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Energy retrofit of an office building by substitution of the generation system: performance evaluation via dynamic simulation versus current technical standards

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Abstract. Constructions built in Italy before 1945 (about 30% of the total built stock) feature low energy efficiency. Retrofit actions in this field can lead to valuable energetic and economic savings. In this work, we ran a dynamic simulation of a historical building of the University of Pisa during the heating season. We firstly evaluated the energy requirements of the building and the performance of the existing natural gas boiler, validated with past billings of natural gas. We also verified the energetic savings obtainable by the substitution of the boiler with an air-to-water electrically-driven modulating heat pump, simulated through a cycle-based model, evaluating the main economic metrics. The cycle-based model of the heat pump, validated with manufacturers' data available only at specified temperature and load conditions, can provide more accurate results than the simplified models adopted by current technical standards, thus increasing the effectiveness of energy audits.

1. Introduction

Energy requirements for the residential and tertiary sector account for a significant share of the total energy uses. In Italy, this share is about 30% [1]. In the European Union, according to Directive 2010/31/EU [2], energy costs for heating and cooling of buildings represent about 40% of the total energy uses. For this reason, many programs have been developed in order to encourage policies of energy efficiency and measure progress in this field. Odyssee project, for example, has collected energy efficiency data from all countries in the European Union for the last 2 decades and verified that energy consumption in the building sector has increased by around 1%/year since 1990, mainly in non-residential buildings (characterized by an average specific consumption of about 295 kWh/m^2) [3]. Retrofit actions in this field can lead to significant energy savings.

In Italy, about 30% of constructions were built before 1945 [4]: many of these buildings have low energy efficiency, but are protected against refurbishment, having a significant heritage value, so retrofit actions involving the envelope cannot be applied. In these cases, great energetic and economic savings can be obtained through the substitution of traditional low-efficiency boilers with new high-efficiency generators such as Heat Pumps (HPs).

Current technical standards (see for instance UNI/TS 11300-4 [5]) define the procedure to calculate the performance of HPs during the heating season and evaluate the energetic savings obtained by the installation of these generators. These models are "black boxes", because they require only few manufacturers' data and do not accurately consider the influence of some parameters, viz.: temperature evolution of the external source and of the end-user loop or destination thermal source, conditions of partial load, properties of the working refrigerant, efficiencies of individual components (heat exchangers, compressor or absorption and generation unit), control types, defrosting mode.

A development of a cycle-based model for the simulation of a HP can provide more accurate outputs than "black box" methods: these outputs are necessary for a correct energy audit, hence for a precise estimate of the obtainable energetic and economic savings.

2. Definition of the test case

With the aim of verifying the effective savings that could be obtained by a substitution of an inefficient generator with a HP (simulated through a dynamic model), we chose an existing building of historical value, which can be considered as representative of many Italian PA and office buildings, in terms of characteristics of structure, systems and uses and also in terms of the proposed retrofit measure.

The building used for the test case is known as Palazzo Venera, property of the University of Pisa.

Palazzo Venera is a five-story building in the centre of Pisa (gross volume about 13,000 m^3), facing west on the central street Via Santa Maria and facing east on a courtyard garden. It is bordered on both the southern and northern side by private buildings (heated in the winter season, thus considered as adiabatic surfaces).

We considered only the three central levels (first, second and third floor that are for office use only), excluding the ground floor with classrooms and the under roof space. We divided this volume into six zones, in order to distinguish the east and the west zone of each floor, characterized by the presence of different obstructions and shadings and so by different solar radiation. Table 1 shows the characteristics of each zone in terms of transmittance of opaque walls and windows. We implemented schedules for the presence of people, use of electrical equipment and artificial lighting; they were chosen after inspection and users' interviews. They are different for weekdays and Saturdays; during festivities (in total 14 days of the heating period) and Sundays the building is closed.

There is a fan coil in every office, but not all fan coils are activated during the heating season: so we estimated a number of active fan coils for each zone, as a result of both building inspection and simulated audit. Fan coils are controlled within the proportional band 18°C-20°C.

The distribution system is divided into two loops: the hot water provided by the boiler is distributed in the whole building through a primary loop and the secondary loop of each zone provides energy independently from the other zones.

The heat generator is a traditional natural gas boiler of nominal power 230 kW, with climate control. This boiler is switched on from 7 a.m to 6 p.m., from Monday to Friday, and from 7 a.m. to 1 p.m. on Saturdays, during the heating season of Pisa (1st of November – 15th of April, Heating Degree Days: 1694).

The gas consumption of the whole building has been assigned to the zones in proportion to the building total installed power of fan coil units; as a consequence, 49.9% of the primary energy use is attributed to the 3 simulated floors, corresponding to 102 MWh, according to the last 5 years of natural gas billings.

Table 1. Characteristics of each thermal zone (MTT: Mean Thermal Transmittance, in W/(m^2K) , E east, W west).

Thermal zone	External opaque walls		External glazed elements		N° of fan coils
	Area [m^2]	MTT	Area [m^2]	MTT	
1st floor E	157.7	1.59	31.1	4.08	15
1st floor W	193.3	1.17	42.8	4.08	8
2nd floor E	153.9	1.88	25.9	4.08	15
2nd floor W	192.5	1.17	43.6	4.08	8
3rd floor E	112.2	1.78	25.9	4.08	15
3rd floor W	139.7	1.46	33.1	4.08	8

Further details about the characteristics of the building under exam, including its use, and about the assumptions of the simulation can be found in [6].

3. Dynamic simulation of the building

A full dynamic simulation of Palazzo Venera was run on TRNSYS 17, interfaced with Matlab. As shown in Figure 1, a TRNSYS routine and a Matlab script calculated the energy requirements of the building, simulating the heat exchange of the fan coils. A second Matlab script calculated the performance of the generation system (first the existing natural gas boiler, then a HP with a back-up boiler). The simulation time step was 15 minutes.

In the TRNSYS routine, we modeled the characteristics of the envelope of the analyzed area in terms of transmittance of the opaque walls and windows. We also implemented the air exchange due to infiltrations (0.3 volumes per hour) and the profiles of the presence of users in offices, of the uses of electrical equipment and of artificial lighting.

As for the climatic data, we used hourly external temperature, beam and diffuse solar radiation on the horizontal plane, relative air humidity and wind velocity: all these data were provided in 2012 by the Italian Thermotechnical Committee (CTI). These values were interpolated in order to obtain four data points per hour, according to the chosen simulation time step. On the west side, the buildings in front of Palazzo Venera were considered as obstructions for the radiation and the sloped roof as a horizontal shading for the third floor only. On the east side, the south-east wing of the building itself is a vertical shading.

A Matlab routine, directly linked to the TRNSYS simulation, calculated the heat provided in each zone by the fan coils, considered by TRNSYS as a purely convective internal gain. The supply temperature to the six zones was calculated for every time step as a function of the corresponding external temperature.

When fan coils in a zone were active, the routine would calculate the return temperature with the energy balance expressed by Equation 1, valid for each emitter:

$$\dot{m}c\left(T_s - T_r\right) = UA\left(\frac{T_s + T_r}{2} - T_i\right) \qquad (1)$$

where $\dot{m}$ is the water mass flow rate of a fan coil unit (250 kg/h), c is the water specific heat, T_s and T_r are, respectively, the water supply and return temperatures, U is the total heat transfer coefficient and A the area of the heat exchange coil of the unit (from manufacturer's datasheets), and T_i is the internal air temperature, calculated by TRNSYS at each time step and for each air node. The U-value of the fan coil unit was found by manufacturers' datasheets.

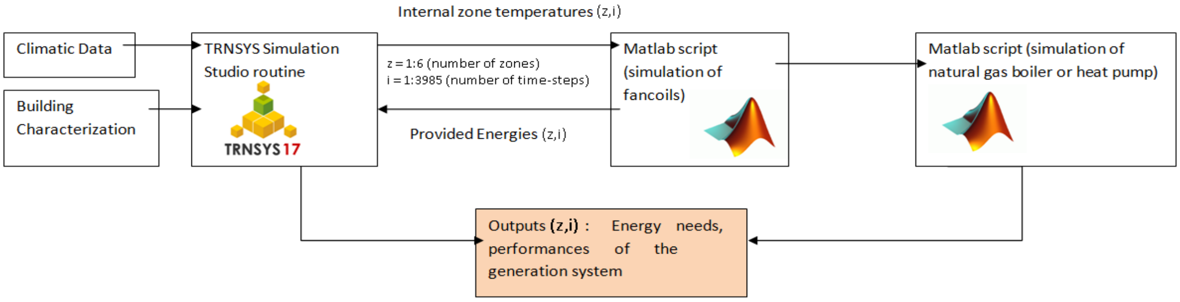

Figure 1. Simulation flow diagram of the routines and software.

Due to the low amount of contained water, fan coils can be considered steady systems, thus no transient terms were included in Equation 1. Once T_r is obtained, the energy Q_{heat} delivered to the zone by all the fan coil units is given by Equation 2:

$$Q_{heat} = \mathrm{n}\,\dot{\mathrm{m}}\,\mathrm{c}\left(\mathrm{T_s}\text{-}\mathrm{T_r}\right)\cdot \mathrm{t} \qquad (2)$$

where n is the number of fan coil units in the zone and t is the duration of the time step. The energy gain calculated for each zone and time step was used in the TRNSYS simulation at the subsequent time step due to convergence issues.

As a result of this first part of simulation, TRNSYS provided, for the entire heating season, the evolution of internal temperatures of the examined zones (e.g., air, mean radiant and operative temperatures), share-outs of global energy use among the zones and specific contributions of heat losses (transmission and infiltration) and gains (internal and solar). Figure 2 presents these results through a pie chart, relative to the whole heating season and to all the zones: in the graph legend we reported the value of each contribution and its relative weight.

In the second part of the simulation, we evaluated the primary energy used by the natural gas boiler. We summed the energy needs provided by TRNSYS with the heat losses due to the distribution and the generation system. The two latter terms were calculated using the methodologies described in the Italian standard UNI/TS 11300-2:2008 [7] and the efficiency data provided by the manufacturer of the generator.

The resulting primary energy use for the analyzed zones (accounting for the 49.9% of the energy requirements of the whole building) is equal to 111 MWh.

The 8.8% deviation between this output and the average consumption based on the last five years of billings (102 MWh) confirms appropriate accuracy of the developed method. The seasonal efficiency of the boiler is 94.9%. We also calculated that the total electric energy absorbed by pumps, fans and other auxiliaries is 5.2 MWh. Using the primary energy factor for electric energy (equal to 2.174, according to the Italian Regulatory Authority for Electricity and Gas), we found that the overall primary energy use per gross volume is 14.9 kWh/m^3.

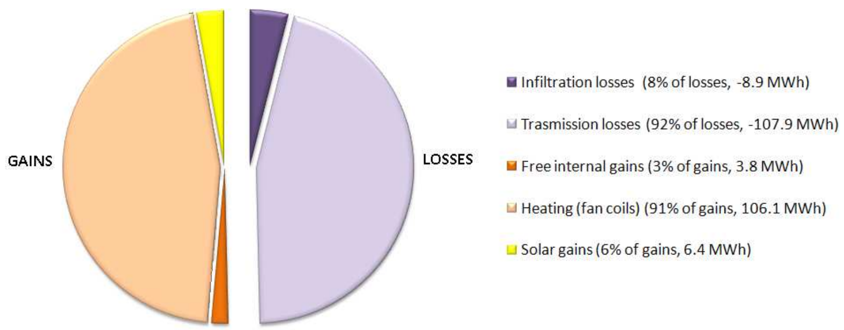

Figure 2. Energy balance of the building envelope in the heating season.

4. Description of the heat pump system cycle-based model

In order to evaluate the effectiveness of a retrofit action consisting in the substitution of the generator, we hypothesized that the energy requirements of the analyzed volume would be satisfied by an air-to-water electrically-driven modulating HP. Based on the manufacturer's data, the nominal thermal power of the HP was 100 kW, while the maximum power was 130 kW. The declared COP at external source temperatures 7°C and mean end-user loop temperature 42.5 °C was 3.48. An auxiliary natural gas boiler, with the same nominal performance of the existing one, provided back-up energy out of the working range of the HP.

The HP seasonal heating performance was obtained by simulating the evolving inverse thermodynamic cycle, calculated at every time step. We modeled all the thermodynamic transformations of the refrigerant (compression, condensation, expansion and evaporation), similarly to Jin [7], Armstrong et al. [9], Zakula [9], Corberan et al. [11] and Carbonell et al. [11]. In literature, there are several models characterized by different procedures for calculating the thermodynamic states and flow rate of the refrigerant during the cycle. For the cycle-based model that we propose, we used the following assumptions:

- the isentropic efficiency and the overall electro-mechanical efficiency of the scroll compressor depend on the compression ratio, similarly to [12];
- the UA-value of the evaporator and of the whole condenser are determined from manufacturers' data (U: total heat transfer coefficient of the coils of the heat exchangers; A: heat transfer area of the coils of the heat exchangers);
- the ratio between U of the condenser and U of the superheater is fixed;
- the heat exchanged in the subcooler of the condenser is a fixed percentage of the total heat exchanged in the condenser;
- the temperature of the refrigerant at the exit of the evaporator is 1 K higher than the evaporation temperature;
- energy losses due to defrosting cycles are considered through a COP penalization, depending on external temperature and relative humidity, as proposed in [13].

The HP under exam uses R134a as refrigerant: this fluid has a high critical temperature (over 100°C), so its use is strongly recommended when the emitters are fan coils. The thermodynamic characteristics of R134a were provided to the Matlab routine by a property database. For every time step, the routine calculated temperatures, pressures, enthalpies and densities of the refrigerant in correspondence of every single HP component. The compressor speed was also determined. If the speed of the scroll were less than the minimum modulation value, the HP would switch off and the energy requirement of that time step would be satisfied by the back-up boiler. In addition, if the speed of the scroll were greater than its maximum value, the scroll would work at maximum power and the residual energy would be provided to the building by the boiler.

As for the condenser and the evaporator, the Matlab routine used the ε-NTU method [15], verifying the energy balance in the heat exchanger for both the refrigerant side and the secondary side (water in the condenser, air in the evaporator). The throttle valve was considered isenthalpic and controlled the superheat of the refrigerant at the evaporator exit. As already mentioned, the compressor was a scroll type connected to an inverter: as every reciprocating compressor, the flow rate in the scroll is proportional to the compressor speed and independent from the provided pressure ratio.

In summary, at each time step, the Matlab routine calculated the heat exchanges, the electric energy requirement and the performance of the HP.

5. Performance results: cycle-based simulation vs. technical standard

5.1 Calculation by cycle-based model

First, we verified that, at the same source temperatures, the calculated COP differed by less than 5% from the COP declared by the manufacturer.

The calculated balance temperature of the building – heating system was 2.1°C, as shown in Figure 3. If the building required a greater heat power than the one provided by the HP (red solid line), the boiler would provide the residual energy. If the building required a lower heat power than the minimum deliverable by the HP (red dashed line), this power would be provided by the boiler only.

The resulting Seasonal Performance Factor (SPF) of the HP was 3.8, with minimum values of 1.9 reached at the lowest external temperatures and maximum values above 6 under partial load conditions and mild temperatures. The number of on/off cycles undergone by the HP unit during the 144 heating days was only 165. Unlike black-box models, the present cycle-based simulation could find performance improvement at partial loads, which are the most frequent operative conditions. Defrost cycles entailed a 2.2% penalization of SPF.

The strong influence of the external temperature on COP is shown in Figure 4, in which the profile of external temperature and of COP during five working days (between January and February) are represented. The *inertia* of the building also influences the profile of COP, as it is shown in the third curve of the figure (Monday).

Figure 5 shows the Primary Energy Ratio (PER) of the whole heating system (HP and back-up) as a function of the load factor (or Capacity Ratio, CR). Minimum values were reached when only the boiler was active (lowest partial loads); high efficiency values were reached at intermediate partial loads and tended to decrease when the ratio of the energy provided by the boiler and the total energy required by the building increased. The strips of data observable in the graph are due to the particular heating control, that is a zone heating control: when a zone reaches the upper dead-band temperature (20°C), all its fan coil units switch off, so there is not a control on each single unit, but a control on sets of fan coil units.

The HP required 24 MWh_{el} to heat the building. The natural gas boiler required 14 MWh of primary energy and its mean seasonal efficiency was 95.1%. The primary energy required for the whole heating system was equal to 77.4 MWh (also considering the electric energy absorbed by pumps, fans and other auxiliaries, equal to 5.2 MWh) leading to a 38% saving of primary energy (about 46 MWh) with respect to the original system. The seasonal PER was 1.6 (69% higher than the efficiency of the existing boiler).

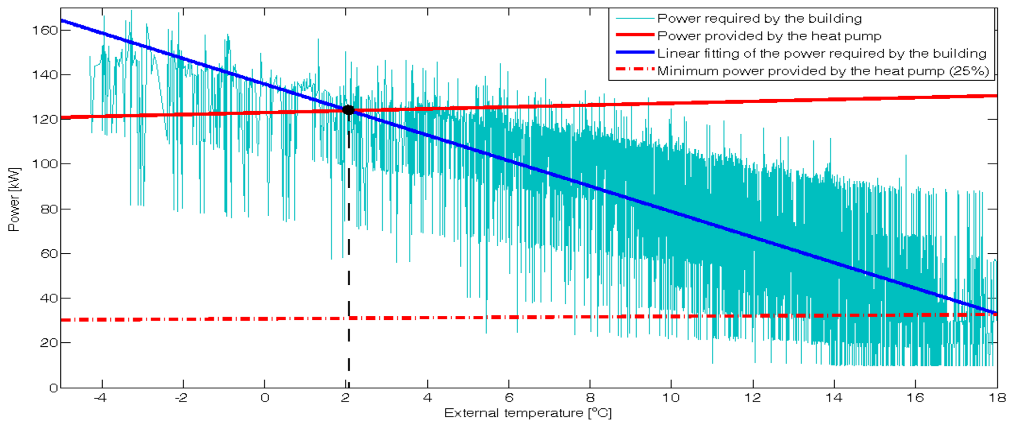

Figure 3. Balance temperature of the system.

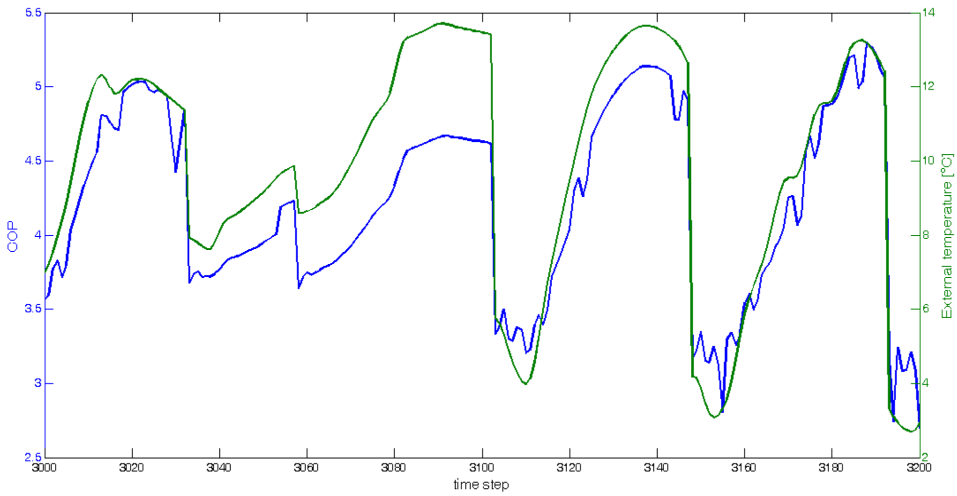

Figure 4. Profiles of external temperature and COP during five working days.

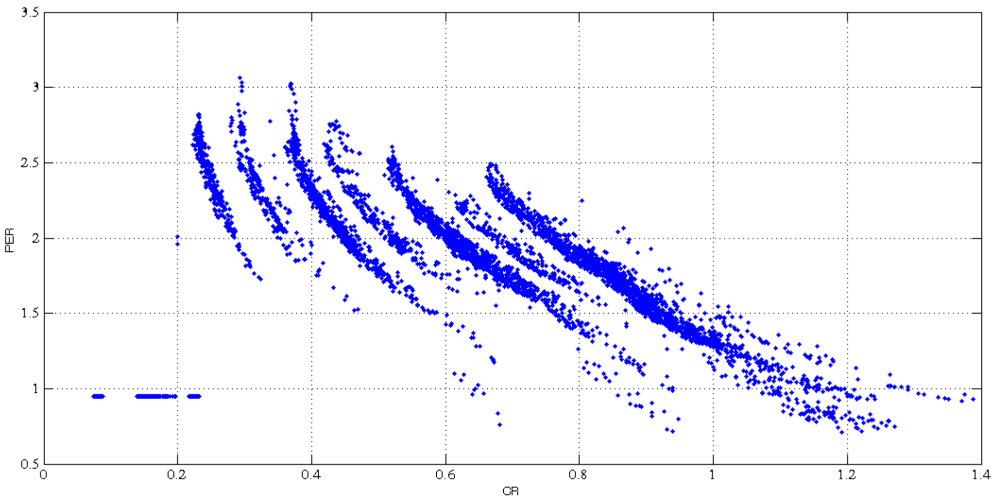

Figure 5. PER vs. CR of the whole heating system (HP and boiler).

5.2 Calculation by current technical standard

An alternative simulation of the HP performance was run on spreadsheets implementing the quasi-steady state procedure described in Italian Standard UNI/TS 11300-4 [5]. According to this standard, the energy provided and the monthly and seasonal performance of a HP can be calculated by interpolation of manufacturers' data of COP at particular temperatures of the secondary fluids in the heat exchangers. We used the same HP of thermal nominal power 100 kW employed for the cycle-based simulation.

The calculation showed that the chosen HP could satisfy the monthly energy requirements of the building, without the auxiliary boiler, but with a SPF of 2.3 (39% lower than one obtained with the cycle-based simulation). The procedure described in technical standard UNI/TS 11300-4 leads to underestimate values of COP because it does not take into account the effects of intermittent heating and climate control, thus leading to lower load factors during the heating season and a higher source temperature of the end-user loop. These two elements negatively affect the HP performance; particularly, low CR values entail great performance penalization, according to the COP reduction factor defined in [15].

6. Economic evaluation of the investment

Once we verified the energetic effectiveness of the substitution of the traditional boiler with a HP, we performed an economic analysis of the retrofit action. We developed a specific routine for the investment analysis, requiring, as inputs, the energetic savings obtained with the retrofit action, costs of the energetic vectors and of the retrofit action, maintenance costs for the original and the retrofit system, inflation and discount rates and possible government incentives.

The cost of the new heating system (HP and auxiliary boiler) was 47 k€. The estimated lifetime of this new system was 15 years. The cost of a new boiler, with the same performance and characteristics of the current one, whose remaining useful life was 2 years, was 9 k€. The maintenance costs increased of 100 € per year with the substitution of the boiler. According to current state laws, the installation of a HP is boosted by the Italian government with a 10-year refund of 65% of the investment.

Two simulations were run, considering different scenarios for the inflation rates. In any case, the economic analysis showed that the substitution of the generator would lead to significant profits. Table 2 summarizes the inputs of the analysis and the resulting indexes for the evaluation of the investment, using the energetic savings obtained with the cycle-based model.

Table 2. Economic analysis: inputs and resulting indexes.

Inputs					
Discount rate	Electric energy cost	Natural gas cost	General inflation rate	Electric energy inflation rate	Natural gas inflation rate
2%	165 €/MWh$_{el}$	72 €/MWh$_{th}$	1st scenario: 2%	3%	3%
			2nd scenario: 4%	7%	7%

Results			
Discounted Payback Period (DPP)	Net Present Value (NPV)	Profitability Index (PI)	Internal Rate of Return (IRR)
1st scenario: 7 years	45 k€	0.95	14%
2nd scenario: 6 years	49 k€	1.0	17%

Two similar simulations were run, using the same specific routine for the investment analysis but using the energetic savings obtained with the methodology described in current technical standard. In this cases, the substitution of the boiler with the heat pump was not cost-effective, with no payback of the investment.

7. Conclusions

We presented a procedure for accurately predicting the energetic and economic impact of a paradigmatic retrofit measure in a protected office building: the substitution of a traditional boiler with an air-to-water modulating electric Heat Pump (HP). Acting on the generation system can have a large impact on the overall system efficiency; besides, particularly in historical buildings, it is a feasible and common solution, unlike other ones involving the protected envelope.

By modeling all the subsystems and coupling software like TRNSYS, Matlab and a refrigerants' property database, it was possible to perform a full dynamic simulation of the building and its plant. Similar all-inclusive methods are recently under development (see, for instance, [17]).

The calculated baseline energy consumption of the test case was coherent with the available history of natural gas billings. The main results for the HP system were: 38% of primary energy savings with respect to the existing boiler and around 15% of internal rate of return of the investment. The proposed energy efficiency measure could have wide application, given that the accuracy of the underlying dynamic models allows operating in a frame of reliability.

On the other hand, following the HP performance evaluation procedure defined in current technical standards, the energetic efficiency of the HP system (in terms of primary energy ratio) resulted only 11% higher than the original boiler, with no payback of the investment. This major underestimation by the technical standard in terms of HP performance pushes towards the adoption of dynamic physically-based methods, as the one presented herein, in order not to penalize the HP technology in evaluations for energy audits or in design trade-offs.

Experimental validation of the proposed model by application to existing plants and by continuous monitoring in laboratory facilities is in view.

Possible further developments are:

- optimization of the climate control curve and of the control logic that switches on/off the HP and the back-up generator, in order to maximize the system PER;
- proposal and evaluation of quasi-steady state methods, alternative to the ones suggested by current standards and tailored to energy audits (e.g., taking into account the actual heating hours of the building), to be implemented in dedicated software, like SEAS (Simplified Energy Auditing Software) [17].

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References

[1] ENEA 2003 *Risparmio Energetico nella Casa. Sviluppo Sostenibile* Booklet G1-034-0
[2] European Parliament 2010 *Directive 2010/31/EU* Official J. European Union
[3] 2012 *Odyssee Project* European Energy Efficiency Database
[4] ISTAT 2001 *14° General Census of Population and Housing* Italian Institute of Statistics
[5] UNI 2012 *UNI/TS 11300-4* Italian Unification Body
[6] Testi D, Schito E, Menchetti E and Grassi W 2014 Dynamic simulation of a heat pump serving a historical building: seasonal performance and economic evaluation *Proc. 49th AiCARR Int. Conf. (Rome)*
[7] UNI 2008 *UNI/TS 11300-2* Italian Unification Body
[8] Jin H 2002 *Parameter Estimation Based Models of Water Source Heat Pumps* Ph.D. Thesis Oklahoma State University
[9] Armstrong P R , Jiang W, Winiarski D, Katipamula S, Norford L K and Willingham R A 2009 *HVAC&R ASHRAE* **15** 366
[10] Zakula T 2010 *Heat Pump Simulation Model and Optimal Variable Speed Control for a Wide Range of Cooling Conditions* Master Thesis Massachusetts Institute of Technology
[11] Corberan J M , Finn D P, Montagud C, Murphy F T and Edwards K C 2011 *Energy and Buildings* **43** 82
[12] Carbonell S D, Cadafalch R J, Pärlisch P and Consul S R 2012 Numerical analysis of heat pumps models: comparative study between equation-fit and refrigerant cycle based models *Proc. Int. Conf. on Solar Heating, Cooling and Buildings, EuroSun 2012 (Rijeka, HR)*
[13] Nardotto D 2009 *Analisi Sperimentale e Modellizzazione di Circuiti Frigoriferi con Compressore ad Inverter Impiegati nella Refrigerazione Commerciale* Ph.D. Thesis University of Padua
[14] Lazzarin R, Busato F, Nardotto D and Noro M 2009 *Studio del Brinamento delle Batterie su Pompe di Calore a Compressione* Report RSE/2009/31 (Rome: ENEA)
[15] Incropera F P and DeWitt D P 2002 *Fundamentals of Heat and Mass Transfer (5th Ed.)* (New York: Wiley)
[16] CEN 2012 *EN 14825* European Committee for Standardization
[17] Buonomano A, Calise F and Palombo A 2012 *Applied Energy* **91** 222
[18] Testi D, Menchetti E, Schito E and Grassi W 2013 An open access tool for building energy audits harmonizing European standards *Proc. Building Simulation Applications Conf., BSA 2013 (Bozen-Bolzano, IT)*