the effects of future planning decisions from a whole city level down to a more local level. | Baseline | Municipality heating energy demand modelling for current and future scenarios |
| Analytical approach | Bottom up | Bottom up | Bottom up | It is based on GIS techniques and incorporates a number of sub-models. | Bottom-Up, GIS based | GIS based |
| Underlying methodology | Monthly method of EN ISO 13790 (according to national standards of Austria) | Simplified thermal model (2-nodes), and Simplified Radiation Model, Energy Conversion Models | Monthly balancing based on DIN V 18599 (fully compatible to CEN EPBD standards) | Data is collected on individual building or road scale and then aggregated to produce postcode or regional scale outputs. | Monthly demand calculation acc. to energy performance certificate (ISO 13790), calibrated with real energy consumption (electricity, gas) | DIN V 4108-6, DIN V 4701-10, heat period balancing |
| Special focus on renewables | No | Yes | Yes | No | No | No |
| Geographical coverage | Mainly national; international coverage possible | From few buildings to the building district | Building district. | Building scale for domestic and commercial, road level for traffic. Aggregated to postcode and regional scale. MapInfo used to present the outputs. | – Regional and building district<br>– Residential and non-Residential buildings | – Regional, city and building district<br>– Residential buildings |

*Table 1. Continued*
*Tabelle 1. Fortsetzung*

| Properties/ Tool-Name | Citycalc | CitySim | MODER District Energy Concept Adviser (MODER D-ECA) | EEP | EneRAlp Tool | Gem-EB |
|---|---|---|---|---|---|---|
| INPUT-Information needed – Data requirements | Open public data: geometrical information of the building | 3D geometrical data, physical data (constructions, glazing ratios, ventilation), and occupational data of buildings | Data on building envelope U-values, type of included building services systems and central energy supply systems (e.g. district heating unit, etc.). | – The domestic sub-model uses built form and age to group properties into 100 different types. Each type has an associated $CO_2$ emission, SAP rating, and yearly energy cost.<br>– The non-domestic sub-model provides energy use figures for 48 different types of commercial property using floor area and type of property.<br>– The industrial sub-model includes 16 different industrial sectors using output figures from industries.<br>– Spatial Analysis procedures are used within the traffic sub-model for every road within a region. | Municipality provided non-public data and energy supplier main datasets: AGWR II, geodata's, electricity and gas consumption | – Digital maps<br>– Classes based on construction age and building type<br>– Number of floors |
| Commercial or freeware | Freeware; Commercial version for further options | Command-line Solver: free, Graphical User Interface: commercial (free for academics) | Freeware | Freeware | Commercial | Freeware |
| Open source | No | No | No | Advice would be required to set it up | No | Yes |
| Language | German | English | English, German | English | German | German |

*Table 1. Continued*
*Tabelle 1. Fortsetzung*

| Properties/ Tool-Name | Citycalc | CitySim | MODER District Energy Concept Adviser (MODER D-ECA) | EEP | EneRAlp Tool | Gem-EB |
|---|---|---|---|---|---|---|
| Tool status | Finalized, ongoing updates | Finalized with ongoing updates and new features | D-ECA finalized<br>MODER D-ECA under development (ready in autumn 2018) | Finalised | Finalized | Finalized |
| Organization/ project developing the tool | Developed within the Austrian (FFG) funded project ‚Citycalc' | EPFL and kaemco, Lausanne, Switzerland | Fraunhofer Institute for Building Physics, Germany<br>Projects:<br>1. D-ECA: „Energieeffiziente Stadt – EnEff:Stadt"<br>2. D-ECA, international versions: IEA EBC Annex 51 „Energy efficient communities" [20]<br>3. MODER D-ECA: EU Horizon 2020 MODER (680447) [21] | Welsh School of Architecture, Cardiff University | – University of Innsbruck and alpS<br>– Projects: EU project ‚SINFONIA' City project: ‚Baseline for Innsbruck' | – Technical University of Munich (TUM), Lst. Prof. Hausladen<br>– Projects: Energieleitplanung Ismaning, Energienutzungspläne Iphofen, Weyarn |
| Web link | [22] | [23] | [24] | [25] | [26] | [16] |

Finally, a modular approach is developed in Simstadt. A virtual 3D model on open standard CityGML [6] is used allowing various levels of details. Then, the geometrical quality of 3D City Model is controlled and repaired using the module of CityDoctor [36]. As a next step, the Geodata management is done with novaFactory [37] and the energy features as well as energy scenarios of the buildings are added in geographical data. Building energy features are included as a database using Energy ADE [7].

In some cases some specific input data might be available. E.g. in Energy Atlas Berlin [38] the electrical consumption is taken from the energy company [39], while a simplified estimation approach exists also for annual gas consumption depending on living area, and the hot water production is considered as a standard value of 600 kWh/(person · yr) according to IWU [40].

### 3.3 Calculation and simulation methods

A variety of implemented methods (from simplified calculations up to sophisticated dynamic simulations) are distinguished mainly to the following categories: calculations based on heated areas or energy certificate, monthly energy balance calculations and dynamic simulations.

For example, the space heating demand is calculated in Energy Atlas Berlin with a simplified approach based on the heated area (which is the product of a factor, ground area and the number of storeys) and the electricity demand as a function of the number of person per household [41]. GemEB is developed considering two important issues: Firstly the smaller the building is, the higher the external surface area to volume ratio (S/V) and therefore, the specific heating demand is higher. Secondly, the bigger the building is, the possibility of partially heating (some rooms are not heated) is increased resulting also to a lower specific heating demand than expected. Thus, the heating demand of reference buildings is calculated based on the size and the age classification of the building (according to IWU [40]), and an empiric factor is implemented to calculate the consumption of the building. A significant reduction of computational time is achieved by implementing the methodology of "Shoebox" models [42] in UMI. Another way to reduce the computational time is by to reduce the number of simulated buildings by clustering them with similar structural properties [43].

In the majority of the tools from the Tables 1 and 2, monthly calculation method is used, mainly based on ISO 13790 [18]. The monthly energy balance model described

*Table 2. Energy district tools (using information from the developers)*
*Tabelle 2. Distrikt-Tools für Energiebedarfsberechnungen (Daten wurden von den Entwicklern geliefert)*

| Properties/Tool-Name | Hotmaps toolbox | Invert/EE-Lab | SimStadt | SOLENE | TEASER |
|---|---|---|---|---|---|
| Focus on supply or demand side | Both | Demand side with some aspects of supply side e.g. district heating grid module | Demand side | Developed thanks to suppliers and now focus on demand side. | Demand side |
| General and specific purposes of energy models | Short-term analysis and long-term forecasting and scenario analysis including:<br>(1) Mapping heating and cooling energy situation;<br>(2) Model the energy system;<br>(3) Supporting the comprehensive assessment of efficient heating and cooling according to the Energy Efficiency Directive;<br>(4) Comparative assessment of given scenarios until 2050 | It is a dynamic techno-socio-economic simulation tool that evaluates the effects of different policy packages on the total energy demand, energy carrier mix, $CO_2$ reductions and costs for space heating, cooling, hot water preparation and lighting in buildings, including development scenarios of the building stock, its energy demand and district heating grid expansion up to 2030/2050/2080 for various scenario assumptions. | Baseline calculation (diagnosis of actual energy demand, embodied energy, $CO_2$), renewable potential assessment (irradiance, PV), forecasting scenarios (building refurbishment) | It requires to design a district and to mesh the urban surface and volume. Relying on this mesh, the tool realises the coupling between a radiative model, a thermoradiative model for different kind of urban surfaces and a CFD model. It can evaluate the impact of the urban planning choices on the urban heat island, on the building energy demand as well as indoor or outdoor thermal comfort. | Data enrichment for buildings and automated generation of simulation models for Modelica |
| Analytical approach | It consists of several modules including bottom up and -top-down approaches. In both variants, GIS based analysis is used. | Bottom-up; some elements of top-down models are also integrated (e.g. resource potentials, diffusion restrictions, budget restrictions); the district heating module also includes a GIS component. | Bottom-up, 3D-GIS based (open 3d city model CityGML) | Bottom–up: from surface and building energy balance to microclimate modelling | Top-Down |
| Underlying methodology | Each module has its own methodology:<br>– economic assessment of investment options (efficiency measures in building stock, industry, etc.)<br>– hourly balancing of supply and demand for regions and districts<br>– economic optimization of generation portfolios for heating and cooling supply<br>– statistical analysis of building stock data and it's supply technologies | Nested logit approach; Weibul distribution; Static monthly balance approach for energy needs and delivered as well as final energy demand; Optimization for district heating and gas grid modelling from the network operator's point of view. | Heating/Cooling demand: standard monthly energy balance DIN 18599 (dynamic simulation in current development).<br>DHW and Electrical demand: statistical models | Based on the equations of heat transfer (radiation, conduction, convection) and mass transfer (fluid mechanics), balances are realized on each cell of the district. Surface and building energy balances are done using finite difference methods. | Dynamic building model VDI guideline 6007-1 |

*Table 2. Continued*
*Tabelle 2. Fortsetzung*

| Properties/Tool-Name | Hotmaps toolbox | Invert/EE-Lab | SimStadt | SOLENE | TEASER |
|---|---|---|---|---|---|
| Special focus on renewables | Yes | Yes | Solar photovoltaic suitability and production assessment. | No. Not for now, but e.g. solar potential at district scale and natural ventilation potential can be estimated. | No |
| Geographical coverage | – Local, regional and national level for EU-28<br>– Residential and non-residential buildings | – National (and some elements, in particular regarding grid modelling on spatially high resolution); several case studies also on local and regional level; EU-28 (plus NO and CH)<br>– Residential and non-residential buildings | – Multi-scale application, from building level (mono or mixed usage) to regional level<br>– Residential and non-residential buildings | Building district | Non-residential and residential buildings (German statistical data, but not limited to this) |
| INPUT-Information needed – Data requirements | Open public data: EU-28 compatible: Provision of Default Open data (can be modified by the user) base for EU-28 with the aim to be applicable for cities in all EU member states | Non-public data in general<br>– Disaggregated building stock data and installed heating, hot water and cooling systems<br>– Techno-economic data for building renovation and heating systems<br>– Energy prices<br>– Resource potentials, diffusion restrictions etc.<br>– Specification of agents<br>– Policy specification<br>– Scenarios of future growth of building stock<br>– Climate data | Depends on the selected analysis/workflow. All workflows require at less a 3d city model of good quality. Some workflows require additionally a set of minimum semantic data (heating demand: building function and year of construction). Further relevant data may be used to refine the model. | Open public data; Meteorological data (no data can be needed in case of academic study) | Net floor area, building age, building usage and rough cubature (height and number of storeys) |
| Commercial or freeware | Freeware | Commercial | Currently internal use only. No licence yet. | Both | Freeware |
| Open source | Yes | No | Not yet | Partly open source | Yes |
| Language | English | English | English | French | English |
| Tool status | Under development: first release of test-components planned in 2017 | Finalized, ongoing updates | Under development | Finalized, ongoing updates | Under development, stable version |
| Organization/project developing the tool | EU H2020 project ‚Hotmaps' with 16 partners and TU Wien as coordinator. | – Vienna University of Technology/EEG<br>– more than 40 projects (http://www.invert.at/projects.php) for different cities, regions and countries (including EU-28 plus NO, CH and IS). | – HFT Stuttgart, with the support of MOSS and GEF<br>– German national projects: SimStadt (2013-2016) and SimStadt 2 (2017–2020). | The tool was developed thanks to PhD thesis. | RWTH Aachen University, Institute for Energy Efficient Buildings and Indoor Climate |
| Web link | [27] | [28] | [29] | [30] | [31] |

on ISO 13790 and the transient model described on VDI 6007 are compared against measured data in [34], aiming to be used for the energy simulation of buildings within a district or urban area. The comparison of both thermal models showed minor deviations and therefore both models can be used for city district energy simulation demand. The advantages of monthly method compared to dynamic simulations are the minimized computational time and often the less amount of required input data.

Since computational power is increasing, dynamic hourly simulations are included in many tools. For example, Hotmaps toolbox enables hourly balancing between supply and demand, TEASER uses a thermal network R-C model for dynamic simulations in Modelica [44], Solene couples a radiative, a thermoradiative, and a CFD model [45], CitySim includes a simplified 2-nodes model [46], and dynamic simulations is going to be an option in SimStadt, too.

In district energy modelling, the number of assumptions is relative high and therefore, when measured consumption data are available, a calibration improves the accuracy. This was done for the Innsbruck SINFONIA case study using the EneRAlp Model, in which the heating and electricity energy results are calibrated against the real energy consumption provided by the energy supplier [11].

Statistical analysis is also used e.g. in SimStadt for DHW and electricity demand, and in Hotmaps toolbox for the building stock and supply technologies.

## 4 Use of appropriate boundary conditions

### 4.1 Uncertainties in available input data

In most cases, the real quality of the building envelope due to partial renovation is unknown. Besides construction date and rough information about the thermal quality of the building envelope, there is almost no information about enhancements of wall, window and roof components over time. Moreover, the difference between treated and gross floor area is another reason for deviations between measured and calculated heating energy. According to [47], the uncertainties of the available data are the user behaviour and heating system. For example, in some buildings the heat source technology was changed only in a few flats (e.g. gas instead of wood oven) making it hardly possible to gather information about the energy consumption of the whole building. Additionally, low accuracy of available data might lead to inappropriate calculation results, such as inaccurate building volume (due to unheated rooms), unknown indoor temperatures during the heating season, various heating periods (less or no heating during the night), air change rate (window opening and infiltration) and user behaviour (occupancy).

The correlation between building's compactness and specific heating demand was discussed in [48]. Smaller dwelling units, which tend to be found in larger, more compact buildings, have higher average temperatures, according to [49]. This effect is even higher in historic buildings. Additionally, the need to categorize the buildings to refurbished and non-refurbished is discussed in [50], since it influences a lot the energy performance.

The influence of the user behaviour on the energy performance of the building was investigated via comparison of dynamic simulations and monitoring data in [51]. Energy consumption data from energy bills, which were derived from the facility companies, were analysed. The investigated variables of user behaviour were a) indoor set point temperature, b) air change rate due to window opening and c) domestic hot water (DHW) demand. It was shown that the measured distributions (using measured data of 3.3 million flats) could be reproduced by making certain assumptions about the user behaviour. The monitoring data show that the average DHW demand is not influenced significantly by the building energy level, while its share of the total consumed energy increases with better energy performance buildings. The results show that in good energy performance building, equivalent heating reference temperature and window air change rate were increased as compared to poor performance buildings, leading to higher thermal comfort and improved indoor air quality.

### 4.2 The so called 'performance gap'

Many authors have reported significant differences between calculated energy demands and measured energy consumption, which are often briefly referred to as a "performance gap". In many cases, the energy consumption of buildings with low efficiency (where the occupants operate their homes more economically) is overestimated by the calculation procedures, whereas the energy consumption is underestimated for higher performance buildings. The first deviation is called the "prebound effect" in [52], analogously to the „rebound effect". The rebound effect describes a situation where the real energy saving is less than calculated, e.g. due to increasing demands in energy services after efficiency improvements [53].

In reality, the so called "performance gap" could be characterized as a misleading observation due to the following aspects:

- Improper statistics use and no consideration of extreme user behaviour. For example, often user behaviour is estimated using a few measured cases instead of a qualitative and quantitative sample. In [54], measurement and calculation results were compared using a statistic approach, including also extreme user behaviours.
- Inappropriate calculation methods and assumptions e.g. disregard of thermal bridges or correction factor for the g-value of the window, when the implemented g-value is not a function of the angle of solar radiation. Both effects would lead to less calculated heating demand than in reality.
- Inaccurate characteristic values of construction materials and components. Often, characteristic values (e.g. efficiency of heat recovery ventilation units or U-value of windows) from manufacturer's datasheets were inserted in calculations, but these values usually tend to be optimistic or not verified/certified leading to unrealistic behaviour. The use of values from certified products (e.g. from Passive House Institute) minimizes the influence of this effect and improves strongly the calculation accuracy.
- Missing of quality assurance control after construction and component installation. Construction errors and improper installation lead to less efficiency in reality

than expected e.g. air leakages or high pressure losses in the ducts of the ventilation system.

The difference between calculated and measured consumptions is strongly reduced in very efficient buildings. Very good agreement between measured and calculated energy for Passive Houses is shown e.g. in [55, 56].

### 4.3 Simulation study

As already discussed above, and summarized in [52], there is a large number of studies that consistently show a significant overestimation of the (measured) heating energy consumption for buildings with a high (calculated) heating energy demand. Simultaneously, many scientific monitoring projects have shown that such a difference does not exist for Passive Houses, where consumption and demand are similar, provided that the typical actual indoor temperature of 21.5 °C [57–59] is used in the calculations with e.g. the PHPP [60]. This situation is consistently reflected in a correlation given by [61], one of the few references that try to provide a solution to the observed overestimation of heating energy consumptions. From data for ca. 1700 buildings, the authors derive an empirical correlation formula for the measured heating energy consumption $Q_M$ as a function of the heating energy demand $Q_C$ calculated under standard conditions (cf. also Figure 3 below):

$$Q_M = Q_C\left(-0.2 + \frac{1.3}{1 + \frac{Q_H}{500\,\text{kWh}/(\text{m}^2\,\text{yr})}}\right) \quad (1)$$

The data underlying this correlation are mainly from a range of heating energy demands between 150 and 350 kWh/(m² yr) (here, the characteristic values are given with reference to square meters of useful floor area, i.e. the sum of the areas of all rooms, excluding e.g. exterior and interior walls as well as staircases).

It should be noted that measured heating energy consumptions scatter significantly. Schröder et al. [62] reports standard deviations of 30 to 50 % for the heating energy consumptions of buildings in identical size and building age classes.

From the good agreement in the range of Passive Houses, one can conclude that the calculation algorithms are able to model the relevant physical processes. Taking this as a starting point, it seems likely that the discrepancies at higher heating demands are due to incorrect boundary conditions, in particular overestimated room temperatures. Indeed it was shown in [62], based on more than one million measurements in multi-family residential buildings in Germany, that older buildings with poorer efficiency levels exhibit lower average indoor temperatures. For pre-1977 buildings, average room temperatures of 18.1 °C are reported, for post-2002 buildings this value is 18.9 °C. It should be noted, though, that these measurements were made with electronic heat cost allocators, not with scientific instruments.

In the following, it will be shown that a plausible assumption of partial heating can explain the observed discrepancies of consumption and demand. Furthermore, based on this approach, we can provide estimates for the indoor temperature that allow for improved predictions of the heating energy demand.

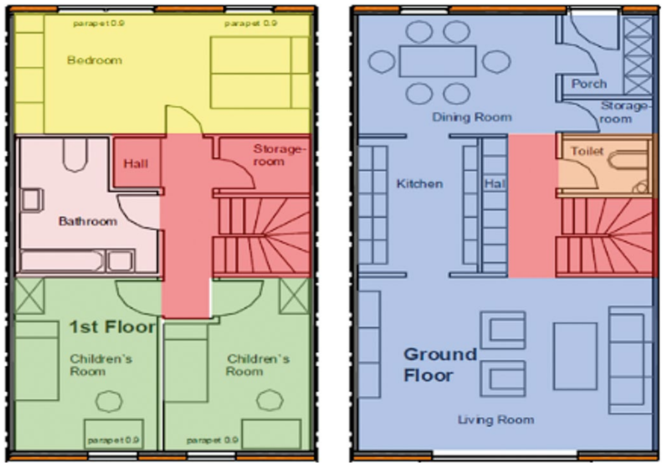


*Fig. 2. Floor plans of the example home*
*Bild 2. Grundrisse der Beispielwohnung*

As an exemplary case for a residential building, the small end-of-terrace house shown in Figure 2 is used. It has a total living area of 120 m² on two storeys. For the simulation, it is divided into 6 thermal zones. 5 different insulation levels are considered, from an uninsulated envelope with single glazing to Passive House insulation with triple glazing and U-values of walls, roof, and basement floor between 0.11 and 0.16 W/(m²K).

Now, 4 different utilisation patterns are applied: a family of five where the children come back from school at 2 p.m.; a similar family where all but one family members are away until 7 p.m.; a working couple that spends the day outside their home; a retired couple that spends most of their time at home. It is assumed that the inhabitants are heating only those rooms which they currently occupy. This is a plausible assumption at least for Germany, where residential buildings usually have hydronic heating systems with room thermostats and residents are charged for heating depending on their individual consumption. In addition to the above, heating is turned off during the night, i.e. from 10 p.m. to 6 a.m. The scenarios are obviously simplified; in reality the heating system cannot instantaneously heat up a room, the inhabitants will sometimes be off for the weekend or winter holidays, some of them will heat certain rooms to a minimum temperature even if not used, etc. Nevertheless, the results give a good indication of the temperatures that may occur in buildings of different insulation levels.

Figure 3 shows the simulation results in comparison with *Loga's* correlation from [61]. The simulation results scatter approximately by a factor of 2 for the same heating demand under standard conditions (here: 20 °C operative room temperature), depending on the chosen scenario. It can be seen that *Loga's* correlation is within the range given by the simulation results. Note: All data in the figure refer to useful heat. *Loga's* correlation originally refers to delivered energy and was transformed accordingly, assuming 91 % efficiency of heat generation and distribution.

It can be concluded that partial heating, both with reference to time and space, can explain the majority of the

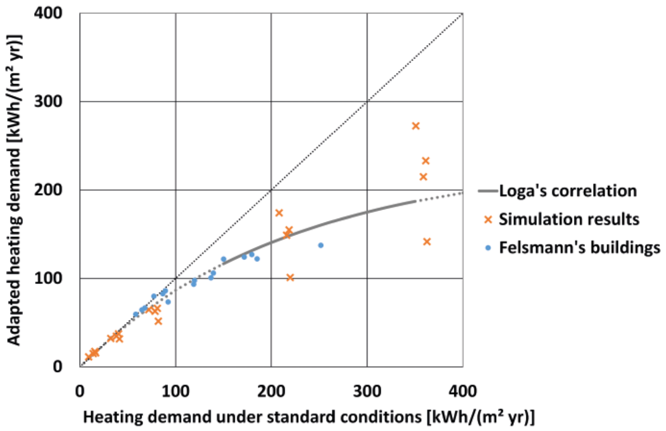


*Fig. 3. Useful heating demand under realistic boundary conditions as a function of the heating demand under standard conditions*
*Bild 3. Nutzbarer Energiebedarf unter realistischen Randbedingungen in Abhängigkeit vom Energiebedarf unter Standardbedingungen*

observed differences between calculations and measurements. It should be noted that this partial heating results in average indoor temperatures that are far below the comfort range and will indeed result in a somewhat reduced thermal comfort; we call the expected value of these temperatures the "equivalent heating reference temperature (EHRT)". Nevertheless, the results appear plausible because rooms that are used for extended periods of time can still be heated to comfortable temperatures in spite of the low averages. It is only for very high heating demands that the simulation still appears to overestimate the observed correlation. Possible reasons include physical effects (reduced heat transfer coefficients due to furniture on exterior walls or carpets on the floor as well as curtains are more relevant for high U-values) as well as social aspects (higher energy cost results in additional reductions of room temperatures; buildings that were not refurbished are more likely to have a low occupancy) which are beyond the scope of this study.

For the use in energy district tools, it is now desirable to predict the equivalent heating reference temperature that provides realistic results for the heating demand. The following factors are expected to be of relevant influence for this temperature:

- The specific heat loss of the building. From a physical standpoint the heat loss, and not the heating demand, is driving the temperature reduction. The higher the heat transfer between inside and outside, the faster the temperature will drop when a room is left and the heating is turned off. As heating demands per square meter of living area are considered here, the specific transmission and ventilation heat loss h per square meter of living area and per Kelvin of temperature difference between inside and outside (in the following briefly: 'total specific conductance') is used.
- The thermal mass of the building structure. For lightweight constructions, a faster temperature drop would be expected after the heating has been shut off. However, simulation test runs revealed that this influence is of minor importance.
- The climate, in particular the average ambient temperature $\theta_a$ during the heating period. In reality, this value depends on the building, because high performance buildings have a shorter heating period. However, for practical purposes, a value that depends only on the climate is used. A temperature, which basically incorporates all months with an average temperature below 10 °C and a part of the months with temperatures between 10 and 16 °C, was chosen, identical to the one calculated in PHPP [60].
- The size of the building or the dwelling units. In smaller buildings, particularly in single family homes, the dwelling units tend to be larger. For these smaller buildings it is easier to reduce the temperature in a specific room because there are less adjacent rooms, which are heated. In fact, [63] shows that, at the same total living area of the building, lower heating demands are found if the dwelling units are smaller. Here, a correction factor from [64] is used: the unheated fraction of a dwelling unit is estimated to be

$$n_{re} = 0.25 + 0.2 \arctan \frac{A_{DU} - 100\ m^2}{50\ m^2} \tag{2}$$

where $A_{DU}$ is the average living area of a dwelling unit. The correction factor for the size of the dwelling unit is then given as

$$f_{re} = \frac{1}{0.5\sqrt{h} \cdot n_{re}{}^2 + 1} \tag{3}$$

A simple and robust, linear correlation for the indoor temperature $\theta_i$ was found to be the most suitable function:

$$\theta_i = \max\Big\{13°C, \min\Big[24°C, \theta_{i,set} - \big(1 - f_{re} + 0.07 m^2K/W \cdot h\big)\big(\theta_{i,set} - \theta_a\big)\Big]\Big\} \tag{4}$$

where $\theta_{i,set}$ is an indoor temperature set point of 21 °C.

The temperature calculated using the formula is shown in Figure 4, in parallel with the dynamic simulation results for the different scenarios and insulation levels of the modelled dwelling unit.

The EHRT $\theta_i$ is usually within the range given by the simulation results, with a certain underestimation of the simulation for high values of h. This latter deviation is desirable because it compensates for the still lower heating demands of buildings with very high heat losses (see above). This result also holds for other European climates; examples are shown in Figure 4. For these climates the suggested correlation can only be a first approximation because of the lack of empirical evidence. In countries where e.g. typical heating systems, occupancy densities, or the importance of heating cost to the inhabitants differ from the situation in Germany, the scenarios used for the simulation may be less representative.

The EHRT can then be used as a heating set point for dynamic simulations or – usually more appropriate for energy district tools and with very similar results – for monthly/annual energy balance calculations. It should be noted that the dynamic simulation results in Figure 4 are not temperature set points, but average temperatures for

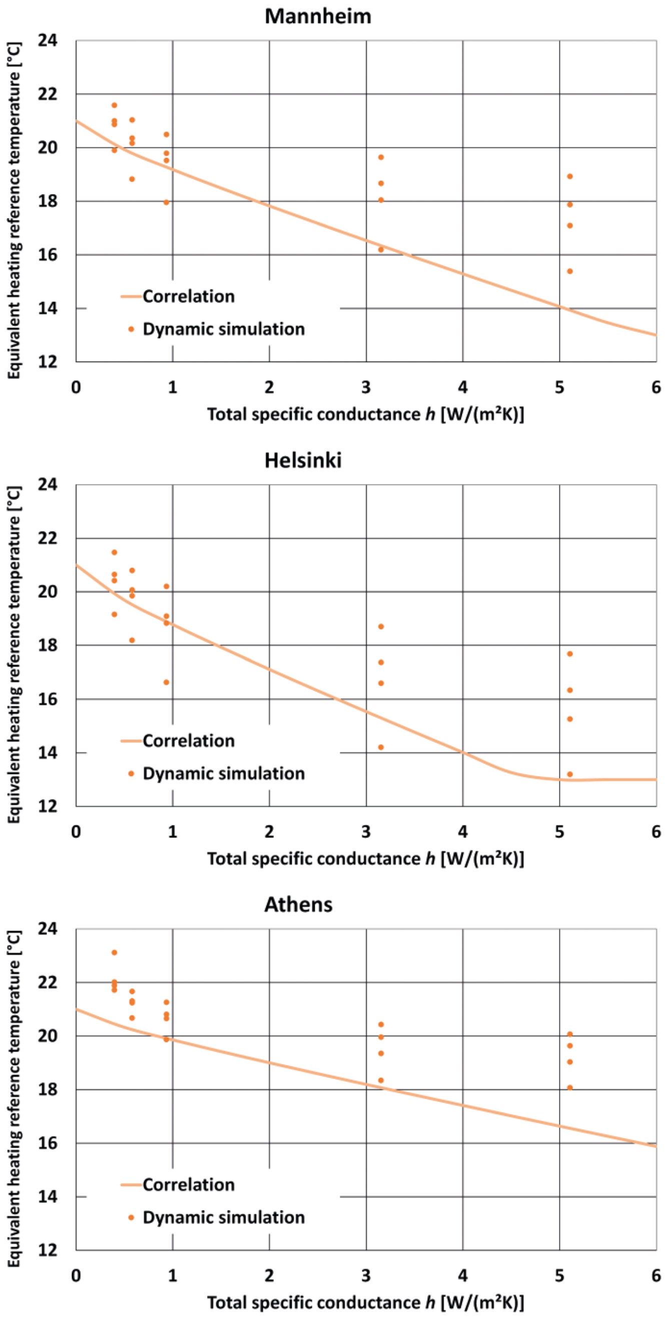


*Fig. 4. Indoor temperature as a function of the specific heat loss per square meter of living area. Correlation based on eq (4)*
*Bild 4 Innentemperatur in Abhängigkeit vom spezifischen Wärmeverlust pro Quadratmeter Wohnfläche. Korrelation nach Gleichung (4)*

the heating period, weighted by the living areas of the building‘s zones. The corresponding average set points are somewhat lower, particularly for low total specific conductances and sunny climates, because solar and internal gains sometimes result in indoor temperatures above the set point even in the heating period. It would have been possible to determine temperature set points that reproduce exactly the same heating demand as determined for partial heating, but, given the large scatter of the data, that would just have suggested a false precision.

In order to verify the suggested correlation, the indoor temperature set points were applied to a range of multifamily buildings following those used in [51]. When compared to the results with standard boundary conditions (here: 19 °C, 0.4 air changes per hour), excellent agreement with *Loga's* correlation was observed (see Figure 3).

## 5 Conclusions

Several tools for energy calculations/simulations of a district, city, region or even a country were developed or are under development. An overview of 11 tools in Europe was presented in this study. A variation with respect to aim and application of the tools can be observed. In most tools, monthly calculation method is used or simplified dynamic simulation methods are developed. Most tools are based on GIS and use the bottom-up approach. The majority of the tools are freeware but often not open source. Even though English is the dominant used language, the national language is preferred in four tools.

The so called 'performance gap' has been discussed. Simulation results showed that the difference between calculated and measured heating demand can be eliminated using appropriate average indoor temperature as equivalent heating reference temperature (EHRT). Additionally, a formula was developed to estimate this temperature $\theta_i$ based on building envelope, living area and ambient temperature, aiming to be used as set point for the indoor temperature in district energy calculations.

In the future, a comparison of the tools with respect to required data input (especially, in case of poor quality data), modelling effort and accuracy is suggested. As for the suggested boundary conditions, validations based on more detailed information from measurements would be useful.

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### References

[1] *Laffont, K., Vafeas, A.*: Review of existing decision support tools for district refurbishment. EC FP7 project Sinfonia Grant agreement no. 609019, 2015.
[2] *Stöglehner, G., Erker, S., Neugebauer, G.*: Tools für Energieraumplanung Ein Handbuch für deren Auswahl und Anwendung im Planungsprozess, Vienna, Austria, 2013. http://www.oegut.at/downloads/pdf/ib_wozubau_tools-erp.pdf (accessed March 21, 2017).
[3] *Reul, L.K., Michaels, H.G.*: Mapping Energy Efficiency for Community-Level Engagement, 2012. http://web.mit.edu/energy-efficiency/docs/EESP_Reul_MappingForEngagement.pdf.
[4] *Miller, G.R,. Warren, J., Geraghty, S., Margerm, K., Molina, J.C.*: Integrated Energy Mapping for Ontario Communities –

Lessons Learned Report, 2011. http://www.canurb.com/doc_download/81-integrated-energy-mapping-for-ontario-communities-lessons-learned-2011.
[5] Runden Tisch GIS e. V., Technische Universität München, 3D-GIS und Energie, 2015. https://rundertischgis.de/images/9_documents/downloads/Leitfaden_3D-GIS_und_Energie_V_1.0.pdf.
[6] CityGML, CityGML homepage, (n.d.). https://www.citygml.org/(accessed March 26, 2017).
[7] *Nouvel, R., Kaden, R., Bahu, J., Kaempf, J., Cipriano, P., Lauster, M., et al.*:, GENESIS OF THE CITYGML ENERGY ADE, in: CISBAT, Lausanne, Switzerland, 2015: pp. 931–936.
[8] Esri, Esri Deutschland, (n.d.). https://www.esri.de/(accessed March 26, 2017).
[9] Berlin3D, Berlin 3D City model, (n.d.). http://www.business-locationcenter.de/berlin3d-downloadportal/.
[10] Hamburg, Transparenzportal Hamburg, (n.d.). http://transparenz.hamburg.de/(accessed March 26, 2017).
[11] *Pfeifer, D.*: Entwicklung , Untersuchung und Bewertung von Berechnungsmodellen zur Erstellung von kommunalen Energiebilanzen im Gebäudebereich, University of Innsbruck, 2017.
[12] *Aksoezen, M., Daniel, M., Hassler, U., Kohler, N.*: Building age as an indicator for energy consumption, Energy Build. 87 (2015) 74–86. doi:10.1016/j.enbuild.2014.10.074.
[13] EPISCOPE, EPISCOPE, (n.d.). http://episcope.eu/monitoring/overview/(accessed March 26, 2017).
[14] TABULA, TABULA WebTool, (n.d.). http://webtool.building-typology.eu/#bm (accessed March 26, 2017).
[15] *Birchall, S., Wallis, I., Churcher, D., Pezzutto, S., Fedrizzi, R., Causse, E.*: D2.1a – Survey on the energy needs and architectural features of the EU building stock. EC FP7 project iNSPiRe Grant agreement no. 314461, 2014. http://www.inspirefp7.eu/wp-content/uploads/2014/08/WP2_D2.1a_20140523_P18_Survey-on-the-energy-needs-and-architectural-features.pdf.
[16] Gem-EB, Gem-EB, (n.d.). www.gem-eb.de (accessed March 26, 2017).
[17] *Frick, J., Reichert, M., Panzehir, M., et al.*: European building and urban stock data collection, 2012. http://www.effesus.eu/wp-content/uploads/2016/01/D-1.1_European-building-and-urban-stock-data-collection.pdf (accessed March 26, 2017).
[18] ISO, ISO 13790. Energy performance of buildings – Calculation of energy use for space heating and cooling., 2008.
[19] *Beeck, N. M. J. P.*: Classification of Energy Models, FEW Res. Memo. 777 (1999). https://pure.uvt.nl/ws/files/532108/777.pdf (accessed May 21, 2017).
[20] EBC Annex 51 Energy Efficient Communities, (n.d.). http://www.iea-ebc.org/projects/completed-projects/ebc-annex-51/(accessed May 26, 2017).
[21] MODER, MODER – Mobilization of innovative design tools for refurbishing of buildings at district level, (n.d.). http://www.vtt.fi/sites/moder/home (accessed March 26, 2017).
[22] CityCalc, CityCalc, (n.d.). http://citycalc.com/(accessed March 26, 2017).
[23] LESO-PB, CitySim Software, (n.d.). http://citysim.epfl.ch/(accessed March 26, 2017).
[24] Fraunhofer IBP, D-ECA, (n.d.). www.district-eca.com (accessed March 26, 2017).
[25] Welsh School of Architecture School Cardiff University, EEP, (n.d.). http://www.cardiff.ac.uk/archi/research/eep/.
[26] EneRAlp, EneRAlp, (n.d.). http://www.alp-s.at/cms/de/land/abgeschlossene-projekte/g08-eneralp/(accessed March 26, 2017).
[27] Hotmaps, Hotmaps, (n.d.). http://www.hotmaps-project.eu/(accessed May 25, 2017).
[28] Invert/EE-Lab, Invert/EE-Lab, (n.d.). http://www.invert.at/(accessed March 26, 2017).
[29] SimStadt, SimStadt, (n.d.). www.simstadt.eu/(accessed March 26, 2017).
[30] Solene, SOLENE, (n.d.). http://aau.archi.fr/crenau/solene/(accessed March 26, 2017).
[31] TEASER, TEASER, (n.d.). https://github.com/RWTH-EBC/TEASER.
[32] umi, umi, (n.d.). http://urbanmodellinginterface.ning.com/(accessed March 26, 2017).
[33] ENTRANZE, (n.d.). http://www.entranze.eu/(accessed May 25, 2017).
[34] *Lauster, M., Teichmann, J., Fuchs, M., Streblow, R., Mueller, D.*: Low order thermal network models for dynamic simulations of buildings on city district scale, Build. Environ. 73 (2014) 223–231. doi:10.1016/j.buildenv.2013.12.016.
[35] *Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T., Müller, D.*: TEASER: an open tool for urban energy modelling of building stocks, J. Build. Perform. Simul. (2017) 1–15. doi:10.1080/19401493.2017.1283539.
[36] CityDoctor, CityDoctor, (n.d.). http://www.citydoctor.eu/(accessed March 26, 2017).
[37] M.O.S.S, novaFACTORY, (n.d.). https://www.moss.de/novafactory/(accessed March 26, 2017).
[38] Energy-Atlas, Energy-Atlas Berlin, (n.d.). http://energyatlas.energie.tu-berlin.de/en/energy-atlas/(accessed March 26, 2017).
[39] Vattenfall, WINTER ADE, (n.d.). https://www.vattenfall.de/(accessed March 26, 2017).
[40] IWU, Deutsche Gebäudetypologie – Systematik und Datensätze, Darmstadt, Germany, 2005.
[41] *Kaden, R., Kolbe, T. H.*: CITY-WIDE TOTAL ENERGY DEMAND ESTIMATION OF BUILDINGS USING SEMANTIC 3D CITY MODELS AND STATISTICAL DATA, in: Int. J. 3-D Inf. Model., 2014: pp. 163–171.
[42] *Dogan, T., Reinhart, C.*: Automated conversion of architectural massing models into thermal “shoebox” models, BS2013 13th Conf. Int. Build. Perform. Simul. Assoc. (2013) 3745–3752. http://www.ibpsa.org/proceedings/BS2013/p_1123.pdf.
[43] *Elci, M., Narmsara, S., Kagerer, F., Herkel, S.*: Simulation of Energy Conservation Measures and Its Implications on a Combined Heat and Power District Heating System: a Case Study, in: BS201313th Conf. Build. Perform. Simul. Assoc., International Building Performance Simulation Association, Chambery, France, 2013: pp. 104–111.
[44] Modelica, Modelica and the Modelica Association, (n.d.). https://www.modelica.org/(accessed March 26, 2017).
[45] *Morille, B., Musy, M., Malys, L.*: Preliminary study of the impact of urban greenery types on energy consumption of building at a district scale: Academic study on a canyon street in Nantes (France) weather conditions, Energy Build. 114 (2016) 275–282. doi:10.1016/j.enbuild.2015.06.030.
[46] *Walter, E., Kämpf, J.H.*: A verification of CitySim results using the BESTEST and monitored consumption values, in: Proc. 2nd Build. Simul. Appl. Conf., Bolzano, Italy, 2015: pp. 215–222. https://infoscience.epfl.ch/record/214754.
[47] *Eicker, U., Nouvel, R., Schulte, C., Schumacher, J., Coors, V.*: 3D-Stadtmodelle für die Wärmebedarfsberechnung, in: BauSIM 2012, 2012: pp. 1–7.
[48] *Zadow, O.*: Werkzeuge für den Energienutzungsplan (ENP), 2012.
[49] *Born, R., Diefenbach, N., Loga, T.*: Energieeinsparung durch Verbesserung des Wärmeschutzes und Modernisierung der Heizungsanlage für 31 Musterhäuser der Gebäudetypologie, Darmstadt, Germany, 2003. http://www.iwu.de/fileadmin/user_upload/dateien/energie/klima_altbau/GebTyp_Im

pulsprogramm_Hessen_22_01_2003.pdf (accessed March 26, 2017).

[50] *Michelsen, C., Müller-Michelsen, S.*: Energieeffizienz im Altbau: Werden die Sanierungspotenziale überschätzt? Ergebnisse auf Grundlage des ista-IWH-Energieeffizienzindex, Wirtschaft Im Wandel. 16 (2010) 447–455. http://hdl.handle.net/10419/143850 (accessed March 26, 2017).

[51] *Felsmann, C., Schmidt, J.*: Auswirkungen der verbrauchsabhängigen Abrechnung in Abhängigkeit von der energetischen Gebäudequalität, Dresden, Germany, 2013.

[52] *Sunikka-Blank, M., Galvin, R.*: Introducing the prebound effect: the gap between performance and actual energy consumption, Build. Res. Inf. 40 (2012) 260–273. doi:10.1080/09613218.2012.690952.

[53] *Sorrell, S., Dimitropoulos, J.*: The rebound effect: Microeconomic definitions, limitations and extensions, Ecol. Econ. 65 (2008) 636–649. doi:10.1016/j.ecolecon.2007.08.013.

[54] *Feist, W.*: Warum sind Messwerte oft höher als der zuvor berechnete Bedarf?, 2007. http://passiv.de/former_conferences/Passivhaus_D/pdf/Passivhaus_Messergebnisse_Stand_der_Technik.pdf (accessed March 26, 2017).

[55] *Schnieders, J., Hermelink, A.*: CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building, Energy Policy. 34 (2006) 151–171. doi:10.1016/j.enpol.2004.08.049.

[56] *Peper, S., Feist, W.*: Energy efficiency of the Passive House Standard: Expectations confirmed by measurements in practice, Darmstadt, Germany, 2015. http://www.passiv.de/downloads/05_energy_efficiency_of_the_passive_house_standard.pdf (accessed May 26, 2017).

[57] *Peper, S., Feist, W.*: Klimaneutrale Passivhaussiedlung Hannover-Kronsberg Analyse im dritten Betriebsjahr, Darmstadt, Germany, 2002. www.passiv.de/downloads/05_cepheus_analyse-im-dritten-betriebsjahr.pdf (accessed May 26, 2017).

[58] *Peper, S., Feist, W., Pfluger, R.*: Ein nordorientiertes Passivhaus, Darmstadt, Germany, 2004. http://www.passiv.de/downloads/05_passivhaus_nordorientiert.pdf (accessed May 26, 2017).

[59] *Peper, S., Grove-Smith, J., Feist, W.*: Sanierung mit Passivhauskomponenten Messtechnische Untersuchung und Auswertung Tevesstraße Frankfurt a.M., Darmstadt, Germany, 2009. http://www.passiv.de/downloads/05_tevesstrasse_messtechnische-begleitung.pdf (accessed May 26, 2017).

[60] *Feist, W.*: PHPP – Passive House Planning Package, (1998). http://passiv.de/en/04_phpp/04_phpp.htm (accessed April 18, 2017).

[61] *Loga, T., Diefenbach, N., Born, R.*: Deutsche Gebäudetypologie, Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden, Darmstadt, Germany, 2011.

[62] *Schröder, F. P., Papert, O., Boegelein, T., Navarro, H., Mundry, B.*: Reale Trends des spezifischen Energieverbrauchs und repräsentativer Wohnraumtemperierung bei steigendem Modernisierungsgrad im Wohnungsbestand, Bauphysik. 36 (2014) 309–324. doi:10.1002/bapi.201410045.

[63] *Schröder, F., Altendorf, L., Greller, M., Boegelein, T.*: Universelle Energiekennzahlen für Deutschland Teil 4: Spezifischer Heizenergieverbrauch kleiner Wohn häuser und Verbrauchs- hochrechnung für den Gesamtwohnungsbestand, Bauphysik. 33 (2011) 243–253. doi:10.1002/bapi.201110026.

[64] *Loga, T., Born, R., Großklos, M., Bially, M.*: Energiebilanz-Toolbox, Arbeitshilfe und Ergänzungen zum Energiepass Heizung/Warmwasser, Darmstadt, Germany, 2001.

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# Bibliography


[1] Directive 2010/31/EU, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. The European Parliament and the Council of the European Union., Off. J. Eur. Union. L153 (2010) 13–35. doi:10.3000/17252555.L_2010.153.eng.

[2] European Environment Agency, Energy and environment report 2008, 2008. doi:10.2800/10548.

[3] iPHA, Passive House certification criteria. https://passivehouse-international.org/index.php?page_id=150&level1_id=78.

[4] PHI, Passive House requirements. http://www.passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm.

[5] B. Zeno, W. Feist, EnerPHit Planerhandbuch - Altbauten mit Passivhaus Komponenten fit für die Zukunft machen, Darmstadt, Germany, 2012. http://www.passiv.de/de/03_zertifizierung/02_zertifizierung_gebaeude/04_enerphit/04_enerphit-planer-hb.htm.

[6] W. Feist, The world’s first Passive House, Darmstadt-Kranichstein, Germany. doi:10.13140/RG.2.1.4012.7526.

[7] SENTECH Inc., Review of selected home energy auditing tools, 2010.

[8] K.H. Kim, J.S. Haberl, Development of a home energy audit methodology for determining energy-efficient, cost-effective measures in existing single-family houses using an easy-to-use simulation, Build. Simul. 8 (2015) 515–528. doi:10.1007/s12273-015-0238-3.

[9] K.H. Kim, J.S. Haberl, Development of a home energy audit methodology for determining energy and cost efficient measures using an easy-to-use simulation: Test results from single-family houses in Texas, USA, Build. Simul. 9 (2016) 617–628. doi:10.1007/s12273-016-0299-y.

[10] C. Xia, Y. Zhu, B. Lin, Building simulation as assistance in the conceptual design, Build. Simul. 1 (2008) 46–52. doi:10.1007/s12273-008-8107-y.

[11] M. Gustafsson, F. Ochs, S. Birchall, G. Dermentzis, C. Bales, C. Dipasquale, T. Calabrese, D2.2 Report on Auditing tool for assessment of building needs. EC FP7 project iNSPiRe Grant agreement no. 314461, 2015. http://www.inspirefp7.eu/wp-content/uploads/2015/10/WP2_D2-2_20151030_PP4_Report-on-Auditing-tool-for-assessment-of-building....pdf.

[12] W. Feist, PHPP - Passive House Planning Package, (1998).

http://passiv.de/en/04_phpp/04_phpp.htm (accessed April 18, 2017).
[13] iNSPiRe EU fp7, European Commission 7th Framework Programme project. Grant agreement no. 314461; Title: Development of Systematic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems; Duration: 2012-10-01...2016-09-30.
[14] D. Siegele, Measurement and Simulation of the Performance of a Façade-integrated MVHR with Micro Heat Pump. Master Thesis, 2015.
[15] S. Birchall, I. Wallis, D. Churcher, S. Pezzutto, R. Fedrizzi, E. Causse, D2.1a - Survey on the energy needs and architectural features of the EU building stock. EC FP7 project iNSPiRe Grant agreement no. 314461, 2014. http://www.inspirefp7.eu/wp-content/uploads/2014/08/WP2_D2.1a_20140523_P18_Survey-on-the-energy-needs-and-architectural-features.pdf.
[16] MathWorks, Matlab 2013a. https://de.mathworks.com/products/matlab.html (accessed April 18, 2017).
[17] B. Hafner, Carnot Toolbox, (2012). https://fh-aachen.sciebo.de/index.php/s/0hxub0iIJrui3ED.
[18] T. Afjei, R. Dott, A. Genkinger, Wärmepumpe und Solarthermie – Kurzberichte zu den Projekten SOFOWA und EFKOS, 18. Tagung Des BFE-Forschungsprogramms Wärmepumpen Und Kälte, 27. Juni 2012, HTI Burgd. (2012) 76–87.
[19] F. Ochs, G. Dermentzis, D. Siegele, W. Feist, Feasibility of a Micro-heat Pump - Energy Performance Simulations, in: Adv. Build. Ski. 2014 - Conf. Proc. 9th ENERGY FORUM, Bressanone, Italy, 2014: pp. 817–832.
[20] E. Leonardi, Micro-Heat Pump for a Renovated Multi Family House – Simulation Based Analysis of the Performance and Thermal Comfort. Master Thesis, 2015.
[21] S.A. Klein, A. Beckman, W. Mitschell, D. A., TRNSYS - A TRaNsient SYstems Simulation program, (2011).
[22] G. Dermentzis, F. Ochs, W. Feist, Calculation of primary energy and seasonal performance factor of heat pump in a Passive House (Internal document PHI), 2012.
[23] P. Strachan, K. Svehla, I. Heusler, M. Kersken, Whole model empirical validation on a full-scale building, J. Build. Perform. Simul. 9 (2016) 331–350. doi:10.1080/19401493.2015.1064480.
[24] C. Bisanz, Heizlastauslegung im Niedrigenergie- und Passivhaus, Darmstadt, Germany, 1999.
[25] S. Peper, W. Feist, Energy efficiency of the Passive House Standard: Expectations confirmed by measurements in practice, Darmstadt, Germany, 2015. http://www.passiv.de/downloads/05_energy_efficiency_of_the_passive_house_standard.pdf (accessed May 26, 2017).
[26] D. Johnston, D. Farmer, M. Brooke-Peat, D. Miles-Shenton, Bridging the domestic building fabric performance gap, Build. Res. Inf. 44 (2016) 147–159. doi:10.1080/09613218.2014.979093.
[27] W. Ebel, M. Großklos, J. Knissel, T. Loga, K. Müller, Wohnen in Passiv-und Niedrigenergiehäusern - Eine vergleichende Analyse der Nutzerfaktoren am Beispiel der ‚Gartenhofsiedlung Lummerlund' in Wiesbaden-Dotzheim,

Darmstadt, Germany, 2003. http://www.iwu.de/fileadmin/user_upload/dateien/energie/neh_ph/endbericht_ph-wiesbaden.pdf (accessed April 18, 2018).
[28] J. Reiß, H. Erhorn, Messtechnische Validierung des Energiekonzeptes einer großtechnisch umgesetzten Passivhausentwicklung in Stuttgart-Feuerbach, Stuttgart, 2003.
[29] W. Feist, T. Loga, M. Großklos, Durch Messungen bestätigt – Jahresheizenergieverbrauch bei 22 Passivhäusern in Wies-baden unter 15 kWh/$m^2$ Wohnfläche, BundesBauBlatt. 3 (2000) 23–27.
[30] S. Peper, W. Feist, O. Kah, Messtechnische Untersuchung und Auswertung – Klimaneutrale Passivhaussiedlung Hannover Kronsberg, 2001. http://passiv.de/downloads/05_cepheus_19_messung.pdf (accessed July 6, 2017).
[31] W. Feist, Thermische Gebäudesimulation: kritische Prüfung unterschiedlicher Modellansätze, C.F. Müller, 1994.
[32] J. Schnieders, A. Hermelink, CEPHEUS results: measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building, Energy Policy. 34 (2006) 151–171. doi:10.1016/j.enpol.2004.08.049.

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