D2.2 Report on Auditing tool for assessment of building needs

Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems

iNSPiRe
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1 Introduction

Energy audits are the first step towards increased energy efficiency in buildings. Through analysis of the building's energy consumption, an energy audit provides a foundation for the identification of energy conservation opportunities and the choice of appropriate energy conservation measures.

Energy auditing tools can offer support in the assessment and planning process of new and renovated building aiming to achieve high energy efficiency.

Task 2.4 of the iNSPiRe project comprised three subtasks, all involving numerical simulations:

- The first subtask focused on developing detailed and validated models of the primary target buildings as well as demo cases buildings for further use in other WPs (WP3, 4 and 6). This was reported on in an earlier WP1 deliverable, D2.1c.

- The second focused on complementing the missing information from the open literature in terms of energy needs for the addressed building stock. This involved developing an innovative approach based on the numerical detailed simulation of the primary target buildings. This deliverable is reported through the database on the iNSPiRe website.

- The third involved the development of an easy-to-use energy auditing tool that will be used as guidance for planners, designers and other stakeholders to find optimal solutions for future renovation projects. This involved the selection and modification of an existing tool to meet the iNSPiRe requirements. It will also be tested using the target and demo-case buildings and the renovation kits developed within iNSPiRe.

This report (D2.2) covers the work associated with this third subtask and includes:

- A review over existing energy auditing tools in Europe

- The development of an energy auditing tool, including modifications to the selected tool, calibration and validation.
2 Energy audit of buildings

Although the degree of complexity of energy audits can vary from one case to another, every audit typically involves the following steps:

- Data collection and review
- System survey and measurements
- Observation and review of operating practices
- Data analysis

The scope of a building energy audit of buildings may also include recording various characteristics of the building envelope, such as the area and the overall heat transfer coefficient (U-value) of different building parts. Furthermore, the air leakage through the building envelope, which is strongly affected by window construction and quality of door seals, should be measured or estimated. The goal is to quantify the building's overall thermal performance, which can then be used to estimate the energy demand. The accuracy of this estimation can be greatly improved if energy billing history and local temperature recordings are available. The audit may also assess the efficiency, physical condition and programming of mechanical systems such as the heating, ventilation, air conditioning equipment and thermostat.

2.1 Energy auditing process

The course of an energy audit can be divided into four stages:

1. Benchmarking
2. Pre-audit/Inspection
3. Detailed audit
4. Investment grade audit

In the first stage, the building performance is assessed through comparison between the actual energy consumption of the building, derived from energy bills, and a reference consumption level for that building type. It is also possible to compare the measured values to a computer model, thus avoiding the need to normalize the values to fit the reference case. This model can then further be used in stage two, where the installed systems and their respective energy consumption are studied. Building and system models are then calibrated against the actual energy consumption and are used to provide better understanding of the building's performance, operating patterns and occupant behavior. They can also be used to identify the required measurements to be performed in stage three. In the detailed audit stage, on-site measurements, sub-metering and monitoring data are used to refine the calibration of the models. This includes comprehensive mapping of the operating characteristics of all energy consuming systems, as well as investigation of situations that cause variations in the load profile on short or long term basis (e.g. daily, weekly, monthly, annual). When the calibration criteria are satisfied, the results provided by the models can be used to assess the selected energy conservation opportunities and measures in stage four.
2.2 Energy auditing tools

A number of software or tools exist that facilitate the energy auditing process. These have various areas of application and include:

- Calculation tools
  - Monthly data
  - Hourly data
- Energy certification tools
- Energy simulation tools
  - Buildings
  - Mechanical systems (HVAC)
- Building physics tools
  - Building envelope
  - Thermal bridges
  - HVAC
  - Lighting

Some of these tools have other applications which go beyond the scope of the energy audit, including indoor air quality, solar/climate analysis, ventilation/airflow, water conservation, atmospheric pollution.
3 Review of existing auditing tools

A survey was undertaken to review the existing tools/software for energy auditing or energy certification used across the EU-27 (country by country), as well as building energy calculation and simulation tools used globally. This was followed by the choice of a suitable tool for the purposes of the project. The results of the review are presented in Annex I, sections 6.1 and 6.2.

3.1 Scope of the review

The scope of this review included an assessment of:

- Language
- Application (residential, non-residential or both)
- Flexibility/Possibility of modification/Open source code
- Accessibility and cost
- Time resolution of calculations (annual, monthly, daily, hourly, dynamic)
- Expertise required
- Inputs and outputs
- Computer platform/Programming language
- Recently updated

3.2 Choice of tool

Some tools were excluded from the final selection. Reasons for this included:

- The software was available in local language only
- The software offered limited area of use
- The software was not possible to modify
- The software required a high level of expert knowledge to use

As the basis for the auditing tool, PHPP (Passive House Planning Package) [1] from the German Passive House Institute was selected. The reasons for selection were:

- It is available in English
- It includes monthly balance calculation
- Residential buildings can be assessed
- It is not freeware but inexpensive (400 euro for a license)
- It is a familiar tool for project partner UIBK
- It is based on MS Excel – easy to install and to use
• The new version of the tool is imminent, which will include economic calculation and possibility for parametric analysis

• UIBK have collaborated with the Passive house Institute and have been given permission to modify PHPP within the framework of the iNSPiRe project
4 Development of auditing tool

Following the review, the chosen tool (PHPP) was modified to meet the needs of the iNSPiRe project. It was then calibrated and validated against TRNSYS [2] and MATLAB Simulink [3] to ensure accurate results within the range of application.

4.1 Features of PHPP

PHPP is an easy-to-use planning tool for energy efficient buildings, intended for architects and planning experts. The reliability of the calculation results and ease of use of this planning tool has already been experienced by several thousand users. PHPP allows easy planning of passive houses, NZEBs or renovations, e.g. according to the EnerPhit standard [4].

PHPP offers a broad range of features for building energy calculations, including calculation of heating and cooling demand, heating and cooling load, passive components database (opaque, transparent, frame, thermal bridge), shading, ground losses and DHW losses (distribution/storage).

The calculation of heating and cooling demand is based on EN ISO 13790 [5] and is presented as a monthly balance. Heating and cooling loads are calculated as the maximum average over 24 hours for two design days each. For heating, one cold and sunny day and one mild and cloudy day are selected for calculation. For cooling, the two days used for calculation are the day of the year with the highest temperature (but not necessarily the highest solar radiation) and the day with the highest solar radiation (but not necessarily the highest temperature). In contrast to the heating design days, where the design days are selected based on a building simulation, the cooling design days are selected by analyzing hourly climate data. Design data is on the safe side as building dynamics are not taken into account.

The energy and HVAC system components include boilers, heat pumps (air/ground source), MVHR, compact units solar PV and solar thermal. The compact unit is a combined heat pump and air-to-air heat exchanger unit, which delivers space heating through the ventilation air as well as domestic hot water (see section 4.3.2). Other heat pump applications in PHPP are based on the compact unit calculation sheet and algorithms, with improved flexibility regarding sources (air, water, brine), sinks (air, water), functionality (space heating, domestic hot water), heating distribution system (air heating, floor heating, radiators), storage and control strategies.

There are also some limitations to the tool:

- Zoning – the building is modelled as a single zone
- Cooling – the accuracy of cooling load calculations requires validation
- Daylighting
- Control optimization
- Large solar systems (large storage)
- Combined solar and heat pump systems (series, parallel)
- Sorption heat pump and multi-split heat pump – to be added in future versions
4.2 Calibration of heating and cooling demand

In order to ensure good precision in the calculations of heating and cooling demand for the whole range of buildings and climates used within the iNSPiRe project, PHPP was compared against transient simulation with TRNSYS 17.

4.2.1 Single zone residential building

The model used in the comparison for a single zone building represents a detached single family house (SFH) with two floors and with a total living area of 97.2 m$^2$ an unheated cellar below the ground floor. It was previously defined within the iNSPiRe project as a typical European single family house [6]. Error! Reference source not found. shows a sketch-up model of the SFH implemented in Google Sketch-up using TRNSYS plug-in. In the calibration process, the whole house was modelled as a single zone in both TRNSYS and PHPP.

The house has external shading device on the windows, and is oriented is 45° toward East. The tilted saddle roof has slope angle of 30°. In this study, in contrast to [6], balcony and reveal shading are not considered, for sake of simplicity. In the TRNSYS model, the thermal capacitance of the zone was incremented 20 times compared to the default value in order to account for additional capacitance of furniture, carpet, etc.

![Figure 1: Google Sketch-up model of the single family house in the single zone residential building comparison](image)

For the TRNSYS model, some parametric studies were performed to investigate the influence of shading and ventilation control and the use of operative temperature instead of convective to control heating and cooling. This analysis is found in Annex III.

**Boundary conditions**

The heating and cooling demands were calculated with a set point temperature of 20 °C for the winter and 25 °C for the summer, respectively. The control of the (ideal) cooling and (ideal) heating was based on the convective zone temperature. Climate data for seven different European locations was used, covering a wide range of climatic conditions in terms of heating
and cooling degree days per year. The locations used were: Stockholm, Sweden; Gdansk, Poland; London, UK; Stuttgart, Germany; Lyon, France; Madrid, Spain; and Rome, Italy.

The calibration was performed for three levels of heating demand (HD) for each climate:

- the existing building – before renovation (“EX”)
- renovation to reach HD of 45 kWh/(m²·a) (“45”)
- renovation to reach HD of 25 kWh/(m²·a) (“25”)

For the renovated cases, windows were replaced by 2- or 3-pane windows with a corresponding quality of frame (good or high quality). An insulation layer with a conductivity of 0.04 W/(m·K) was added to the external surfaces (external walls, ground and roof) in order to reach the appropriate energy level (as shown in Table 1). Furthermore, mechanical ventilation with heat recovery (MVHR) with efficiency of 0.85 was used if applicable (see Table 5).

For all the investigated existing buildings (7 cases), the construction data (i.e., wall layers, window quality) are defined within iNSPiRe based on statistical data for the U-values. The appropriate insulation thickness to reach the renovation standard is calculated using PHPP. Pre-defined assumptions (i.e., for windows, frame, MVHR) are used based on experience and are explained in the further paragraphs.

Table 1: Insulation thickness [cm] depending on climate and building energy level

<table>
<thead>
<tr>
<th></th>
<th>WALLS</th>
<th>GROUND</th>
<th>ROOF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>45</td>
<td>EX</td>
</tr>
<tr>
<td>STO</td>
<td>40</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>GDA</td>
<td>36*</td>
<td>12.4</td>
<td>0</td>
</tr>
<tr>
<td>STU</td>
<td>24</td>
<td>21.4</td>
<td>0</td>
</tr>
<tr>
<td>LON</td>
<td>16.5</td>
<td>12.9</td>
<td>0</td>
</tr>
<tr>
<td>LYO</td>
<td>12.8</td>
<td>8.7</td>
<td>0</td>
</tr>
<tr>
<td>MAD</td>
<td>8.9</td>
<td>6.3</td>
<td>0</td>
</tr>
<tr>
<td>ROM</td>
<td>3</td>
<td>7.5</td>
<td>0</td>
</tr>
</tbody>
</table>

*Remark: In order to avoid an error in TRNSYS for the renovated case with a heating demand of 25 kWh/(m²·a) in the climate of Gdansk, it was necessary to modify the wall construction of the external wall in TRNSYS. Polystyrene with 0.035 W/ (m·K) instead of polystyrene with 0.040 W/ (m·K) with the corresponding thickness to obtain the required heating demand was chosen.

Figure 2 shows the U-values for the existing buildings (EX) for walls, roof and ground floor implemented in TRNSYS.
Three different quality levels of windows (and also one model for the door) were defined, as shown in Table 2. The overall heat transfer coefficient of the frame include the linear between glass and frame as well as the installation thermal bridge. The door is modelled as a window with a frame ratio of 99% with a U-value corresponding to the definitions in the PHPP ($U_{\text{door}} = U_{\text{window}} + 0.2 \text{ W/(m}^2\cdot\text{K)}$).

**Table 2: Windows defined in PHPP and TRNSYS for the SFH**

<table>
<thead>
<tr>
<th></th>
<th>GOOD</th>
<th>MEDIUM</th>
<th>POOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{\text{glass}}$ (W/m$^2$K)</td>
<td>0.59</td>
<td>1.4</td>
<td>2.83</td>
</tr>
<tr>
<td>$U_{\text{frame}}$ (W/m$^2$K)</td>
<td>1.93</td>
<td>3.34</td>
<td>4.2</td>
</tr>
<tr>
<td>$U_{\text{window}}$ (W/m$^2$K)</td>
<td>0.86</td>
<td>1.79</td>
<td>3.10</td>
</tr>
<tr>
<td>$R_{\text{frame}}$ (m$^2$K/W)</td>
<td>0.52</td>
<td>0.30</td>
<td>0.24</td>
</tr>
<tr>
<td>$1/R_{\text{frame TRN}}$ (KJ/(hr*m$^2$K))</td>
<td>10.34</td>
<td>27.82</td>
<td>52.87</td>
</tr>
</tbody>
</table>

*Internal and external heat transfer resistance are not included*

PHPP was utilized to determine the required qualities for each building heating demand level depending on the climate, as shown in Table 3.
Table 3: Windows quality (glass and frame) depending on climate and heating demand level

<table>
<thead>
<tr>
<th>Region</th>
<th>25</th>
<th>45</th>
<th>EX</th>
</tr>
</thead>
<tbody>
<tr>
<td>STO</td>
<td>GOOD</td>
<td>GOOD</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>GDA</td>
<td>GOOD</td>
<td>GOOD</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>STU</td>
<td>GOOD</td>
<td>GOOD</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>LON</td>
<td>GOOD</td>
<td>GOOD</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>LYO</td>
<td>GOOD</td>
<td>GOOD</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>MAD</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>ROM</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
</tr>
</tbody>
</table>

Internal gains were divided into gains from persons, based on the IEA SHC Task 44 occupation profile [7], and from electrical appliances. The investigated SFH was assumed to have occupancy heat gains of 2.4 W/m² and electrical gains of 1.6 W/m², giving a total of 4 W/m². It was assumed that 60% of this is distributed by convection and 40% by radiation. Internal humidity sources of 1.84 g/(m²·h) are used. For dehumidification, the maximum indoor absolute humidity is set to 12 g/kg, corresponding to 60% relative humidity for 25 °C cooling set point temperature.

Table 4 shows the effective values of infiltration and n_50-values according to blower-door test, depending on climate and building energy level. These values were defined in PHPP with internal calculation with (wind protection coefficients e = 0.07 and f = 15).

Table 4: Infiltration rate [1/h] based on PHPP calculation depending on climate and energy level

<table>
<thead>
<tr>
<th>ENERGY LEVEL</th>
<th>Infiltration rate [1/h]</th>
<th>n_50 rate [1/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>STO</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>GDA</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>STU</td>
<td>0.07</td>
<td>0.006</td>
</tr>
<tr>
<td>LON</td>
<td>0.07</td>
<td>0.006</td>
</tr>
<tr>
<td>LYO</td>
<td>0.07</td>
<td>0.006</td>
</tr>
<tr>
<td>MAD</td>
<td>0.07</td>
<td>0.006</td>
</tr>
<tr>
<td>ROM</td>
<td>0.07</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Mechanical ventilation was considered for all building standards with an air change rate of 0.40 /h, while heat recovery was considered only for those buildings renovated to 25 kWh/(m²·a) and for Nordic and Northern Continental climates for the 45 kWh/(m²·a) (see Table 5).

The effective air change rate for mechanical ventilation was calculated in TRNSYS according to:

\[ n_{\text{mech,eff}} = n_{\text{mech}} \cdot (1 - \eta_{\text{PHI}}) \]
where $n_{mech,eff}$ is the effective ventilation air rate, $n_{mech}$ is the ventilation air rate (0.4 l/h) and $\eta_{PHI}$ is the heat recovery efficiency.

**Table 5: Efficiency of heat recovery depending on climates and heating demand level**

<table>
<thead>
<tr>
<th></th>
<th>25</th>
<th>45</th>
<th>EX</th>
</tr>
</thead>
<tbody>
<tr>
<td>STO</td>
<td>0.85</td>
<td>0.85</td>
<td>0</td>
</tr>
<tr>
<td>GDA</td>
<td>0.85</td>
<td>0.85</td>
<td>0</td>
</tr>
<tr>
<td>STU</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LON</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LYO</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>MAD</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ROM</td>
<td>0.85</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

In both models, the heat recovery system was bypassed during the summer in all climates and building energy levels (where active).

An unheated cellar below the ground floor was considered. Thermal bridges were calculated depending on the presence of wall, ground and cellar wall (perimeter) insulation. In the TRNSYS building model the ground floor is coupled with the ground temperature (boundary surface). The monthly ground temperatures were derived from PHPP for each case, based on EN ISO 13370 [8]. These temperatures were interpolated in TRNSYS to obtain the hourly ground temperature.

In PHPP, external wall dimensions were used, while in TRNSYS internal wall dimensions were used. To account for this difference, additional thermal bridge coefficients were calculated in TRNSYS. Thermal bridges were separated to those with losses toward the ground and those with losses toward the ambient. Additionally, thermal bridges are defined for the ground losses via the cellar-wall junction. The linear thermal transmittance to the ambient (ext) and to the ground (here: to the cellar) were defined as follows:

$$\psi^{TRNSYS}_{ext} = \frac{(U \cdot A)^{PHPP}_{ext} - (U \cdot A)^{TRNSYS}_{ext}}{L_{ext}}$$  \hspace{1cm} (2)

$$\psi^{TRNSYS}_{gr} = \frac{(U \cdot A)^{PHPP}_{gr} - (U \cdot A)^{TRNSYS}_{gr}}{L_{gr}}$$  \hspace{1cm} (3)

where $L_{ext}$ is the thermal bridge length toward the ambient [m] and $L_{gr}$ toward the ground [m], $(U \cdot A)^{PHPP}_{ext}$ and $(U \cdot A)^{TRNSYS}_{ext}$ are the transmission losses toward the ambient per unit of temperature in the PHPP and TRNSYS model [W/K], respectively, and $(U \cdot A)^{PHPP}_{gr}$ and $(U \cdot A)^{TRNSYS}_{gr}$ are the transmission losses toward the ground per unit of temperature in the PHPP and TRNSYS model [W/K], respectively.
Remark: In case of theoretically possible negative thermal bridges, it has to be set to zero as negative values are not accepted by TRNSYS; here, only very small negative thermal bridges occurred, so the error of this simplified approach is negligible.

External shading was assumed for all climates. For sake of simplicity, the balcony and the reveal shadings were not considered for shading, only the roof overhang.

In the PHPP the shading was implemented with a fixed reduction factor for temporary sun protection of 0.3 (70% of solar radiation is blocked) activated during the summer (i.e. non-heating period). In the TRNSYS model an external shading with a fixed factor of 0.7 (70% of the solar radiation is blocked) was implemented and activated during the summer (i.e. non-heating period).

**TRNSYS simulations**

PHPP, heating and cooling demand were calculated independently using two separate algorithms (one for the heating period and one for the cooling period). Thus, external shading and HR can vary during “winter” and “summer” (e.g., shading is ON only for the cooling calculations and does not affect heating calculation).

In the TRNSYS model, two sets of simulations were performed with a “simplified approach” for the external shading and the heat recovery by-pass during the summer; namely:

1. Heat recovery is switched ON all the year (if applicable, see Table 5) and the external shading is switched OFF all the year, similar to PHPP approach for heating
2. Heat recovery is switched OFF all the year and the external shading is switched ON all the year (with a shading factor of 0.7), similar to PHPP approach for summer overheating protection

The results for heating demand and heating load were taken from the first set of simulations, while the results for cooling demand and cooling load were taken from the second set of simulations and compared with the PHPP results.

**Detailed comparison – Case study for STU_25**

Figure 3 and Figure 4 show the monthly heating demand (HD) and cooling demand (CD), respectively, for TRNSYS and PHPP for the case STU_25. The monthly values for HD are always (except in March) higher in PHPP, while for the CD the monthly values are always (except in July) higher in TRNSYS. The higher value of PHPP for the monthly CD in July is due to particular algorithms present in the PHPP that overestimate the CD to be on the safe side. With this safety factor, the CD has good agreement on annual basis.

Remark: Distributing this safety factor to the all months in the (main) cooling period would also lead to an acceptable agreement on monthly basis. This approach is just being discussed.
Figure 3 shows the monthly transmission losses for both models for STU_25. In order to compare the monthly values between the two tools for transmission losses, it was necessary to define in TRNSYS the “winter” and “summer” period depending on the monthly values of heating and cooling demand. Thus, the year (similarly to PHPP algorithms) was split in two periods: cooling period (April-September) and heating period (October-December and January-March) and the monthly values of TRNSYS results were taken from the second set of simulations and first set of simulations, respectively. The same procedure was executed for
the comparison of monthly air losses and solar gains. In the heating period, the absolute values of the relative deviations were below 20%; in the non-heating period, the agreement is not as good as for the heating period and the absolute values of the relative deviations are above 75%. The higher values of monthly transmission losses in PHPP for all months (except October) are corresponding to the higher monthly HD and the lower CD. The high deviations between TRNSYS and PHPP in April and September can be explained with the profile of the internal temperature (i.e. convective temperature of the building zone). In PHPP, the internal temperature is assumed to be 20 °C in the winter season and 25 °C and in summer season; no transition season exists in PHPP. Thus, in periods where there is 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.

Figure 5: Monthly transmission losses – Comparison TRNSYS/PHPP

Figure 6 shows the monthly air losses (ventilation + infiltration) for both models. The absolute values of the relative deviations are, in many months, below 5%. In the months of April and September, the same considerations as for the transmission losses apply.
Figure 7 shows the monthly solar gains for both models. Generally, the agreement is good and the absolute value of the relative deviations is below 6% in the most of months. In January, the relative deviation is 18%. The lower solar gains during the summer period are a result of the activation of the external shading control in both models that blocks the 70% of the solar radiation.

PHPP delivers slightly higher values than TRNSYS for the monthly heating demands (see Figure 3, in particular the period November-February). This can be explained by the higher
monthly transmission losses (see Figure 5) and the lower monthly solar gains (see Figure 7) in PHPP. In the same way, the higher values of TRNSYS compared to PHPP for the monthly cooling demand (see Figure 4) can be explained with the lower monthly transmission losses and the higher monthly solar gains.

Figure 8 shows the TRNSYS average daily heating load (HL) and the PHPP HL for the case STU_25. The heating period calculated with TRNSYS is approximately 140 days and the maximum daily heating load is 1581 W (16.27 W/m²). The maximum daily HL calculated with PHPP is 2187 W (encircled in the figure) with a relative deviation - compared to TRNSYS – of 38%.

PHPP uses specific algorithms to calculate the heating and cooling demand and the heating and cooling load. The annual heating demand is calculated in according to the “monthly method” of the EN ISO 13790 [9], where the energy balance is calculated for each month. This calculation method is a semi-dynamic method and it does not fully consider thermal storage effects. The maximum HL is calculated considering the maximum value between two different HL values calculated in different weather situations: cold but sunny winter day and moderately cold but overcast day. The calculation of the heating load in PHPP is on the safe side by purpose. This aspect is very important because, in the PHPP, the maximum daily heating load is used to estimate the performances of the heating system.

Figure 9 shows the TRNSYS average daily cooling load (CL) and the PHPP CL for the case STU_25. The TRNSYS cooling period is approximately 100 days; similarly to the heating load, the PHPP maximum daily CL (1040 W, encircled in the figure) is higher compared to TRNSYS (900 W) with a relative deviation of 15%.

Figure 8: TRNSYS daily heating load and PHPP heating load
Figure 9: TRNSYS daily cooling load and PHPP cooling load

Figure 10: Heating demand and absolute deviation in TRNSYS/PHPP
Comparison for all cases

Figure 10 shows the heating demand calculated in TRNSYS and PHPP and their absolute deviations for all cases. In the renovated cases the absolute values of the deviations are below 5 kWh/(m²·a), except for MAD_45 and ROM_45; in these cases (i.e. renovated cases), the agreement is better for the climates of GDA, STU, LON and LYO, where the absolute values of the deviations are below 3.23 kWh/(m²·a). Generally, for the existing cases, the absolute deviations are higher compared to the renovated cases, but the relative deviations are lower and in absolute value below 7% (except for STO_EX where the relative deviation is 21%). The existing case for the climate of Stockholm are worth further investigation because of the higher absolute deviation (33.45 kWh/(m²·a)) compared to the all others cases.

Figure 11 shows the comparison between TRNSYS and PHPP (with relative deviation) for the cooling demand. For the colder climates (STO, GDA, STU and LON), the CD is insignificant, and thus the comparison between the two tools is meaningless. For the warmer climates (LYO, MAD and ROM) the absolute values of the relative deviations are below 27%. In these climates the absolute values of the absolute deviations are below 4.3 kWh/(m²·a), except for ROM_45 where the absolute deviation is almost 6 kWh/(m²·a). Generally, the cooling demand profile is reasonable, but the agreement is not as good as for the heating demand.

Figure 12 shows the maximum daily heating load and the relative deviations between TRNSYS and PHPP. PHPP has the higher heating load in all cases except STO_EX. The HL calculations of PHPP are on the safe side by purpose for the design of the heating system. Generally, the agreement is better in the renovated cases - compared to the non-renovated cases – where the absolute values of the absolute deviations are below 6.2 W/m² (except in the climate of Rome). In the “45” and non-renovated cases, the absolute values of the relative
deviations are below 19%. In all the cases of ROM, the absolute values of the relative deviations are above 37%.

![Figure 12: Maximum daily heating load and relative deviations TRNSYS/PHPP](image)

![Figure 13: Maximum daily cooling load and relative deviations TRNSYS/PHPP](image)
Figure 13 shows the maximum daily cooling load and the relative deviations between TRNSYS and PHPP. Similarly, to the heating load results, PHPP has higher cooling load than TRNSYS in all cases (except for ROM_45). In the warmer climates (LYO, MAD and ROM), the agreement is better in the renovated cases - compared to the non-renovated cases – where the relative deviations are below 23%. In the non-renovated cases of the warmer climates, the absolute values of the absolute are above 10.6 W/m².

Figure 14 shows the correlation between the HL and HD. Generally, there is an overestimation in the PHPP compared to TRNSYS; in the case of ROM_EX, the PHPP heating load is not close to the value coming from the linear approximation.

Conclusions

For the cooling demand, the agreement is not as good as for the heating demand, but still acceptable on an annual basis. In the warmer climates (LYO, MAD and ROM), the absolute values of the relative deviations are below 27%. In these climates, the agreement is better in the renovated cases compared to the non-renovated cases, with absolute values of the deviations below 2.8 kWh/(m²·a) (except for ROM_45). The monthly values of the CD in PHPP should not be taken for detailed analysis because of the safety factor in the algorithm which leads to an overestimation in the warmest month.

For the maximum daily heating and cooling load, PHPP has higher values compared to TRNSYS in the majority of cases. For the heating load, the agreement is better in the renovated cases compared to the non-renovated cases, with the absolute values of the deviations are below 6.2 W/m² (except in the climate of Rome). For the cooling load, in the warmer climates (LYO, MAD and ROM), the comparison is better in the renovated cases (relative deviations below 23%) compared to the non-renovated cases (relative deviations above 22%). For these climates, in the renovated cases the absolute values of the deviations are below 3.6 W/m².
4.2.2 Multi-zone office building

The multi-zone building comparison was performed for an office building with five floors and a floor area of 810 m² (“small”) or 1620 m² (“large”) per floor. The PHPP model had only one zone, while in TRNSYS the building was modelled with two zones per floor, one on the southern and one on the northern long sides of the building, and three floors: ground floor, middle and top floor (see Figure 15). Outputs for the middle floor were then multiplied by three to represent the other two middle floors. Walls and floors separating the zones were modelled as adiabatic. The thermal capacitance of the zone was incremented 10 times to account for additional capacitance of furniture. The building was oriented 45° towards East.

![Figure 15: Office building models used in TRNSYS. Left: “small” office building; Right: “large” office building.](image)

**Boundary conditions**

The comparison was done for seven European climates: Stockholm, Sweden; Gdansk, Poland; London, UK; Stuttgart, Germany; Lyon, France; Madrid, Spain; and Rome, Italy. Two construction types were modelled for each climate, representing different construction periods: 1945-1970 (“period I”) and 1980-1990 (“period III”). U-values of building parts and g-values of glazing are shown in Table 6. The glazing ratio of the external walls was set to 30% for period I and 60% for period III. The windows had a frame ratio of 20%, and the listed U-values include both glazing and frame.

Heating and cooling demands and loads were calculated with set points of 21 °C for heating and 25 °C for cooling, respectively. The control of the (ideal) cooling and (ideal) heating was based on the convective zone temperature.

Ground coupling was modelled according to EN ISO 13370 [8] for slab-on-grade, with monthly average values of the disturbed ground temperature in PHPP and hourly profiles, generated from the PHPP values, in TRNSYS.
Table 6: U-values of walls, ground floor and roof and g-values of glazing for all climates and construction periods, as implemented in TRNSYS

<table>
<thead>
<tr>
<th></th>
<th>Ext. walls</th>
<th>Ground floor</th>
<th>Roof</th>
<th>Windows</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U [W/(m²·K)]</td>
<td>U [W/(m²·K)]</td>
<td>U [W/(m²·K)]</td>
<td>g [%]</td>
</tr>
<tr>
<td>STO</td>
<td>1945-1970</td>
<td>0.54</td>
<td>0.40</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>0.36</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>GDA</td>
<td>1945-1970</td>
<td>1.19</td>
<td>1.07</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>0.64</td>
<td>0.89</td>
<td>0.44</td>
</tr>
<tr>
<td>STU</td>
<td>1945-1970</td>
<td>1.44</td>
<td>1.31</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>0.80</td>
<td>0.51</td>
<td>0.50</td>
</tr>
<tr>
<td>LON</td>
<td>1945-1970</td>
<td>1.74</td>
<td>1.55</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>0.83</td>
<td>1.12</td>
<td>0.65</td>
</tr>
<tr>
<td>LYO</td>
<td>1945-1970</td>
<td>2.06</td>
<td>1.66</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>1.15</td>
<td>0.93</td>
<td>0.83</td>
</tr>
<tr>
<td>MAD</td>
<td>1945-1970</td>
<td>2.17</td>
<td>2.38</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>1.74</td>
<td>0.80</td>
<td>1.39</td>
</tr>
<tr>
<td>ROM</td>
<td>1945-1970</td>
<td>1.78</td>
<td>0.76</td>
<td>2.07</td>
</tr>
<tr>
<td></td>
<td>1980-1990</td>
<td>0.80</td>
<td>0.60</td>
<td>1.69</td>
</tr>
</tbody>
</table>

Internal gains from people, appliances and lights were set to “on” (1) or “off” (0) according to a schedule, as shown in Figure 16. The office was assumed to be occupied from 9 a.m. to 6 p.m. every Monday-Friday with exception for lunch, two weeks holiday in summer and some days around Christmas and New Year. In PHPP, monthly average values were used. One person per 9 m² was considered, each contributing 120 W of heat, corresponding to activity level “seated, very light writing” according to ISO 7730 [10]. The contributions from appliances and lights were 12.5 W/m² and 25 W/m², respectively.

Figure 16: Schedules for presence of people, appliances and lights and ventilation in the office building
The mechanical ventilation supplied 40 m³/h per person and was activated during office hours +1 hour before and 1 hour after (see Figure 16). In addition, a constant infiltration rate of 0.15 h⁻¹ was used.

External shading was used for all climates and building types, with a shading factor of 0.7, i.e. blocking 70% of the incoming radiation. In PHPP, a constant shading factor was used during the cooling period, while in TRNSYS the shading was activated when the total radiation on the respective wall exceeded 100 W/m² (deactivated when <50 W/m²), the convective temperature in the zones was greater than 24 °C (deactivated when <23 °C) and the 24 hour moving average ambient temperature was above 12 °C.

**Results of the comparison**

Figure 17 shows the heating demand and relative difference in TRNSYS and PHPP for all building types and climates. The agreement is within ±10% for the period I buildings, both the small and the large and for all climates, and for the period III buildings in the colder climates of Stockholm, Gdansk and Stuttgart. The heating demand is, in most cases, slightly higher in TRNSYS than in PHPP. The difference is particularly large for the period III buildings in the warmer climates of London, Lyon, Madrid and Rome. Besides the lower U-values of the building envelope, the period III building also has twice as large windows as the period I building. This increases the influence of on the one hand the solar gains and shading control, on the other hand the heat transfer through the windows, which in all cases have higher heat transfer coefficients than the walls.

![Figure 17: Heating demand in TRNSYS and PHPP for all climates and building types](image-url)
Figure 18 shows the cooling demand and relative difference in TRNSYS and PHPP for all building types and climates. Here, there are only a few cases where the relative difference between TRNSYS and PHPP is within ±10%. In absolute numbers, however, the agreement is good in all cases except in the warmer climates of Lyon, Madrid and Rome, where PHPP calculates a much higher cooling demand than TRNSYS.
Figure 19 shows the heating load and relative difference in TRNSYS and PHPP for all building types and climates. PHPP calculates a higher heating load than TRNSYS for all cases, the relative difference ranging from 5% for Madrid I_small to 38% for Rome III_large. In absolute numbers, the difference is around 10 W/m² in most of the cases.

Figure 20 shows the cooling load and relative difference in TRNSYS and PHPP for all building types and climates. In most cases, PHPP gives a higher cooling load than TRNSYS. Exceptions are found in the climate of Stockholm, where the TRNSYS cooling load is higher than in PHPP for I_small, I_large and III_large. The absolute differences are relatively low, below 5 W/m², except in the climates of Lyon, Madrid and Rome where they go up to 10-12% for the small buildings.

![Figure 20: Cooling load in TRNSYS and PHPP for all climates and building types](image)

**Conclusions**

For multi-zone building models where the transmission losses are relatively high, i.e. where the U-values of the building envelope are high, there is good agreement between TRNSYS and PHPP in the calculation of annual heating demand. In the other category of office buildings studied, with lower U-values and larger window areas, the influence of solar gains becomes more significant, and the difference between TRNSYS and PHPP increases. The difference is larger in warmer and sunnier climates like Lyon, Madrid and Rome, less apparent in London and negligible in Stockholm, Gdansk and Stuttgart. For the annual cooling demand, the agreement is quite good for Stockholm, Gdansk and Stuttgart, while the relative differences in warmer climates in some cases go up to 40-60%. Regarding heating and cooling loads of the multi-zone building, the agreement between TRNSYS and PHPP is also better for colder climates.
4.3 Validation of energy system applications

The many features and components of PHPP have been validated in previous studies [11-15]. The development of PHPP into an energy auditing tool to meet the requirements set within the iNSPiRe project included validation of new energy system applications, specifically heat pumps and solar thermal.

4.3.1 Heat pumps

The validation of the PHPP heat pump application was performed for four different systems using several sink temperatures and several heat pump types (Table 7). The sink temperatures correspond to the appropriate heating distribution system. The selected sink temperature ($\theta_{\text{sink}}$) is 24 °C, 28 °C or 35 °C for floor heating, 40 °C for radiators and 55 °C for air heating. The validation models are presented in Table 8. Performance data of the heat pumps were provided by Test Center WPZ [16]. The reference building used was SFH15 from IEA SHC Task 44 [7] adapted to 15 kWh/(m²·a) heating demand in the climate of Innsbruck, Austria. For the validation the calculation results are compared to results from the calculation tool JAZcalc [17], the simulation tool Delphi [18] with daily input data and MATLAB/Simulink using the Carnot blockset [3] with hourly input data (Table 7). Additionally, validation for the reference building is conducted for several climates [19].

**Table 7: Systems and conditions for validation**

<table>
<thead>
<tr>
<th>Case</th>
<th>Functionality</th>
<th>Monovalent / bivalent</th>
<th>$\theta_{\text{sink}}$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heating</td>
<td>Monovalent</td>
<td>[24 28 35 40 55]</td>
</tr>
<tr>
<td>2</td>
<td>DHW</td>
<td>Monovalent</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Heating &amp; DHW</td>
<td>Monovalent</td>
<td>[28 35 40 55]</td>
</tr>
<tr>
<td>4</td>
<td>Heating &amp; DHW</td>
<td>Bivalent</td>
<td>[28 35 40 55]</td>
</tr>
</tbody>
</table>

**Table 8: Models and methods used in the validation**

<table>
<thead>
<tr>
<th>Name in figures</th>
<th>Program platform</th>
<th>Method</th>
<th>Control strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHPP on/off</td>
<td>Excel</td>
<td>Calculation</td>
<td>on/off</td>
</tr>
<tr>
<td>PHPP ideal</td>
<td>Excel</td>
<td>Calculation</td>
<td>ideal</td>
</tr>
<tr>
<td>JAZcalc</td>
<td>Excel</td>
<td>Calculation</td>
<td>on/off</td>
</tr>
<tr>
<td>Delphi</td>
<td>Delphi</td>
<td>Simulation with daily input data (PHI)</td>
<td>on/off</td>
</tr>
<tr>
<td>Simulink</td>
<td>MATLAB/Simulink</td>
<td>Simulation with hourly input data</td>
<td>on/off</td>
</tr>
</tbody>
</table>

**Air-source heat pumps**

In Figure 21, Case 3 (see Table 7) is shown for one of the ten heat pumps. The annual electricity consumption of the system is plotted versus the sink temperature. The agreement
between ‘Simulink’ and ‘PHPP on/off’ is good, whereas the other two methods underestimate the electricity consumption. Their resulting consumption is the range of that of the ‘PHPP ideal’.

Figure 21: Electrical energy consumption of an air-source heat pump for heating and DHW demand (case 3). Example of a single family house (SFH15) of Passive House standard in Innsbruck.

The results of Case 4 for heating and DHW with sink temperature $\theta_{\text{sink}} = 55$ °C are shown for ten heat pumps in Figure 22. The agreement between the ‘PHPP on/off’ and ‘Simulink’ is good for all heat pumps.

Figure 22: Electrical energy consumption of ten bivalent systems (case 4 with $\theta_{\text{sink}} = 55$ °C). Example of a single family house (SFH15) of Passive House standard in Innsbruck.
In Figure 23, the results of Case 1 are presented for sink temperature $\theta_{\text{sink}} = 35 \, ^\circ\text{C}$. The heating distribution system is floor heating without store. The results of ‘PHPP on/off’ are slightly more conservative than ‘Simulink’, except in the climate of Dublin.

Heat pumps with horizontal ground heat exchanger (GHX)

The validation of heat pumps with GHX was performed for the same conditions and cases as for the air source heat pumps (see Table 7). The depth of ground heat exchanger was 1 m. The results for Case 4 are presented in Figure 24. Except for ‘Delphi’, which underestimates the electricity use of the heat pump, all methods deliver similar results.
The results of Case 1 for sink temperature $\theta_{\text{sink}} = 35$ °C and floor heating without store are presented in Figure 25. The agreement is relatively good in all climates. The results are quite similar in Madrid and the results of ‘PHPP on/off’ are slightly more conservative than ‘Simulink’ in the other climates, except for Dublin, Hamburg and Freiburg.

**Heat pumps with vertical ground heat exchanger (VGHX)**

Figure 26 shows the electricity consumption of a heat pump with vertical ground heat exchanger assessed in different climates. The sink temperature is 35 °C and the heating distribution system is floor heating without store (Case 1). In the MATLAB/Simulink platform, the model of CARNOT EWS [20] was used for the validation. The results of ‘PHPP on/off’ are slightly more optimistic than ‘Simulink’ in Thessaloniki, Bolzano, Dresden and Warsaw.
4.3.2 Compact unit – “micro heat pump”

The validation of the compact unit, or micro heat pump (m-HP), was performed with TRNSYS, for a single family house with a heating demand of 25 kWh/(m²·a) (later referred to as “25") for seven different European locations: Stockholm, Sweden; Gdansk, Poland; London, UK; Stuttgart, Germany; Lyon, France; Madrid, Spain; and Rome, Italy. The building model is described in section 4.2.1. A parametric study was performed to investigate the influence of the MVHR effectiveness in the TRNSYS model. Finally, the final energy demand of the m-HP was re-calculated with a modified PHPP, in which the maximum daily HL calculated with TRNSYS was implemented in order to be able to distinguish the deviation due to the algorithm and due to the overestimation of the heating load in PHPP. In addition to the results shown in this section, control optimization of the compact unit in TRNSYS was performed (see Annex IV), as well as an investigation of the influence of maximum heating load calculation in PHPP (see Annex V).

The compact unit is a combined heat recovery unit and heat pump, where the heat pump uses the exhaust air from the heat recovery unit as source. The m-HP is modelled with a performance map using a lookup-table. The performance map (see Figure 27 and Table 9) was developed using a simplified physical model implemented in MATLAB and validated with monitored data coming from the functional model installed at the Innsbruck University [21]. The performance map was obtained with a constant volume air flow rate of 115 m³/h. The heat recovery unit was modelled with an efficiency of 0.85. A back-up electrical heater was applied in both PHPP and TRNSYS when the compact unit heating capacity is not enough to cover the heating load of the house.

![Figure 27: m-HP heating capacity as a function of the air temperature coming into evaporator (exhaust air of the MVHR) for different compressor speeds](image)

**Table 9: Average COP of the m-HP depending on the compressor speed**

<table>
<thead>
<tr>
<th>Compressor speed [rpm]</th>
<th>COP [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>3.22</td>
</tr>
<tr>
<td>2000</td>
<td>3.07</td>
</tr>
<tr>
<td>3000</td>
<td>2.52</td>
</tr>
<tr>
<td>4500</td>
<td>2.03</td>
</tr>
</tbody>
</table>
In PHPP, an algorithm based on the so called “bin method” (see Figure 28 (right)) is used to calculate the electrical consumption of the heat pump and the backup-heater (if present). The load duration curve of the building (i.e. sorted heating power vs. time) is approximated as a linear curve. An example is plotted in Figure 28 together with the heating capacity of a heat pump, which increases with ambient temperature. Both the heating capacity of the heat pump and the load duration curve are approximated with a linear curve. For the linear approximation of the load duration curve (red line in the figure), PHPP calculates the duration of the heating period \( t_{\text{end,heating}} \) using as input the maximum heating load for time equal to zero and the total heating demand (the area of the triangle generated by the red line with the x and y axis). \( Q_{\text{hp (bin)}} \) represents the heating energy covered by the heat pump, while \( Q_{\text{dir}} \) represents the heating energy covered by the electric back-up heater (direct electricity).

The heating load in PHPP is overestimated compared to the simulation results, to be on the safe side for system design. This leads to an underestimation of the heating period and thus, the calculation of direct electricity \( (Q_{\text{dir}}) \) might be overestimated. In addition to this simplified approach of linearizing the load duration curve, there are further aspects which may affect accuracy of the calculation of direct electricity \( (Q_{\text{dir}}) \) such as the capacity of the heat pump and consequently the share of back-up heating, the control strategy and the dimensioning of heat distribution system.

![Figure 28: Simulated and approximated load duration curve and heating capacity of the HP (left) and load duration curve and heating capacity of the HP in the heating period (right) [22]](image)

The “heat pump” sheet of PHPP was modified to be able to calculate the energy performance of the micro-heat pump. The required input data in the modified “heat pump” sheet are the performance map, the temperature efficiency of the heat recovery, as well as the “high” temperature, i.e. sink temperature \( (\theta_{\text{sink_high}}) \), and the “low” \( (\theta_{\text{sink_low}}) \) supply air temperature. The performance map includes the COP and the heating capacity for various test points with the source and sink temperatures as independent variables.

The temperature efficiency of the heat recovery is defined as follows:

\[
\eta_{\text{HX}} = \frac{\theta_{\text{ext}} - \theta_{\text{exh}}}{\theta_{\text{ext}} - \theta_{\text{amb}}} 
\]  

\[ (4) \]
where $\theta_{exh}$ is the exhaust air temperature, $\theta_{ext}$ the extract air temperature (equal to indoor temperature in single zone model), $\theta_{amb}$ is the ambient air temperature and $\eta_{HX}$ the efficiency of heat exchanger, which is varied to match the calculated exhaust air temperature the corresponding temperature derived from the physical MVHR model. The temperature at the test point with the highest RPM and the lowest ambient temperature is defined as “high” supply air temperature while with the lowest RPM and the highest ambient temperature as “low” supply air temperature.

The performance map of the m-HP regarding COP and heating power was derived from a steady state physical model (based on refrigerant cycle) developed in MATLAB [21]. The inlet and outlet air temperatures of the condenser and evaporator as well as the temperatures of the heat recovery are derived from the physical model, too. The physical model is validated against measured data measured at the PASSYS test cells of University of Innsbruck.

Three main modifications were implemented:

1. Source temperature
2. Calculated heating capacity
3. High and low supply air temperature

The exhaust air temperature calculated using equation (4) was used as source temperature instead of ambient air temperature. The calculated heating capacity of the heat pump was modified. The linear approximation approach remained, but was implemented as a function only of the source temperature instead of a function of both source and sink temperature. In the “ideal” control strategy the sink temperature was calculated based on the building heating load.

![Figure 29: COP of the m-HP derived from physical model [21] for various compressor speed and COP calculated by the PHPP the “low” and “high” working supply air temperature](image)
The “high” supply temperature is highest working supply temperature at the maximum heating load and is hence defined as the temperature at the test point with the highest compressor speed and the lowest ambient temperature, while the “low” supply temperature is the supply temperature at the lowest possible heating load. Hence, the test point with the lowest compressor speed and the highest ambient temperature was used. The test points of the COP derived from the physical model versus the COP calculated in PHPP are shown in Figure 29. The agreement is quite good within the normal working range, which includes low ambient temperature at high compressor speed and high ambient temperature at low speed.

**Results of the comparison**

Figure 30 shows the heating energy delivered by the heating system (m-HP and back-up heater) for both tools. The total supplied energy is in the same range, but deviations occur regarding the share of back-up heating. In all climates, the fraction of the heating energy delivered by the heat pump is lower in PHPP compared to TRNSYS. The deviation is higher in cold climates such as Stockholm and Gdansk, but also in Madrid. The overestimation of the share of back-up energy can be explained by the linear approximation of the heating load in the PHPP in combination with the HL, which is on the safe side. Depending on the profile of the HL duration curve, this approximation leads to an overestimation of the heating energy delivered by the back-up heater compared to TRNSYS.

![Figure 30: Heating energy delivered by the heating device (heat pump and back-up heater) for TRNSYS and PHPP](image)

Figure 31 shows the total annual electricity consumption in TRNSYS and PHPP for the heat pump, back-up heater, fans and pre-heater. An overestimation of the electricity consumption in PHPP is shown for all climates. These deviations are mainly caused by the different share of back-up heating. The electricity consumption of fans, pre-heater and compressor are quite

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similar in both tools for all climates. In all climates (except for LON) the electricity consumption of the heat pump compressor is lower in PHPP than in TRNSYS.

![Figure 31: Annual electricity consumption for heat pump (HP), back-up heater (postH), fans (FANS) and pre-heater (preH) - Comparison TRNSYS/PHPP](image)

A more detailed comparison of the back-up electricity is presented in Figure 32. For all climates (except for MAD) the absolute values of the deviations are above 5.6 kWh/(m$^2\cdot$a). PHPP has higher values compared to TRNSYS in all climates and in GDA_25 the absolute value of the deviation is 9.1 kWh/(m$^2\cdot$a).

![Figure 32: Back-up heater electricity consumption and absolute deviation TRNSYS/PHPP](image)
Figure 33 shows the seasonal performance factor (SPF) of the heat pump. The agreement is very good for the climates of Madrid and Lyon, where the absolute values of the relative deviations are below 5%. The comparison is less good for the colder climates and for Rome, with relative deviations above 11%.

Figure 33: SPF of the heat pump and relative deviation TRNSYS/PHPP

Figure 34: SPF of the heating system and relative deviation TRNSYS/PHPP
The total SPF of the heating system is shown in Figure 34. TRNSYS has higher values compared to PHPP for all climates, with relative deviations of 13-34%. The relative deviations are high in colder climates with values above 29%. The SPF of the system is strongly influenced by the electricity consumption of the back-up heater (see Figure 32), which explains the relatively high deviations.

Conclusions
The comparison of PHPP and TRNSYS was performed for a single family house with a heating demand of 25 kWh/(m²·a) and for seven different European locations. The agreement between the two tools regarding the total electricity consumption as well as for the SPF of the heat pump and of the heating system is relatively good for the climate of Madrid, but for the others climates the agreement might be expected to be better. The highest deviations were observed in the share of back-up heating. The agreement between the two tools could be improved, in particular for the colder climates (Stockholm, Gdansk and Stuttgart). The limitation is the approach of the linear approximation of the load duration curve in combination with the algorithm for the calculation of direct electricity share in PHPP.

A more detailed investigation was performed in the PHPP to check the influence of the maximum heating load on the calculation of the back-up energy share (see Annex V). Using the TRNSYS maximum heating loads in PHPP, the agreement between the two tools regarding the total supplied energy and electrical energy consumption is improved but still the back-up share is overestimated in PHPP (except MAD) in particular for the cold climates. Further improvement might be obtained with improved prediction of the load duration curve. For general trends the accuracy of the algorithm is acceptable.

Different control strategies were tested in the TRNSYS model in order to find the appropriate controller for the micro-heat pump and the back-up heater (see Annex IV). Controllers based on standard TRNSYS types (as Type 22 and Type 23) have limitations due to their sensitivity to the time step of the simulation and simulation settings. Therefore, simplified controllers are used based on linear equations (both heat pump and back-up heater). Further investigations should focus on the use of standard TRNSYS types with different simulation settings and smaller time steps.

4.3.3 Solar thermal
PHPP allows the estimation of the solar fraction of a solar system for domestic hot water and solar space heating. The so-called f-chart method [23] is used for this calculation.

In [24] it was shown that the solar fraction calculated with PHPP is overestimated compared to simulation results by MATLAB/Simulink and the CARNOT Toolbox. The back-up energy is underestimated by more than 20%. The main reason for these deviations can be attributed to an underestimation of the storage losses. PHPP only considers the losses for the standby section of the storage with the set temperature of the domestic hot water, while losses of the solar section of the storage and higher temperatures in the standby section due to solar loads are neglected. The reason for this simplification is that the f-chart method does not consider storage losses because the algorithm does not include calculation of the storage temperature. The f-chart method assumes a “well insulated” storage, which means storage losses are considered but only in a very small amount. The expanded phi-f-chart algorithm would allow the calculation of a storage temperature and therefore explicit storage losses, but this algorithm
is quite complex and can be solved only iteratively. For this reason the existing f-chart algorithm is expanded by a calculation method for the storage temperature. The aim is to calculate two mean storage temperatures separated for the standby and solar section of the storage.

Compared with the f-chart algorithm an analogous approach was chosen for this problem: several simulations were taken to generate a polynomial which depends on the collector area and the solar radiation. For the domestic hot water, four different storage sizes (313 l, 391 l, 490 l and 755 l), eight different collector areas (between 2 and 16 m²) and three different energy demands were compared. For the solar space heating two different storage sizes (1000 l and 2000 l) and ten different collector areas (between 5 and 50 m²) were considered. All possible combinations were calculated for all seven reference climates, giving a total of 812 simulation runs. The storages are insulated with 10 cm mineral wool and thermal bridges due to connections to the storage are considered.

A so-called temperature factor for each month was calculated by a polynomial for the standby and solar section depending on the collector area $A_{col}$:

$$f_{\text{temp}} = c_6 \cdot A_{col}^5 + c_5 \cdot A_{col}^4 + c_4 \cdot A_{col}^3 + c_3 \cdot A_{col}^2 + c_2 \cdot A_{col} + c_1 \quad (1)$$

Tables listing the coefficients for the standby section and the solar section polynomials are found in Annex II, section 7.1.

The used coefficients are independent of the location (except for the solar radiation) and also of the storage size. Without this simplification it would be necessary to use a higher degree polynomial, which would increase the effort considerably.

The monthly mean temperature for the standby section of the storage was determined with:

$$T_{\text{standby}} = \frac{1}{(Q_{\text{use}}/252)^{0.3}} \cdot f_{\text{temp,standby}} \cdot A_{col}^2 \cdot I_{col} + 55 \quad (2)$$

The monthly mean temperature for the solar section of the storage was determined with:

$$T_{\text{solar}} = \frac{1}{(Q_{\text{use}}/252)^{0.4}} \cdot f_{\text{temp,solar}} \cdot A_{col}^2 \cdot I_{col} + 20 \quad (3)$$

where $A_{col}$ is the collector area, $I_{col}$ the solar radiation on the collector surface and $Q_{\text{use}}$ the energy consumption (DHW or solar heating and DHW).

The monthly losses for the standby and solar section for a domestic hot water system can be calculated with:

$$Q_{\text{losses,standby}} = 0.21 \cdot U_{A_{\text{storage,standby}}} \cdot (T_{\text{standby}} - T_{\text{amb}}) \quad (4)$$

$$Q_{\text{losses,solar}} = 0.49 \cdot U_{A_{\text{storage,solar}}} \cdot (T_{\text{solar}} - T_{\text{amb}}) \quad (5)$$

The monthly losses for the standby and solar section for a solar space heating system can be calculated with:

$$Q_{\text{losses,standby}} = 0.30 \cdot U_{A_{\text{storage,standby}}} \cdot (T_{\text{standby}} - T_{\text{amb}}) \quad (6)$$

$$Q_{\text{losses,solar}} = 0.70 \cdot U_{A_{\text{storage,solar}}} \cdot (T_{\text{solar}} - T_{\text{amb}}) \quad (7)$$

where $U_{A_{\text{storage,standby}}}$ and $U_{A_{\text{storage,solar}}}$ are the UA-values for the different sections. $T_{\text{amb}}$ is the temperature of the room with the storage.
The constants are empirically determined values which consider the different types of systems and the fact that the f-chart method already includes storage losses for a “well insulated” storage.

The presented method is an empirical method, which can be used for reasonable sizes of collector area and storage. A standard insulated storage is assumed. With a better insulated storage the storage losses will be overestimated, with a poorer insulated one underestimated.

Figure 35, Figure 36 and Figure 37 show the results for the solar domestic hot water system for the climate of Stuttgart with different collector areas and a storage size of 490 l. Figure 35 shows the solar fraction calculated with the old algorithm of PHPP, the improved one and the reference simulation with MATLAB/Simulink and the CARNOT Toolbox. The deviations between simulation and PHPP calculation are negligible. Figure 36 shows the storage losses and Figure 37 the back-up energy demand. All results show good agreement with the MATLAB CARNOT-model.

Figure 35: Solar fraction for DHW; location: Stuttgart; storage size: 490 l

Figure 36: Storage losses for DHW; location: Stuttgart; storage size: 490 l
With the actual method the solar fraction ratio can be calculated accurately for moderate climates, such as Stuttgart. For hotter and colder climates, like Rome or Stockholm, the results of the method lead to an underestimation of the solar fraction ratio caused by the f-chart algorithm. Figures showing results for other climates and other storage sizes are found in Annex II.

The new algorithm for solar heating slightly overestimates the solar fraction for solar space heating. Compared with the existing algorithm, much better results can be obtained. For a better agreement, an adaption of the f-chart algorithm would be necessary. However simulation parameters in CARNOT also have a high influence on the simulation results. Systems with higher flow temperatures lead to higher solar fraction ratios; in this case a low temperature system was assumed.
5 Conclusions

This report gives a review over energy auditing and certification tools used in European countries, as well as building energy calculation and simulation tools used globally. Further, the choice of one of these calculation tools to be developed into a versatile auditing tool is described, followed by a description of its features and the calibration and validation procedures.

Many of the tools used for energy auditing and energy certification in Europe are only available in the local language of the respective country, which limits the selection for an auditing tool that is intended to be useable all over Europe. Commercial software for building energy calculation and simulation, on the other hand, often require a high degree of expertise and are not possible to modify.

As basis for the auditing tool of the iNSPiRe project, PHPP from Passive House Institute in Germany was chosen. PHPP is a MS Excel based, monthly balance energy calculation tool for buildings, featuring calculation of heating and cooling demands, heating and cooling loads, solar gains, ground losses, DHW losses, heat pump systems, solar thermal and solar PV. Along with the broad range of relevant features, the reasons PHPP was found suitable for the auditing tool included the possibility of modifying the source code, the low price and the fact that it is in English. Comparisons with TRNSYS building models show that the presented auditing tool can be used for monthly energy balance calculation with good precision in different climates, both for single- and multi-zone buildings models. Some differences were seen, partly because PHPP tends to overestimate heating and cooling loads to be on the safe side when it comes to sizing of HVAC systems, and there is still some room for improvement. The models for air source and ground source heat pumps show good agreement with hourly simulations with MATLAB Simulink. For the compact unit, including heat recovery unit and a small heat pump, the PHPP model was compared to TRNSYS. Good agreement was found in some cases, while for others further calibration might be necessary to improve the precision of the model. The algorithm for solar thermal systems shows good agreement with Simulink for a central European climate like Stuttgart, while for hotter and colder climates the solar fraction is underestimated.

The auditing tool developed as part of iNSPiRe will be used as guidance for planners, designers and other stakeholders to find optimal solutions for future renovation projects. Some features remain to be added or validated, for example sorption heat pump and multi-split heat pump, as well as larger buildings, but the current version already offers a good range of opportunities for energy auditing and choice of energy renovation measures. The new version of PHPP will also include economic calculation and the possibility of performing parametric analyses.
6 Annex I - Review of energy calculation tools

6.1 Software for energy certification

<table>
<thead>
<tr>
<th>Country</th>
<th>Software</th>
<th>Developer/Provider</th>
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<tr>
<td>Austria</td>
<td>Archiphysik</td>
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<td>Ecoline</td>
<td>Ecotech</td>
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<td></td>
<td>Gebäudeprofi</td>
<td>ETU GmbH</td>
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<td>GEQ</td>
<td>Zehentmayr Software</td>
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<td>Belgium</td>
<td>3G-software</td>
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<tr>
<td>Czech Republic</td>
<td>Svoboda Software</td>
<td>K-CAD</td>
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<td></td>
<td>Protech Energy Efficiency Calculator</td>
<td>Protech</td>
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<td>Finland</td>
<td>IDA ICE</td>
<td>EQUA</td>
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<td></td>
<td>Riuska + MagiCAD Room</td>
<td>CADCOM, Sweden</td>
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<td></td>
<td>DOF-Energia</td>
<td>D.O.F. tech</td>
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<td>Lamit</td>
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<td>Etlas Oy</td>
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<td>CADS Planner Hepac</td>
<td>Kymdata Oy</td>
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<td>France</td>
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<td>CSTB</td>
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<td>Germany</td>
<td>5S: Energie High End</td>
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<tr>
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<td>Bauterm EnEV X / Bauterm 18599</td>
<td>bmz-software</td>
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<td></td>
<td>BKI Energieplaner</td>
<td>BKI</td>
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<td></td>
<td>Dämmwerk 2014</td>
<td>Bauphysik Software</td>
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<td></td>
<td>Energie - Energieeffizienz Gebäude EnEV 2014 / DIN V 18599</td>
<td>Grüner</td>
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<td>Energieeffizientes Gebäude EnEV</td>
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<td>EnEV + 18599</td>
<td>ennovatis GmbH</td>
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<td></td>
<td>EnEV Planungsprogramm</td>
<td>Wienerberger</td>
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<td>EnEVplus</td>
<td>WEKA Bausoftware</td>
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<td></td>
<td>EnEV-XL</td>
<td>Institut Wohnen und Umwelt</td>
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<td>EVA Software</td>
<td>Ingenieurbüro Leuchter</td>
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<td>EVEBI</td>
<td>Envisys Software</td>
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<td></td>
<td>Hottengroth Energieberater Professional</td>
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<td>jEnEV</td>
<td>EnEV-Soft</td>
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<td></td>
<td>LEGEP - Warme und Energie</td>
<td>Legep Bausoftware</td>
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<td></td>
<td>LinEner EnEV 2009/2014</td>
<td>Linear Software</td>
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<td>PHPP 8</td>
<td>Passivhaus Institut</td>
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<td></td>
<td>ProKlimaHaus 2015</td>
<td>KlimaHaus (CasaClima)</td>
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<td>Rowa-Soft</td>
<td>ROWA-Soft GmbH</td>
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<td>Thermoplan EnEV</td>
<td>EnEV 2014 EnEV 8.1, Ziegelwerk Beilenberg</td>
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<td>Ziegel EnEV</td>
<td>AG Mauerziegel</td>
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<td></td>
<td>ZUB Helena Ultra</td>
<td>ZUB Kassel e.V.</td>
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<tr>
<td></td>
<td>EnerCalc</td>
<td>Uni Wuppertal / EnoB</td>
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### Table 11 - Software used for energy certification in European countries (2)

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<thead>
<tr>
<th>Country</th>
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<td>TEE-KENAK V1.29</td>
<td>Institute of Environmental Research and Sustainable Development</td>
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<td>Hungary</td>
<td>Win Watt</td>
<td>Bausoft Pécsvárad Kft.</td>
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<td>Ireland</td>
<td>DEAP</td>
<td>Sustainable Energy Authority of Ireland</td>
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<td>Italy</td>
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<td>ACCA Software</td>
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<td>EC700 calcolo prestazioni energetiche degli edifici versione 6.0</td>
<td>Edilclima</td>
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<td>TERMOLOG Epix 5 versione 2014.08</td>
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<td>Namirial TERMO V.3</td>
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<td>Euclide Certificazione Energetica v. 6.01</td>
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<td>Mc4 Suite v. 2014-2.0</td>
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<td>ENORM</td>
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<td>BuildDesk Energy Certificate Professional</td>
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<td>UK</td>
<td>EES Design SAP 2012</td>
<td>Elmhurst Energy Systems</td>
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<td>NHER Plan Assessor</td>
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### Table 12 - Software used for energy certification in European countries (3)

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### 6.2 Software for building energy calculation and simulation

**Table 13 - Software for building energy calculation and simulation (1)**

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<td>Building Energy</td>
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<td>Software Tools</td>
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<td>load storage calculations, residential/commercial</td>
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<td>AFT Mercury</td>
<td>Applied Flow</td>
<td>Optimization, pipe optimization, pump selection, duct design,</td>
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<td>Technology</td>
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<td>AkWarm</td>
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<td>Archelios PRO</td>
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<td>Cellar, heat loss, design rules</td>
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<td>CEP Energy Management Software for Buildings</td>
<td>Association of Energy Engineers</td>
<td>Energy management, environmental performance, CO&lt;sub&gt;2&lt;/sub&gt; footprint</td>
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<td>CHP Capacity Optimizer</td>
<td>Building Energy Software Tools</td>
<td>Cogeneration, capacity optimization, distributed generation</td>
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<td>COMFIE</td>
<td>IZUBA énergies</td>
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<td>CYPE Building Services</td>
<td>CYPE</td>
<td>Building services, sizing, HVAC, plumbing, sewage, electricity, solar, acoustic behaviour analysis</td>
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<tr>
<td>Czech National Calculation Tool</td>
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<td>Energy performance certificate, delivered energy, energy demand calculation</td>
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<td>Delphin</td>
<td>Delphin Technology</td>
<td>Coupled heat, air and moisture transport, porous materials, building envelope</td>
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<td>Demand Response Quick Assessment Tool</td>
<td>Demand Response Research Center</td>
<td>Demand response, load estimation</td>
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<td>DEROB-LTH</td>
<td>Lund University</td>
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<td>DesiCalc</td>
<td>InterEnergy Software</td>
<td>Desiccant system, air-conditioning, system design, energy analysis, dehumidification, desiccant-based air treatment</td>
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<td>DesignBuilder</td>
<td>DesignBuilding Software</td>
<td>Building energy simulation, visualisation, CO&lt;sub&gt;2&lt;/sub&gt; emissions, solar shading, natural ventilation, daylighting, comfort, CFD, HVAC simulation sizing, early-stage design, building energy code compliance checking, OpenGL EnergyPlus interface, building stock modelling</td>
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<tr>
<td>DeST</td>
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<td>Building simulation, design process, calculation, building thermal properties, natural temperature, graphical interfaces, state space method, maximum load</td>
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<td>D-Gen PRO</td>
<td>Gas Technology Institute</td>
<td>Distributed power generation, on-site power generation, CHP, BCHP</td>
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<td>DOE-2</td>
<td>James J. Hirsch &amp; Associates (JJH)</td>
<td>Energy performance, design, retrofit, residential/commercial buildings</td>
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<td>EA-QUIP</td>
<td>Association for energy affordability</td>
<td>Building modeling, energy savings analysis, retrofit optimization (work scope development), investment analysis, online energy analysis tool, multi-family building</td>
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<td>eBench</td>
<td>eBench</td>
<td>Energy benchmarking, environmental benchmarking, energy audit, invoice verification and reconciliation, performance contract verification</td>
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<tr>
<td>EcoDesigner STAR</td>
<td>Graphisoft</td>
<td>For architects, integrated in BIM software, one click evaluation</td>
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<tr>
<td>Ecotect</td>
<td>Autodesk</td>
<td>Environmental design and analysis, conceptual design, solar control, overshadowing, thermal design and analysis, heating and cooling loads, natural and artificial lighting, LCA, LCC, geometric and statistical acoustic analysis</td>
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<td>CANMET</td>
<td>Whole building performance, building incentives</td>
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<td>EE4 CODE</td>
<td>CANMET</td>
<td>Standards and code compliance, whole building energy performance</td>
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<td>EED</td>
<td>Building Physics</td>
<td>Earth energy, boreholes, ground heat storage, ground source heat pump system (GSP)</td>
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<td>Efficiency Smart</td>
<td>Efficiency Smart</td>
<td>Energy data visibility, operational energy efficiency measures, energy savings, alerts, reports, peak demand management, schedule adjustments, meter data, interval data</td>
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Table 15 - Software for building energy calculation and simulation (3)

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<td>EnerCAD</td>
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<td>EnerCAD</td>
<td>Building energy efficiency, early design optimization, architecture oriented, LCA</td>
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<td>Energinet - Energy Management Software</td>
<td>Cebyc AS</td>
<td>Cost effective energy management</td>
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<tr>
<td>EnergyActio</td>
<td>EnergyActio</td>
<td>Energy efficiency, continuous improvement, energy cost</td>
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<tr>
<td>EnergyDeck</td>
<td>EnergyDeck</td>
<td>Energy tracking and analysis, benchmarking, portfolio ranking, community sharing, project tracking</td>
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<tr>
<td>Energy Expert</td>
<td>NorthWrite</td>
<td>Energy tracking, energy alerts, wireless monitoring</td>
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<td>EnergyGauge USA</td>
<td>University of Central Florida</td>
<td>Residential, energy calculations, code compliance</td>
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<tr>
<td>EnergyPro</td>
<td>EMD International A/S</td>
<td>LEED, ASHRAE 90.1, code compliance, energy simulation, commercial/residential</td>
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<td>Energy Profile Tool</td>
<td>EnerSys Analytics</td>
<td>Benchmarking, energy efficiency screening, end-use energy analysis, building performance analysis, utility programs</td>
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<td>EnergySavvy</td>
<td>EnergySavvy</td>
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<td>Oikos</td>
<td>Design, residential buildings, commercial buildings, energy efficiency, load calculations</td>
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<td>Energy Usage Forecasts</td>
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<td>Degree days, historical weather, mean daily temperature, load calculation, energy simulation</td>
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<td>ENERPASS</td>
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<td>Energy performance, design, residential and small commercial buildings</td>
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<td>Ener-Win</td>
<td>Ener-Win</td>
<td>Energy performance, load calculation, energy simulation, commercial buildings, daylighting, LLC</td>
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<td>eQUEST</td>
<td>James J. Hirsch &amp; Associates (JH)</td>
<td>Energy performance, energy use analysis, conceptual design performance analysis, LEED, Energy and atmosphere credit analysis, compliance analysis, LCC, DOE 2, PowerDOE, building design, energy efficiency measures</td>
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<td>eSight</td>
<td>eSight Energy</td>
<td>Energy management, MBV, utility tracking, performance monitoring, benchmarking, bill verification</td>
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<td>ESP-r</td>
<td>University of Strathclyde</td>
<td>Energy simulation, environmental performance, commercial/residential buildings, visualisation, complex buildings and systems</td>
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<td>Elite Software</td>
<td>Energy performance, design, retrofit, residential/commercial buildings</td>
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<td>EZ Sim</td>
<td>Advanced Buildings</td>
<td>Energy accounting, utility bills, calibration, retrofit</td>
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<td>Pacific Northwest National Laboratory</td>
<td>Single buildings, multi-building facilities, central energy plants, thermal loops, retrofit opportunities, LCC, emissions impacts, alternative financing</td>
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<td>Infomind</td>
<td>2D heat transfer, fenestration, thermal bridge</td>
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<td>FloVENT</td>
<td>Mentor Graphics</td>
<td>Airflow, heat transfer, HVAC</td>
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<td>Flownex</td>
<td>Flownex</td>
<td>Fluid flow, dynamic, heat transfer, two phase, slurry</td>
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<td>Dartwin</td>
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<td>Florida Solar Energy Center</td>
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<td>GLD software</td>
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<td>Mathworks</td>
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<td>Carrier</td>
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<td>UCLA</td>
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<td>Software</td>
<td>Developer/provider</td>
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<td>EQUA</td>
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<td>Granlund</td>
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<td>Cradle</td>
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<td>Sefaira</td>
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<td>CSTB</td>
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<td>Kahl Consultants</td>
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<td>State University</td>
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<td>Trane</td>
<td>Energy analyses, load calculation, comparison of system and equipment alternatives</td>
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<td>Tas</td>
<td>EDSL</td>
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<td>SINTEF Byggeforsk</td>
<td>Energy performance, indoor climate simulation, code compliance, load calculation, residential/non-residential</td>
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<td>TOP Energy</td>
<td>gfa! tech</td>
<td>Simulation/optimization of energy systems, energy efficiency, time series analysis, variant comparison, Sankey diagrams, material and energy flow analysis, process optimization</td>
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<td>TRACE 700</td>
<td>Trane</td>
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<td>Aigausol</td>
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<td>TRNSYS</td>
<td>University of Madison, Wisconsin</td>
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<td>tbi3</td>
<td>Aalborg University</td>
<td>Energy performance, design, retrofit, residential/commercial buildings, indoor climate</td>
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*Table 17 - Software for building energy calculation and simulation (5)*
7 Annex II - Validation of solar thermal application in PHPP

7.1 Coefficients for temperature function polynomial

Table 18: Coefficients for polynomial for the standby section

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<td>2.645875E-07</td>
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Table 19: Coefficients for polynomial for the solar section

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</table>
7.2 Validation against MATLAB/Simulink

Figure 38, Figure 39 and Figure 40 show the results of the comparison between PHPP and CARNOT for the solar domestic hot water system for the climate of Stockholm with different collector areas and a storage size of 490 l. Figure 38 shows the solar fraction calculated with the old algorithm of PHPP, the improved one and the reference simulation with MATLAB/Simulink and the CARNOT Toolbox. The deviations between simulation and PHPP calculation are small for small collector areas. For larger collector areas the solar fraction ratio is underestimated by PHPP. Figure 39 shows a good agreement between the storage losses in CARNOT and PHPP. For this reason the f-chart algorithm probably causes the deviations for larger collector areas. Figure 40 shows the back-up energy demand, which is overestimated for larger collector areas.

![Figure 38: Solar fraction for DHW; location: Stockholm; storage size: 490 l](image1)

![Figure 39: Storage losses for DHW; location: Stockholm; storage size: 490 l](image2)
Figure 40: Back-up energy for DHW; location: Stockholm; storage size: 490 l

Figure 41, Figure 42 and Figure 43 show the results for the solar domestic hot water system for the climate of Rome with different collector areas and a storage size of 490 l. The solar fraction ratio is slightly underestimated for small collector areas. For larger collector areas the solar fraction ratio is near 100% with both calculation methods.

Figure 41: Solar fraction for DHW; location: Rome; storage size: 490 l
Figure 42: Storage losses for DHW; location: Rome; storage size: 490 l

Figure 43: Back-up energy for DHW; location: Rome; storage size: 490 l

Figure 44, Figure 45, Figure 46 and Figure 47 show the results for the solar space heating system for the climate of Stuttgart with different collector areas and a storage size of 1000 l. The building has a heating demand of 19 kWh/(m²a). The solar fraction ratio is slightly overestimated and the back-up energy demand is slightly underestimated for larger collector areas. Figure 47 shows the solar energy provided by the collectors. For larger collector areas the f-chart algorithm overestimates the energy.
Figure 44: Solar fraction for solar space heating; location: Stuttgart; storage size: 1000 l

Figure 45: Storage losses for solar space heating; location: Stuttgart; storage size: 1000 l

Figure 46: Back-up energy for solar space heating; location: Stuttgart; storage size: 1000 l
Figure 47: Solar energy for solar space heating; location: Stuttgart; storage size: 1000 l

Figure 48, Figure 49, Figure 50 and Figure 51 show the same results for a larger storage of 2000 l. As before, the solar fraction ratio is slightly overestimated, which is caused by the higher solar energy delivered by the collectors.

Figure 48: Solar fraction for solar space heating; location: Stuttgart; storage size: 2000 l
Figure 49: Storage losses for solar space heating; location: Stuttgart; storage size: 2000 l

Figure 50: Back-up energy for solar space heating; location: Stuttgart; storage size: 2000 l

Figure 51: Solar energy for solar space heating; location: Stuttgart; storage size: 2000 l
The results for Stockholm and Lyon are shown in Figure 52, Figure 53, Figure 54, Figure 55 and Figure 56, Figure 57, Figure 58, Figure 59, respectively. The same house was used for both climates, leading to a heating demand of 30 kWh/(m²·a) for the climate of Stockholm and 10 kWh/(m²·a) for Lyon. The results show the same tendencies as already presented for the DHW and solar space heating.

Figure 52: Solar fraction for solar space heating; location: Stockholm; storage size: 1000 l

Figure 53: Storage losses for solar space heating; location: Stockholm; storage size: 1000 l
Figure 54: Back-up energy for solar space heating; location: Stockholm; storage size: 1000 l

Figure 55: Solar energy for solar space heating; location: Stockholm; storage size: 1000 l

Figure 56: Solar fraction for solar space heating; location: Lyon; storage size: 1000 l
Figure 57: Storage losses for solar space heating; location: Lyon; storage size: 1000 l

Figure 58: Back-up energy for solar space heating; location: Lyon; storage size: 1000 l

Figure 59: Solar energy for solar space heating; location: Lyon; storage size: 1000 l
8 Annex III - Parametric analysis for heating and cooling in single zone TRNSYS model

8.1 Heat recovery by-pass and shading control

In the TRNSYS model, the external shading factor was set to 0.9 (i.e. 90% of the solar radiation is blocked) and the control was activated when the following conditions (based on IEA SHC Task 44 [7]) were all met:

- horizontal global irradiation > 300 W/m² (shading removed if < 250 W/m²)
- room temperature > 24 °C (shading removed if < 23 °C)
- 24 h moving average ambient temperature greater than 12 °C

For the by-pass of heat recovery, the following three conditions had to be verified for activation the TRNSYS model:

- room temperature higher than 23 °C
- room temperature higher than ambient temperature
- 24 h moving average ambient temperature higher than 14 °C

In PHPP, controlled shading and ventilation cannot be implemented in the current version. The shading is implemented with a fixed reduction factor for temporary sun protection of 0.3 (i.e. 70% of the solar radiation is blocked). It was activated during the non-heating period. In the same way, the heat recovery by-pass was activated during the non-heating period. In both tools, the by-pass controller works only in the cases where there is heat recovery during the heating period (see Table 5).

Figure 60 shows the heating demand and the absolute deviation between TRNSYS and PHPP with the automatic heat recovery by-pass and shading controllers implemented in the TRNSYS model. In general, the controllers implemented in the TRNSYS model have minor influence on heating demand. Thus, the same considerations as for Figure 10 (see section 4.2.1) are valid.
Figure 60: Heating demand and absolute deviation in TRNSYS/PHPP

Figure 61 shows the heating demand with TRNSYS depending on the presence of the HR by-pass and external shading control ("CONTROLLED" or "FIXED"). The implemented controllers do not affect the results and the absolute values of the relative deviations are below 1.5%.

Figure 61: Heating demand and relative deviations with TRNSYS depending on the shading and heat recovery by-pass controls
Figure 62 shows the cooling demand with TRNSYS depending on the presence of the heat recovery by-pass and external shading controllers ("CONTROLLED" or "FIXED"). In the warmer climates (LYO, MAD and ROM) the absolute values of the relative deviations are below 17%. In the colder climates, the case “CONTROLLED” presents higher CD compared to the case “FIXED” in most of cases. In particular, for STO the relative deviations are above 33% and in the case of STO_25 the relative deviation is 76%. These results can be explained by the lower sun position during the summer at this latitude, which makes it less reliable to use the horizontal global irradiation as condition for the controller.

![Graph showing cooling demand and relative deviations](image)

*Figure 62: Cooling demand and relative deviations with TRNSYS depending on the shading and heat recovery by-pass controls*

Figure 63 shows the cooling demand and the relative deviations between TRNSYS and PHPP. For the warmer climates, where the CD is appreciable, the absolute values of the relative deviations are below 20% (except for MAD_25). Hence, for these climates, the fixed external shading factor of 0.3 used in the PHPP can be used to predict the cooling demand in case of controlled shading with 90% shading factor.
8.2 Operative temperature for heating and cooling control

The temperature for heating and cooling control in TRNSYS was changed from convective to operative temperature, which was calculated as the average between the convective and the radiative temperature in the zone. In PHPP it is not possible to distinguish between operative and convective temperature.

Figure 64 shows the heating demand and the absolute deviations between TRNSYS and PHPP for the case when the operative temperature is used to control the heating in TRNSYS. In the renovated cases, the absolute values of the deviations are below 7 h/(m²·a), except for MAD_45 and ROM_45, and in most of the cases below 2 kWh/(m²·a). In the existing cases (EX), the agreement is not as good as for the renovated cases and the absolute deviations are in some cases above 20 kWh/(m²·a).
Figure 64: Heating demand and absolute deviation between TRNSYS/PHPP when heating in TRNSYS is controlled by the operative temperature.

Figure 65 shows the heating demand in TRNSYS for convective and operative temperature heating control. In all cases, the use of the operative temperature instead of the convective in TRNSYS results in a higher heating demand. For the renovated cases, the influence of the operative temperature on the heating demand is very small and the relative deviations are below 5% (except for ROM_25). In the existing cases, the influence of the operative temperature is more important, but the relative deviations remain below 13% for all cases.
The higher heating demand in the case the heating is controlled with the operative temperature instead of the convective can be explained through an analysis of the development of the internal temperature. Figure 66 shows the internal temperature for the case STU_EX in case the heating is controlled by the convective (top) or operative temperature (bottom). The operative temperature is higher in the bottom figure compared to top figure. A higher value of the operative temperature leads to higher the transmission losses and, thus, higher heating demand. Also, the figures reveal that it costs more energy to keep the operative temperature at 20 °C than the convective, since the convective temperature is nearly always higher during the heating period.

Figure 66: Internal convective and operative temperature for STU_EX in case the heating is controlled by the convective temperature (top) or the operative (bottom)
Figure 67 shows the cooling demand and relative deviations between TRNSYS and PHPP for the case when the cooling in the TRNSYS model is controlled by the operative temperature. In the warmer climates (LYO, MAD and ROM), the absolute values of the relative deviations are below 27% (except for LYO_EX), while the absolute deviations are below 5.5 kWh/(m²·a), except for LYO_EX where the absolute deviation is 13 kWh/(m²·a).

Figure 67: Cooling demand and absolute deviation between TRNSYS/PHPP when cooling in TRNSYS is controlled by the operative temperature

Figure 68: Cooling demand and relative deviations in TRNSYS depending on cooling temperature control
Figure 68 shows the cooling demand in TRNSYS for convective and operative temperature cooling control. The use of operative temperature instead of convective increases the cooling demand in all cases. In the warmer climates (LYO, MAD and ROM), the influence of the operative temperature on the cooling demand is higher in the existing cases compared to the renovated cases and the relative deviations are above 17%.
9 Annex IV - Control optimization of compact unit in TRNSYS

9.1 Heat recovery efficiency in the TRNSYS model

The mechanical ventilation with heat recovery (MVHR) was modelled in two ways in TRNSYS:

1. with an equation (see equation (1)) (simplified method - “ideal” case) and
2. with a model with a heat exchanger (HX) (type667) and two fans (“real” case).

The simplified approach was implemented in case of “ideal heating” mode (i.e. heating system is not modelled). The effective ventilation air flow rate was reduced (considering a heat recovery efficiency of 0.85) in order to model the lower ventilation losses of the building. In case of micro heat pump (m-HP), a heating system including the MVHR was modelled. The efficiency of the heat exchanger (HX) had to be specified such that the same air losses occur with both methods. A parametric study was performed to find the most appropriate value for the HX efficiency. The heating demand of the “ideal” case was compared with the heating demand of the “real” case by varying the efficiency of the HX in the “real” case. The m-HP model was used in the “real” case with switching off the heating devices (m-HP, back-up heater and electric radiator). The pre-heater was still working as a part of the MVHR. The cases of STO_25, STU_25 and ROM_25 were considered.

Table 20 shows the results of the heating demand for the “ideal” and “real” model, depending on the HX efficiency, for the cases of STO_25, STU_25 and ROM_25. For the cases of STU_25 and ROM_25, the variation of the HX efficiency has a limited influence on the heating demand. In the case of STO_25 the influence of the HX efficiency is higher compared to the other two climates. The most appropriate values to match the ideal heating demand were 0.89, 0.74 and 0.77 for Stockholm, Stuttgart and Rome, respectively. For the sake of simplicity, an efficiency of 0.80 is chosen for all climates, as it is the value most appropriate for all cases.

Table 20: Heating demand for the “ideal” model and “real” model (depending on the HX efficiency)

<table>
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<tr>
<th>HX EFFICIENCY</th>
<th>IDEAL [kWh/(m²-a)]</th>
<th>REAL [kWh/(m²-a)]</th>
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<td>STO_25</td>
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<td>28.9</td>
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<tr>
<td>STU_25</td>
<td>21.9</td>
<td><strong>21.8</strong></td>
</tr>
<tr>
<td>ROM_25</td>
<td>28.2</td>
<td>28.6</td>
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9.2 Micro heat pump control

Three different control strategies were investigated to optimize the control of the m-HP. As reference, the convective indoor temperature was used as a governing temperature for the control of the m-HP. The speed of the compressor varies depending on the indoor temperature. A set point temperature for heating of 20 °C was applied. The different controllers of this study are presented in Table 21. A time step of 6 minutes was used in the TRNSYS Studio file and the case STU_25 was simulated.

Table 21: Heat pump controls tested
Heat pump control

<p>| | |</p>
<table>
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<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>on/off hysteresis + Type 22</td>
</tr>
<tr>
<td>b</td>
<td>on/off + Type 23</td>
</tr>
<tr>
<td>c</td>
<td>on/off + Type “EQUATION”</td>
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</table>

In case “a” controller, Type 2 “on/off HP” was used to switch on and off the m-HP depending on the indoor temperature ($\theta_{\text{in}}$) (m-HP switched ON if $\theta_{\text{in}}$<19°C and OFF if $\theta_{\text{in}}$>21°C) and Type 22 is used to regulate the speed of the compressor. Type 22 is an iterative feedback controller that calculates the required control signal (RPM in this case) to reach the set point of the controlled variable (here the indoor temperature $\theta_{\text{in}}$).

In case “b” controller, Type 23 was used instead of Type 22. Type 23 is a PID controller, but it works with the same logic like Type 22 in order to reach the set point temperature.

The case “c” controller used a simplified approach. Here, the Type 2 “on/off HP” was used to switch the m-HP on and off (as in both controllers previously described) depending on the indoor temperature, and a linear equation was used to regulate the speed of the compressor, having as independent variable the indoor temperature.

Figure 69 shows the indoor temperature and the m-HP compressor speed (RPM) for the controller case “a”. The hysteresis controller works properly (see red circles in the figure). The HP is switched ON when the indoor T drops below 19°C and is switched OFF when the indoor temperature rises above 21°C. Figure 70 shows the RPM sorted vs time for the controller case “a”. Under the given time step of 6 min. the Type 22 seems to not work in a proper way and there are many oscillations of the RPM (see the black arrow in the figure). The behaviour of the type 22 might be improved by smaller time step of the simulation in the dck file (by cost of longer simulation time) and adapted simulation settings such as component order and convergence tolerances. Instead, other simplified control strategies have been tested.
Figure 69: Detail of the indoor temperature (int Temper) and RPM – m-HP control with Type 22

Figure 70: RPM sorted vs time – m-HP control with Type 22
Simulation results of the controller case “b” are presented in Figure 71 and Figure 72. A section of the indoor temperature and the speed of the compressor (RPM) is shown in Figure 72. Similarly to the previous case, the switching of the m-HP works properly, but the RPM is not affected by the oscillations as seen for the Type 22 (see Figure 69).

Figure 72 shows the sorted RPM vs time for the case the Type 23 is used to control the m-HP. The RPM profile is better compared to the case with Type 22 (see Figure 70) and the control is able to avoid the “step behaviour” noted previously in the RPM range between 1600 rpm and 2600 rpm. RPM regulation in the range between 2600 rpm and 4500 rpm (the highest possible rpm) does not occur (see black circle in the Figure 72). An explanation can be given with a more detailed look in Figure 71 at the time range between 100 h and 460 h (see red arrow), where the speed of the compressor should increase much faster in order to reach the maximum (4500 rpm) and avoid the temperature drop until 14°C. This late response of the controller, subsequently, makes it insufficient for this application even if its performance is better compared to the Type 22. Type 23 is a PID controller, but works with the same logic as Type 22 and, thus, is influenced by the same parameters (e.g., time step and simulation settings); hence, the same considerations regarding Type 22 are valid also for Type 23.

Figure 71: Detail of the indoor temperature (int temper) and RPM – m-HP control with Type 23
Figure 72: RPM sorted vs time – m-HP control with Type 23

Figure 73 shows the layout of the TRNSYS model in which the controller case “c” is used to control the m-HP.
Various configurations of the controller’s parameters are investigated in order to find the most appropriate parameters for the controller case “c”. The main three tests are presented in Table 22. Here, the temperature range of the hysteresis was varied as well as the minimum and maximum indoor temperature corresponding to the maximum and minimum RPM (4500 rpm and 1600 rpm, respectively). In Table 22, θ is the indoor temperature of the building and RPM is the speed of the compressor of the m-HP.

Test “ii” is affected by many oscillations of the speed of the compressor, while the test “iii” represents an improvement of the test “i” and presents a better profile for the medium indoor temperature compared to test “i”. The simulation results of the tests “i” and “ii” are not further presented in this report.

Table 22: m-HP control with “EQUATION” - three different controls tested

<table>
<thead>
<tr>
<th>Test</th>
<th>m-HP switched ON</th>
<th>m-HP switched OFF</th>
<th>RPM equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>θ &lt; 19 °C</td>
<td>θ &gt; 21 °C</td>
<td>RPM = -1450·T+32050</td>
</tr>
<tr>
<td>ii</td>
<td>θ &lt; 20 °C</td>
<td>θ &gt; 20 °C</td>
<td>RPM = -2900·T+59600</td>
</tr>
<tr>
<td>iii</td>
<td>θ &lt; 19.5 °C</td>
<td>θ &gt; 20.5 °C</td>
<td>RPM = -2900·T+61050</td>
</tr>
</tbody>
</table>
Figure 74 shows a detail of the simulation results (controller case “c” - test “iii”). The m-HP is switched ON when the indoor temperature drops below 19.5 °C and is switched OFF when the temperature rises above 20.5 °C (see black arrows in the figure). The behaviour of controller case “c” is good and the regulation of the compressor speed is good, too (see also Figure 75). Additionally, the profile for the indoor temperature is good and there are not oscillations regarding the indoor temperature or the speed of the compressor.

From the analysis of the three tested controllers for the m-HP (controller case “a”, “b” and “c”, see Table 21), the controller case “c” seems to be the most appropriate for this application (no oscillations, good match of the indoor temperature with the set point, good regulation of the speed of the compressor and fast enough response of the controller). For the investigated cases, the test “iii” (see Table 22) represents the best solution to control the m-HP and its compressor speed. It is important to note that different time steps of the simulation (instead of 6 min.) and different simulation settings (e.g., component order, tolerances, etc.) might change the performances of the controllers case “a” and “b”.

Figure 74: Detail of the indoor temperature (top) and RPM (bottom) – m-HP control with “EQUATION” (test “iii”)
Figure 75: RPM sorted vs time – m-HP control with “EQUATION” (test “iii”)

Figure 76 shows a detail of the simulation results (indoor temperature and RPM) in case the m-HP compressor speed is controlled with the “EQUATION” type (test “iii”). Within the heating period, there are some time intervals in which, even with full speed of the compressor (4500 rpm), the indoor temperatures continues to drop and the set point cannot be met (see red arrow in the figure). This means that the maximum power of the m-HP is not enough to cover the maximum heating load of the building. Hence, a back-up heater is necessary.

Figure 76: Detail of the indoor temperature and RPM – m-HP control with “EQUATION” (test “iii”)
9.3 Back-up heater control

Three different back-up heater controllers were investigated in TRNSYS. The investigation was performed for the climate of Stuttgart and the building renovated to EnerPHit standard (case STU_25). The simulation time step is 6 minutes. A post heater implemented in the supply air (positioned after the condenser) is used as back-up heater and additionally an electric radiator is placed e.g. in the bathroom for comfort reasons. The post-heater was modelled using the Type 6. Type 6 in TRNSYS models an auxiliary heater able to raise the inlet air temperature to a value fixed or to have a variable outlet temperature (depending on the controlled power).

Table 23 shows the three tested control strategies. In the control a, the outlet air temperature from the back-up heater is constant (52 °C), while in the controls b and c this temperature is varied and controlled depending on the internal air temperature of the building (i.e. with Type 22 in the control b and with the “EQUATION” type in the control c).

<table>
<thead>
<tr>
<th>Back-up heater control</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a</strong></td>
<td>on/off + Type 6</td>
</tr>
<tr>
<td><strong>b</strong></td>
<td>on/off + Type 22 + Type 6</td>
</tr>
<tr>
<td><strong>c</strong></td>
<td>on/off + Type “equation” + Type 6</td>
</tr>
</tbody>
</table>

In all the controllers tested, Type 2 (hysteresis controller named “on/off post-heater”) was used to switch the back-up heater on and off depending on the indoor temperature (ON if $\theta_i \text{in} < 19.25$ °C and OFF if $\theta_i \text{in} > 20$ °C). In addition to this, the equation for the variation of the speed of the compressor was modified to keep the maximum speed (4500 rpm) when the back-up heater is activated.

Figure 77 shows a detail of the simulation results (indoor temperature, RPM and back-up heater control) in the case where the back-up heater is controlled with strategy “a” (see Table 23). The RPM variation and the back-up heater control work good and there is also a good development for the internal temperature. The speed of the compressor (see black arrow in the figure) is maximum (4500 rpm) when 19.5 °C < $\theta_i \text{in} < 20$ °C (back-up heater switched ON).

Problems occurred with control “b” in combination with the control of the post-heater power and matching the indoor temperature. Further results of the simulation with case “b” are not presented in this report. Further investigations of the back-up heater controller “b” should be done in future work by modifying the time step of the simulation and/or the simulation settings.
Figure 77: Detail of the indoor temperature (top), RPM (centre) and back-up heater control (bottom) - Back-up heater control with “a”

Figure 78 shows the TRNSYS model in which the back-up heater controller “c” is implemented. In controller “c” the “on/off post-heater”, depending on the indoor temperature, switches the back-up heater and activates the equation type “RPM_equation” (to keep the maximum RPM when the post heater is activated) and the equation type “T_out_postH” (see red rectangle in the figure). The type “T_out_postH” contains a linear equation for the post heater power that, depending on the indoor temperature, gives as output the air set temperature for the post-heater. With this control, the set air temperature $\theta$ of the back-up heater is varied up to maximum 52 °C (limit for air heating).
Figure 78: TRNSYS model – Back-up heater controlled with “c”

Figure 79 shows a detail of the simulation results (indoor temperature, RPM and back-up heater control) for the controller case of “c” (see Table 23). Similarly to the control “a”, the compressor speed control and the post heater control work properly.
Figure 79: Detail of the internal T (top), RPM (centre) and back-up heater control (bottom) - Back-up heater control with "c"

Figure 80 shows a detail of the sorted indoor temperature with controllers “a” (type 6) and “c” (type EQUATION). The controller “a” leads to a higher indoor temperature, but the difference is not significant. The indoor temperature is below 19 °C during 11 h per year with control a, compared to 15 h for control c.

Table 24 shows the annual electricity consumption (m-HP and back-up heater) when the back-up heater is controlled by controller “a” (Type 6) or “c” (EQUATION). Although, the back-up heater electricity consumption is 13% lower for the controller “c”, the total electricity consumption is very similar in two cases (relative deviation of 1%). The controllers “a” and “c” have the similar performance (see Figure 80 and Table 24) and both represent a good solution for the back-up heater control. However, the controller “c” has the advantage that the heating power can be adapted to different buildings heating loads and makes the control more flexible.
Figure 80: Detail of the internal T sorted for the back-up heater control "a" and "c"

An additional electric radiator is implemented in the simulation model, which is supposed to be located in the bathroom for comfort reasons. The type “Electric RADIATOR” is activated by the back-up heater control and gives as output the electric power delivered by the radiator as a dummy internal gain. The electric radiator power is constant (400 W) and it is assumed that 60% is distributed to the convective node and 40% to the radiative node of the building model, similarly to the internal gains (see paragraph Error! Reference source not found.).

With the implementation of the electric radiator, the heating system control is totally defined in the TRNSYS model. The following upper and lower dead bands of the hysteresis controllers of the TRNSYS model are listed in Table 25.

Table 25: Heating device controls in TRNSYS model

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>Lower dead band</th>
<th>Upper dead band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pump</td>
<td>-0.25 K</td>
<td>0.75 K</td>
</tr>
<tr>
<td>Post heater</td>
<td>-0.5 K</td>
<td>0.25 K</td>
</tr>
<tr>
<td>Electric radiator</td>
<td>-0.5 K</td>
<td>0.25 K</td>
</tr>
</tbody>
</table>

Table 24: Electricity consumption [kWh/(m²·a)] for back-up heater controllers “a” and “c”

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>CONTROLLER “a”</th>
<th>CONTROLLER “c”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pump</td>
<td>7.53</td>
<td>7.58</td>
</tr>
<tr>
<td>Back-up heater</td>
<td>0.968</td>
<td>0.84</td>
</tr>
<tr>
<td>Total</td>
<td>8.498</td>
<td>8.42</td>
</tr>
</tbody>
</table>
Figure 81 shows a detail of the TRNSYS simulation results (for STU_25) with the heating device controls implemented. The m-HP controller switches ON the heat pump when the indoor temperature drops below 19.75 °C while the post-heater and electric radiator control switch ON when the temperature drops below 19.5 °C (see black arrows in the figure). The post heater and the electric radiator (with a constant power of 400 W) work together and at the same time the speed of the compressor is set to the maximum (4500 rpm).

![Graph showing temperature, RPM, and power over time]

Figure 81: Detail of the simulation results of indoor temperature (top), RPM and back-up heater (centre) and electric radiator (bottom)

Finally, a comparison between “ideal” heating and “real” heating (heat pump, back-up heater and electric radiator) was performed. The heating load duration curves are presented in Figure 82 for the case of STU_25. The small differences between the two cases caused due to the more realistic behaviour of the simulated heating system instead of “ideal” heating. Better agreement might be achieved by varying the dead bands of the controllers as well as the power of the electric radiator.
Figure 82: Heating load duration curve for STU_25 – “ideal” (without m-HP) and “real” (with m-HP)
10 Annex V - Influence of maximum heating load calculation in PHPP on the share of back-up energy

One of the main reasons for the deviations between PHPP and TRNSYS in terms of energy performance of the heating system was found to be the share of back-up heating. In PHPP the calculation of the share of the back-up strongly depends on maximum daily heating load and the load duration curve profile. The maximum heating load in the TRNSYS and PHPP and the relative deviations are shown in Table 26. For all climates, the PHPP values are higher compared to TRNSYS with relative deviations above 13% (in absolute value).

<table>
<thead>
<tr>
<th></th>
<th>TRNSYS</th>
<th>PHPP</th>
<th>DEVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>STO_25</td>
<td>16.6</td>
<td>21.0</td>
<td>-26%</td>
</tr>
<tr>
<td>GDA_25</td>
<td>18.8</td>
<td>23.0</td>
<td>-22%</td>
</tr>
<tr>
<td>STU_25</td>
<td>16.3</td>
<td>22.5</td>
<td>-38%</td>
</tr>
<tr>
<td>LON_25</td>
<td>14.8</td>
<td>19.9</td>
<td>-35%</td>
</tr>
<tr>
<td>LYO_25</td>
<td>19.7</td>
<td>25.9</td>
<td>-31%</td>
</tr>
<tr>
<td>MAD_25</td>
<td>22.0</td>
<td>24.9</td>
<td>-13%</td>
</tr>
<tr>
<td>ROM_25</td>
<td>22.5</td>
<td>35.4</td>
<td>-57%</td>
</tr>
</tbody>
</table>

Further investigation was performed in PHPP to check the influence of the maximum heating load on the total electricity consumption. Therefore, the maximum heating load calculated in TRNSYS was used as maximum heating load in PHPP.

Figure 83 shows the annual electricity consumption in TRNSYS and PHPP for the micro heat pump, back-up heater, fans and pre-heater in case the “adapted” maximum HL is used in PHPP. The contribution of the back-up heater on the total electricity consumption is lower compared to the “non-adapted” maximum HL case in PHPP, but still the deviations are high for all cases except the warm climates (i.e., MAD and ROM).
Figure 83: Annual electricity consumption for heat pump (HP), back-up heater (postH), fans (FANS) and pre-heater (preH) – PHPP maximum HL “adapted”

Figure 84 shows the absolute deviations between TRNSYS and PHPP for the energy delivered by the HP for two cases:

1. with HL in PHPP calculated by PHPP (“non-ADAPTED”)
2. with HL in PHPP calculated by TRNSYS (“ADAPTED”)

The “adapted” HL in the PHPP reduces the deviations in all cases. The reduction is more significant in the warmer climates (LYO, MAD and ROM), where the absolute deviations drop below 1.6 kWh/(m²·a).

Figure 84: Absolute deviations between TRNSYS and PHPP for the energy delivered by the HP depending on maximum HL
Figure 85 shows the absolute deviations between TRNSYS and PHPP for the electricity consumed by the back-up heater for the two cases of calculation of the maximum HL and the relative deviation to the total electricity consumption in TRNSYS. The “adaptation” of the HL in PHPP reduces the absolute deviations for all climates, particularly for the climates of LYO and ROM where the relative deviations are above 29%. There are still significant deviations between TRNSYS and PHPP (except for MAD and ROM) and PHPP is very much on the safe side, except for MAD where there is a small overestimation of TRNSYS compared to PHPP.

![Figure 85: Absolute deviations between TRNSYS and PHPP for the back-up heater electricity demand (for the two cases of the PHPP maximum HL) and relative deviation with respect to TRNSYS total electricity demand](image)

Figure 89 show the TRNSYS heating load and the linear approximation in PHPP for the two cases where the maximum heating load is taken a) from the PHPP calculation, or b) from TRNSYS simulation. The heating capacity of the m-HP is also shown in the figure (calculated in PHPP). The area between the blue line (HL of TRNSYS) and the black line (heating capacity of the HP) represents approximately the energy delivered by the back-up heater in TRNSYS. Similarly, the area between the red line and the black line represents the back-up energy in PHPP in the “non-adapted” case, while the area between the black line and the green one represents the back-up energy in the “adapted” case. Thus, with the approach of the “adapted” maximum heating load the difference of the share of back-up can be decreased.
Figure 86: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of STO_25

Figure 87: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of GDA_25
Figure 88: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of LON_25

Figure 89: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of STU_25
Figure 90: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of LYO_25

Figure 91: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of MAD_25
Figure 92: TRNSYS heating load compared to linear approximation of PHPP in “NON-ADAPTED” and “ADAPTED” case – case of ROM

Figure 93 and Figure 94 show the absolute deviations between TRNSYS and PHPP for the SPF_{HP} and SPF_{SYS} for the two cases of the calculation of the maximum HL, respectively. The “adapted” HL has a significant influence on the final energy demand in the climate of LYO compared to the reference case. In the “adapted” HL case, the absolute deviations for the SPF_{HP} increase for all climates (except MAD and ROM). In the climate of MAD, the agreement between the two tools is very good. Generally, the agreement for the SPF of the system is more influenced (compared to SPF for the heat pump) by the “adapted” HL of PHPP. The agreement between the two tools for the SPF of the system is better for all climates in case of “adapted” HL. Here, the absolute deviations drop below 0.59 (in absolute value). For the climates of MAD and ROM the agreement between the two tools is good and the absolute values of the deviations are below 0.04.
Figure 93: Absolute deviation between TRNSYS and PHPP for the SPF_{HP} for the two cases of the maximum heating load in PHPP.

Figure 94: Absolute deviation between TRNSYS and PHPP for the SPF_{SYS} for the two cases of the maximum heating load in PHPP.
12 References


