A DESIGN TOOL TO ASSESS THE EXPLOITATION OF RENEWABLE ENERGY IN BUILDINGS

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ABSTRACT

This paper consists in the presentation of a new simulation tool aimed at the detailed prediction of HVAC systems, developed by the authors in order to fulfill specific needs derived from particular research topics in the field of design and tailored control of HVAC systems fed by heat pumps. This simulation tool has a modular programming design and is developed in order to easily use input data available in documentation from manufacturers and to provide the user with a flexible system design and a full set of control options. In this paper, it is used to evaluate the energy performance of HVAC systems based on heat pumps for DHW (Domestic Hot Water) production and heating/cooling purposes in low energy buildings.

INTRODUCTION

Many building energy simulation tools exist for the assessment of building heating/cooling loads and lighting needs. In particular, some of them perform HVAC system simulation with a high degree of detail [Crawley et al., 2005], thus allowing the user to assess energy consumption for common HVAC systems.

Unfortunately, when involved in specific projects about advanced HVAC systems and devices as well as about new control strategies for HVAC systems, the need for the implementation of an open and fully modifiable software arises. In particular, the authors of this paper decided to develop a simulation tool aimed at the detailed analysis of tailored HVAC systems, being involved in projects about low energy buildings and optimized management of heat pumps, in the frame of prototype coordinated energy grids for the achievement of the smart city target.

In this paper, the new building energy simulation tool under development at University IUAV of Venice is introduced. In particular, this software is aimed at the simulation of HVAC systems under unsteady state conditions, starting from building heating/cooling loads simulated by means of other software.

In particular, in this paper, the software under development is applied to the analysis of typical residential HVAC systems coupled with heat pumps, in order to calculate the global system efficiency and the related renewable energy share.

In section METHODS, the building energy simulation software under development is briefly illustrated and the performed simulations are described. In section RESULTS AND DISCUSSION, the achieved simulation results are shown, together with interesting results arising from the detailed output of the software under development.

METHODS

General description of the simulation software under development

The software is developed in programming language C++, fully exploiting related features such as meta-programming and object-oriented programming, as well as inheritance. As a consequence, the simulation tool itself is structured by means of a fully modular approach, where each physical HVAC device is described by means of a software module.

The following features characterize the program under development:

- Simulation of HVAC systems starting from heating/cooling loads. The software under development is aimed at the detailed simulation of HVAC systems with no reference to building envelope, because it is aimed at the implementation within building design and management software as well as at the verification of advanced control procedures. As a consequence, the software is not aimed at the simulation of the building envelope, hence heating/cooling loads will be input values.
- User-oriented approach. The development of this program aimed to facilitate the work of the user, i.e. the HVAC system designer or the programmer of building management controls, limiting the amount of input data to be found/assumed by the user. As a matter of fact, this simulation tool provides physical models and mathematical tools (such as cubic splines interpolation and multi-variable polynomial approximation) used for a reliable forecast of the performance of the simulated devices, depending on the level of detail available to the user, ranging from mere catalogue data up to detailed

performance tables and curves. Moreover, extensive magnitudes are expressed by means of normalized curves and tables and related specific multipliers, in order to ensure a larger use of previously inputted data and allow the user to build up a flexible archive of devices and performance data.

- Flexible adaptation to parametric optimization and sensitivity analyses. The software under development is intended at the use in optimization and sensitivity analyses, so it exploits an approach in input management aimed at the automatic composition of input files basing on parameter ranges specified by the user or by multi-objective optimization procedures.

In this study, the following software modules were used:

- Module “htpmp”: module representing vapor compression based heat pumps. Two approaches are used to simulate the operation of the heat pump in this calculation module:
  - o Physical approach, via the implementation of the model described by Scarpa et al. [Scarpa et al., 2012], intended to be used in case of low amount of information about the heat pump or for simulations involving heat pumps from a general perspective;
  - o Fully numerical approach, using rated performance of the heat pump, inputted in terms of full capacity and related COP values as a function of the inlet/outlet temperatures of the secondary fluids, exploiting a 3D least squares approximation procedure.

  The performance under part load conditions is calculated by means of user-defined or default [CEN, 2012] PLF-CR (Part Load Factor - Capacity Factor) curves.
- Module “usr”: module representing the thermal units. The user side is described from a general perspective, with no specific reference to the thermal unit terminal, so this object might be used for many cases, ranging from hot water tapping to fan coils and radiators. The input values available for this object can be grouped as follows:
  - o Value of heating/cooling load to be met in the timestep (usually one hour) under calculation
  - o Value of maximum/minimum inlet temperatures allowed in heating/cooling respectively, in order to consider the possible presence of thermostatic mixing valves
  - o Characteristic heat exchange curve in heating/cooling, depending on temperature difference between inlet temperature and room (or water mains) temperature, together with nominal performance and related boundary conditions (for instance using performance rated according to Standard EN 442:1997 [CEN, 1997])
  - o Maximum inlet volume flow rate
  - o Minimum thermal power to be met. This value is the minimum required thermal power below which the heating/cooling operation does not take place. This way the HVAC system is not asked to meet minimal heating/cooling loads, as happens in the real operation, since real HVAC systems are controlled by means of thermostats having proper thermal hysteresis, in order to prevent continuous on-off. This approach is uncommon in usual building energy simulation tools and is suited to mimic a better way the operation of real HVAC systems, especially in case of heat pumps, performing poorly at very low heating/cooling loads (unusual in common operation), corresponding to low capacity ratios (CR).
- Module “whstrg”: module representing the water heat storage. In this module the water volume is split into two parts, one above the other. The module considers heat conduction through the heat storage shell and envelope, heat transfer by means of built-in heat exchangers and direct intakes/outtakes, by means of overall heat transfer coefficient and design flows, through the ε-NTU method, as well as water mixing due to buoyancy driven convection within the heat storage (in case of temperature inversion in the heat storage).

General calculation scheme

The calculation procedure to be used with this software implies a two-step approach:

1. Determination of heating/cooling heat flows by measurements (when embedded in building management controls) or simulations through proper simulation software. In particular, in the present paper, this first step was performed simulating a low energy building by means of EnergyPlus [Crawley et al., 2001].
2. Simulation through the software under development, starting from heating/cooling data measured/simulated in step 1.

This two-step approach might imply inconsistence between the software used to assess the building energy demand (i.e., in the present case, EnergyPlus) and the software under development (used to calculate HVAC system operation and consequent primary energy needs). As a matter of fact, the size of the heat pump or water heat storages, as well as the control strategy, might imply heating/cooling loads are not always matched, thus affecting the indoor comfort. The potential frequency of such inconsistencies is limited indeed, because in HVAC systems water heat storages are used in most of times, in order to provide constant supply of thermal units as well as continuous operation of heat pumps and boilers. Furthermore, the software under development provides remainders used to postpone unmet loads, summing them to the heating/cooling loads of the next calculation time-step, thus mimicking the consequent effects of indoor environment underheating (in winter) or undercooling (in summer). As a consequence, this feature de-couples the plant from the indoor environment, but still keeping track of and recovering from unmet heating/cooling loads, thus further decreasing the potential frequency of inconsistencies implied by the afore-mentioned two-step calculation procedure, ensuring good consistence in the whole building energy simulation even if split into two phases, building heating/cooling demand assessment and building plant energy needs calculation respectively, as far as the delay in heating/cooling loads matching is limited within a few dozens of minutes, thanks to the usual amount of building thermal capacity.

Description of the simulated HVAC system

The HVAC system considered in this paper is resumed in *Figure 1* and consists in a heat pump serving the water heat storage of the heating/cooling circuit as well as the circuit for domestic hot water preparation.

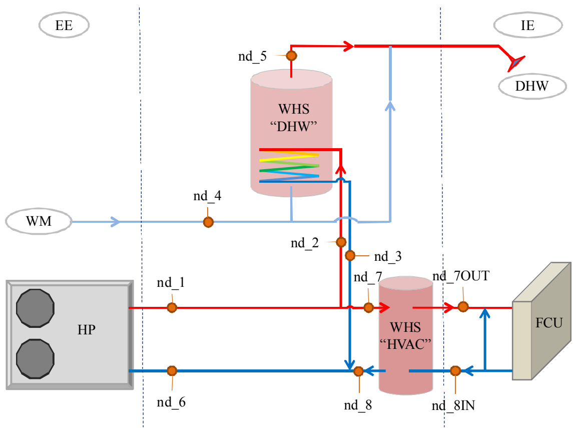


Figure 1 – Scheme of the simulated plant and names of the related mass flow nodes, where: EE: External environment; WM: Water mains; HP: Heat pump; WHS: Water heat storage; IE: Indoor environment; DHW: Domestic hot water; FCU: Fan coil units; HVAC = Heating/Cooling system

The heat pumps simulated in this paper are characterized by the normalized heating/cooling capacities and COP shown in *Figure 2*. The capacities and COP are normalized in order to use the same shape of capacity and COP curves for heat pumps having various nominal capacities. This approach was used in order to highlight the influence due to heat pump nominal capacity neglecting differences in performance due to specific heat pump model and size. In particular, these performance curves refer to typical commercial heat pumps usually equipped with one scroll compressor and R410A refrigerant fluid.

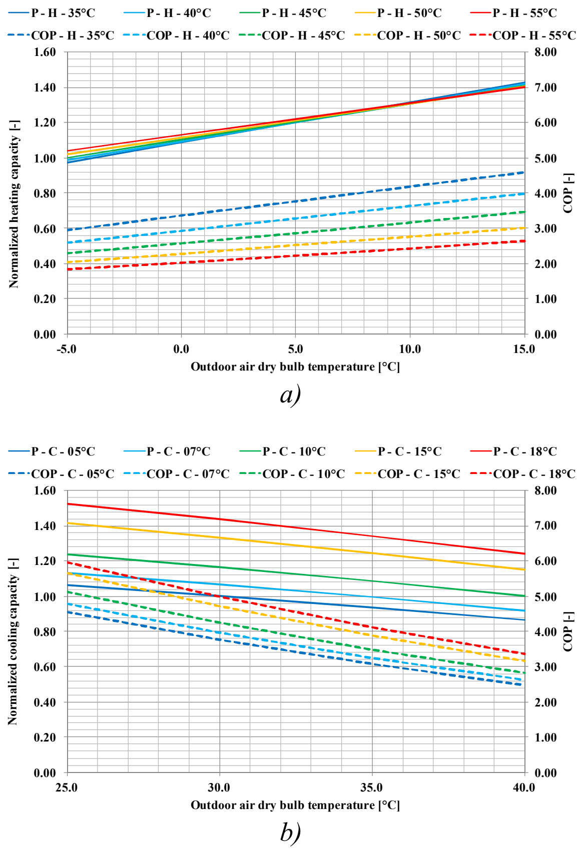


Figure 2 – Normalized full capacity (P) and COP curves depending on outdoor air and outlet water temperatures in a) heating and b)cooling modes

Moreover, two kinds of compressor control were considered: on-off and inverter. In particular, for the computation of heat pump performance under part load conditions, the approach recommended in EN 14825:2012 [CEN, 2012] is used, adopting the curves PLF-CR shown in *Figure 3*. Also in this case the same curves for various heat pump sizes were used, in order to avoid modifications in results due to contingent manufacturer's data and to achieve more general results.

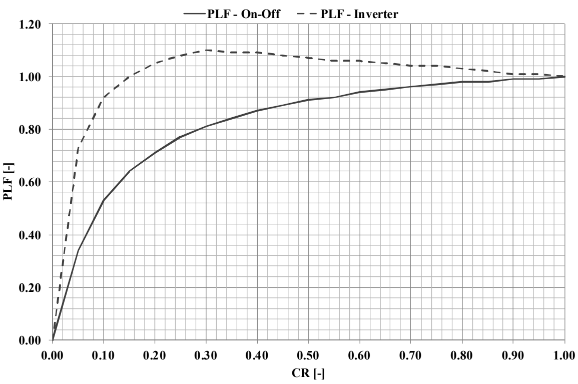


Figure 3 – Curves PLF-CR for On-Off and Inverter-driven heat pumps

The main parameters of the plant were varied, thus performing parametric simulations to analyze the sensitivity of the results to assumptions and specific conditions.

In particular, as regards the HVAC system, the DHW heat storage volume and the HVAC water storage volume were modified in a large range (0.2 m^3, 0.3 m^3, and 0.5 m^3), in order to get the variation of the heat pump performance depending on part load operation, as well as to include in the analysis the consequent heat losses, getting as close as possible to the actual behaviour of the plant. In particular, the water heat storages are provided with a thermal insulation layer with an equivalent U-value equal to 0.4 $W/(m^2{\cdot}K)$ and the control of the DHW heat storage is based on the following set-point temperatures:

- Minimum set-point temperature in the upper part of the water tank: 40°C. When the temperature in the upper part of the water heat storage falls below 40°C, the heat pump is asked to provide heat, until the temperature reaches the value of the maximum set-point temperature.
- Maximum set-point temperature in the lower part of the water tank. The maximum temperature in the lower part of the water tank is 45°C. When the temperature within the heat storage is getting higher than this value, the heat pump is switched off.

The DHW temperature is then tempered by means of a tempering valve limiting the temperature at the tap to 40°C.

Moreover, as mentioned above, different control strategies were considered for the heat pump (on-off mode and inverter-driven compressor) as well as two levels of building envelope performance (low efficiency envelope, LEE, and high efficiency envelope, HEE), in order to consider two ratios of DHW needs to heat pump capacity.

The parameters varied as mentioned above lead to a total amount of 36 simulations that were performed taking advantage of the advanced features embedded in the developed software to assist parametric simulations.

The main parameters characterizing water heat storages simulated by the simulation tool are resumed in *Table 1*, whereas the heat pumps used in this paper are briefly described in *Table 2*.

Various output files are given for the set of simulations: for each simulation of the set, output results averaged in each time-step (here corresponding to one hour) and detailed in each sub-time-step (here corresponding to five minutes), are given, as well as a detailed resume of seasonal energy transfers, efficiencies and renewable energy shares for each device in each operation mode.

In *Figure 4* an example of the detail of the results achievable with the simulation tool under development is shown.

Table 1
Main data about simulated water heat storages (WHS), where "Dir" means direct inflow/outflow

Magnitude	Service code	Option item	Internal volume	Internal height	Average U-value	Min/Max temperature in winter	Min/Max temperature in summer	Source side heat exchanger rated UA	User side heat exchanger rated UA
Unit	-	-	m^3	m	$W/(m^2{\cdot}K)$	°C/°C	°C/°C	W/K	W/K
Devices	DHW	1	0.2	1.25	0.40	40/45	40/45	Dir	1600
	DHW	2	0.3	1.33	0.40	40/45	40/45	Dir	1600
	DHW	3	0.5	1.50	0.40	40/45	40/45	Dir	1600
	HVAC	1	0.2	1.25	0.40	45/50	04/08	Dir	Dir
	HVAC	2	0.3	1.33	0.40	45/50	04/08	Dir	Dir
	HVAC	3	0.5	1.50	0.40	45/50	04/08	Dir	Dir

Table 2
Main data about simulated heat pumps (HP) in cases LEE and HEE

Magnitudes	General code	Option item	Heating – Full capacity [CEN, 2011]	Heating – COP [CEN, 2011]	Cooling – Full capacity [CEN, 2011]	Cooling – COP [CEN, 2011]	Control mode
Units	-	-	kW	-	kW	-	-
Devices	LEE	1	7.0	2.29	7.5	3.24	On-Off
	LEE	2	7.0	2.29	7.5	3.24	Inverter
	HEE	1	4.5	2.29	4.2	3.24	On-Off
	HEE	2	4.5	2.29	4.2	3.24	Inverter

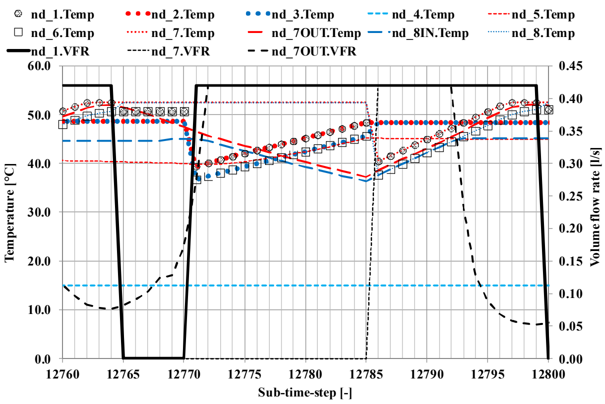


Figure 4 – Example of results achievable by means of the simulation tool under development

Description of the simulated building

Heating/Cooling loads were calculated by software EnergyPlus, using the geometry of a typical detached house as a reference. Two levels of energy efficiency were considered in the specification of the thermal envelope: low energy efficiency (case LEE) and high energy efficiency (case HEE). This way it was possible to examine the behaviour of the HVAC system depending on the ratio of heat pump design capacity to the sizes of DHW and HVAC storages. As a matter of fact, in case LEE and HEE, different heating and cooling design capacities are encountered, with consequent influence on heat pump sizing. In this paper, the heat pump is sized in order to cover both heating and cooling loads, using a safety factor equal to 1.10. In *Table 3* design heating capacities ($P_{LD,H,DES}$) and design cooling capacities ($P_{LD,C,DES}$) are declared for cases LEE and HEE, together with the heat pump full capacities under design boundary conditions ($P_{HP,H,DES}$ and $P_{HP,C,DES}$):

Table 2
Main data about simulated heat pumps (HP), with reference to building configurations LEE and HEE

	Loads		Heat pump	
Case	$P_{LD,H,DES}$ [W]	$P_{LD,C,DES}$ [W]	$P_{HP,H,DES}$ [W]	$P_{HP,C,DES}$ [W]
LEE	7900	7600	8690	9350
HEE	3500	5400	5500	5940

More details on the simulated detached house and the related configurations LEE and HEE are given in the following lines:

- Site: Milan
- Size:
  - Net floor area: 200 m^2
  - Heated volume: 540 m^3
- Envelope:
  - LEE:
    - Vertical walls: U = 0.83 W/(m^2·K)
    - Windows:
      - U = 1.91 W/(m^2·K)
      - SHGC = 0.70
  - HEE:
    - Vertical walls: U = 0.20 W/(m^2·K)
    - Windows
      - U = 1.06 W/(m^2·K)
      - SHGC = 0.51
- Ventilation:
  - LEE: 0.5 m^3/h, with no air-to-air heat recovery
  - HEE: 0.5 m^3/h, with air-to-air heat recovery (ε = 70%)
- Occupancy: 4 people
- DHW demand: 50 l/day per person at 40°C.
- Internal heat gains: 9 kWh/day, distributed during the day with typical scheduling
- Temperature control: active from 7:00 to 21:00 (14 hours), every day

RESULTS AND DISCUSSION

The results of the set of simulations performed are shown in terms of performance indicators on seasonal basis such as the renewable energy ratio (R_{REN}, in *Equation 1*), according with European RES Directive [EU, 2009], average capacity ratio, part load factor, heat pump COP and system COP, both for heating and for cooling.

$$R_{REN} = (E_{Solar} + E_{HP\text{-}ExtSource}) / (E_H + E_{DHW} - E_C) \qquad (1)$$

where:

- R_{REN} is the total fraction of renewable energy used in the plant
- E_{Solar} is the amount of renewable energy exploited by the solar thermal system
- $E_{HP\text{-}ExtSource}$ is the amount of renewable energy exploited by the heat pump and consisting in the heat collected from the outdoor air in heating mode
- E_H is the total amount of energy demand for indoor environment heating
- E_{DHW} is the total amount of energy demand for domestic hot water preparation
- E_C is the total amount of energy demand for indoor environment cooling

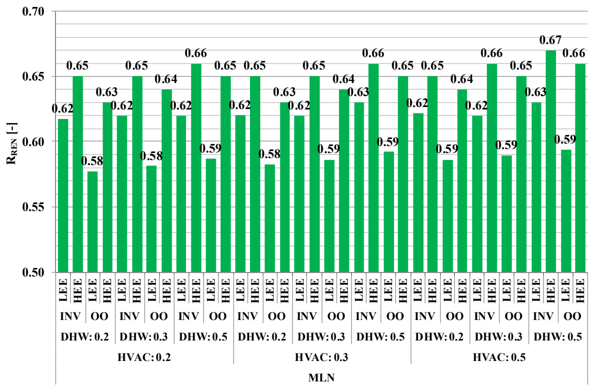
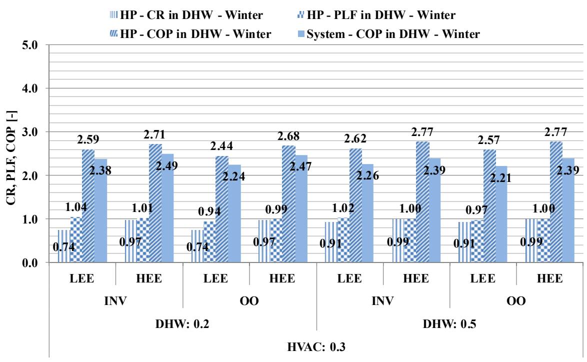


Figure 5 – Share of renewable energy for the simulated cases, where INV = Inverter-driven heat pump, OO = On-Off heat pump, DHW = DHW storage volume (in m^3), HVAC = HVAC storage volume (in m^3)

Figure 5 shows the values of R_{REN} for the simulated configurations. Basing on *Figure 5*, the difference between the best and the worst R_{REN} values is around 14%. In particular, the highest shares in renewable energy exploitation are achieved in case HEE, in particular by means of large water heat storages for DHW preparation and heating/cooling (HVAC). Moreover, in the case of high performance buildings, really small difference arises between on-off and inverter-driven heat pumps. As a matter of fact, in case HEE, the heat pump has a smaller size, so it works at high capacity ratios for the most of time, whereas, in case LEE, the difference between on-off and inverter-driven heat pumps is larger.

The simulations gave more detailed outputs, used to achieve better acquaintance of the improvement on the plant efficiency that may be achieved by each configuration.
For this purpose *Figure 6*, *Figure 7*, and *Figure 8* are shown.



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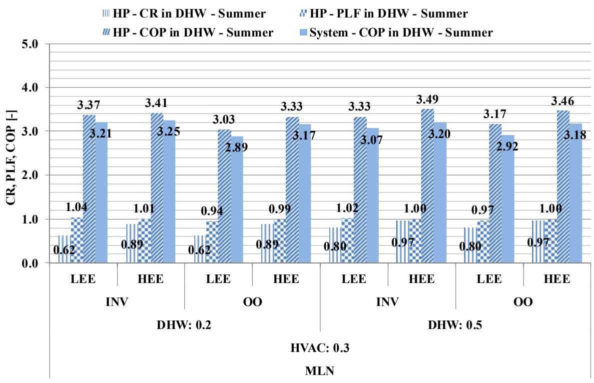
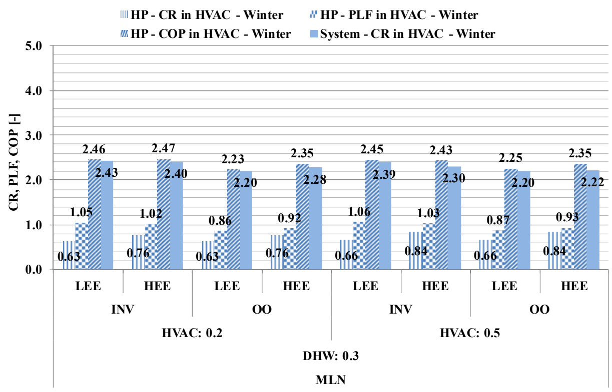


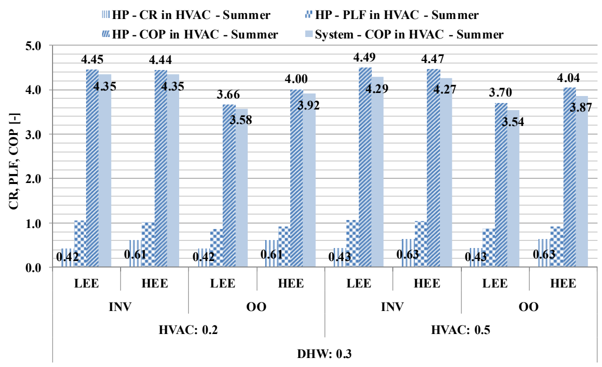
b)

Figure 6 – Average capacity ratio (CR), part load factor (PLF), heat pump COP and system COP for domestic hot water preparation in winter (a) and summer (b)

Figure 6 shows the performance of the system in domestic hot water preparation, in particular for cases with 0.3 m^3 HVAC storage and 0.2 m^3 and 0.5 m^3 for DHW storage. In this figure, average capacity ratio, part load factor, heat pump COP and system COP (i.e. taking into account even heat losses from the DHW heat storage) are shown. In winter, the simulated system COP for DHW preparation ranges from 2.21 up to 2.49, thus resulting in a total difference around 12%. Of course, capacity ratios (CR) increase with the DHW water storage volume, with different consequences on the related average part load factor (PLF). In fact, the PLF of on-off heat pumps improves together with the increase of CR, whereas the PLF of inverter-driven heat pumps decreases along with the increase in CR, because of the PLF-CR curve shape. As a consequence, better PLF are achieved in case LEE and with small DHW storage volume. Anyway, COP do not always increase with PLF. As a matter of fact, in case of HEE, the heat pump works with higher COP due to lower operation temperature. In fact, the heat pump has a smaller size, so, at the beginning of the phase of storage charging, it does work with lower outlet temperatures, hence with better COP. The final value of heat pump COP is a balance of the effects due to PLF increase and heat pump size, in case of inverter-driven heat pumps. In case of on-off control, the relevant increase in PLF implies always the increase of heat pump COP, indeed. As regards the heat pump COP, the best result is achieved in case of inverter-driven heat pump coupled with large DHW storage volume and efficient building. But, in the end, the system COP is better for the configuration with inverter-driven heat pump coupled with the smaller DHW storage and the efficient building. As a matter of fact, the system COP, i.e. the actual COP, is about 8% and 15% lower than the heat pump COP in case of 0.2 m^3 and 0.5 m^3 of DHW storage volume respectively, due to heat losses through the water storage shell.
In summer, the system COP for DHW preparation ranges from 2.89 up to 3.25, thus resulting, even in this case, in a total difference around 12%. The same notes as for the winter period can be performed. Also in this case the best overall performance in DHW preparation comes from the configuration having inverter-driven heat pump coupled with small DHW storage and efficient building. In summer, the lower temperature difference between the DHW storage and the ambient temperature limits the heat losses, so the system COP is about 5% and 8% lower than the heat pump COP in case of 0.2 m^3 and 0.5 m^3 DHW storage volume respectively. Anyway, the system COP shows that no relevant advantage is brought on system COP by larger DHW storage volumes.
Figure 7 shows the performance of the system in heating/cooling, focusing on the system configurations having 0.3 m^3 for DHW storage and 0.2 m^3 and 0.5 m^3 for HVAC storage respectively. In winter, the simulated system COP for HVAC ranges from 2.20 up to 2.43, thus resulting in a total difference around 10%, whereas in summer such a difference is much larger, around 19%, being 3.54 and 4.35 the worst and the best system COP respectively.
In summer, the best performance is achieved by means of inverter-driven heat pumps, with scarce influence due to the water storage volume and building envelope efficiency. On-off heat pumps are much more influenced by the level of heating/cooling loads (LEE and HEE) indeed, much more than in the heating period.
Anyway, also in this case, both for heating and for cooling, no relevant difference in overall system COP due to larger HVAC storage volumes take place. As a matter of fact, heat pump COP are similar in case of 0.2 m^3 and 0.5 m^3 for HVAC storage volumes, whereas the heat losses differ but have a small impact, lowering the COP by about 2÷5%.



a)



b)

Figure 7 – Average capacity ratio (CR), part load factor (PLF), heat pump COP and system COP for heating (a) and cooling (b)

Figure 8 may help to quantify the delay in matching heating/cooling loads in each configuration. In particular, in *Figure 8*, the number of occurrences of delays in heating/cooling loads fulfillment is shown. In a few words, for instance, in case of systems sized for low performance buildings (LEE) and provided with on-off heat pump, and 0.5 m^3 and 0.2 m^3 heat storage volumes for DHW and HVAC respectively (DHW = 0.5 and HVAC = 0.2), the heating/cooling loads may be met with a delay around 1.0 h three times in a year.

The worst situation is expected for configurations having large DHW storage and small HVAC storage volumes, especially when sized to be coupled with high efficiency buildings, and the simulations confirm this. Anyway, the number of occurrences of unmatched heating/cooling loads is low and they are mainly limited within half an hour. Moreover, it is enough to adopt 0.3 m^3 HVAC heat storage volume to get much lower number of occurrences, with no occurrence at all in the case of a 0.5 m^3 HVAC storage volume. This means that no discomfort issues may arise. Moreover, such results may be further improved by proper modification of the control strategy, in order to charge the DHW storage when heating/cooling is not needed, for instance during the night, remembering that, with such a modification, lower COP may take place, due to lower outdoor temperatures at night, hence lowering the global efficiency of the system.

In Figure 8 only results regarding on-off heat pump are shown because of the perfect correspondence with respective results obtained for inverter-driven heat pumps.

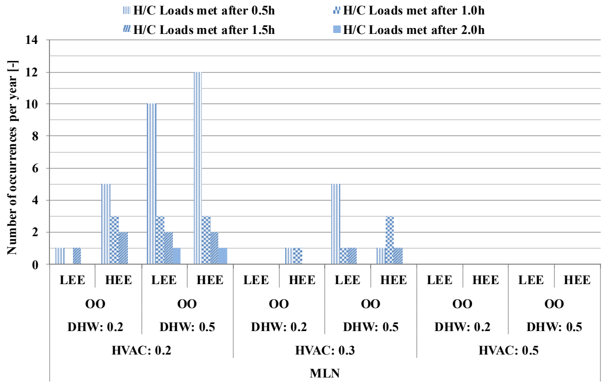


Figure 8 – Occurrences of heating/cooling load matching delays

CONCLUSION

The simulation tool under development allows the user to perform detailed analyses about the operation of HVAC systems, as well as to assess the best system configurations and to adapt controls for the optimized exploitation of renewable energy sources. In particular, in this paper, the simulation tool under development is used to analyze issues that may arise in heat pump systems providing both domestic hot water and heating/cooling. The software showed the best configurations under energy perspectives and allowed even the evaluation of possible discomfort issues that might take place in case of under-sized heat pumps.

The results showed overall differences around 15% in the exploitation of outdoor air thermal energy, according with European RES Directive, and the best results were achieved by means of inverter-driven heat pumps coupled with high efficiency building envelopes. However, in case of inverter-driven heat pumps, no relevant difference is encountered between systems sized for low energy buildings and systems sized for traditional buildings, whereas larger differences are found in case of on-off heat pumps.

More results highlighted the trend of average capacity ratio, part load factor, heat pump COP and system COP in DHW preparation and HVAC operation, in winter and in summer, identifying inverter-driven heat pumps as the key choice, able to ensure constantly high performance, no matter the heat storage volume and the level of energy efficiency of the building coupled with the system.

In general, however, the results show a scarce influence on heat pump performance due to heat storage volume, mainly due to the higher heat losses taking place across the shell of large heat storages, ensuring, on the other hand, better performance on the heat pump side. In fact, larger volumes of DHW and HVAC storages can increase the reliability of the system, and ensuring lower cycling and the ready fulfilment of HVAC demand. On this aspect, the results showed that, even in case of large DHW water storages, the smallest HVAC storage volume (0.2 m^3) can provide sufficient thermal energy to feed the system during periods in which the heat pump is used to charge the DHW storage.

NOMENCLATURE

Symbols

P = Power [W]
E = Energy [kWh]
R = Ratio [-]

Subscripts

C = Cooling purposes
COP = Coefficient of Performance (used in a general meaning, i.e. both for heating and for cooling purposes)
DES = Design
DHW = Domestic Hot Water preparation
H = Heating purposes
HP–ExtSource = From the external source of the heat pump
LD = Loads
REN = From renewable energy sources
Solar = From solar energy sources

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