Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2811 – 2817

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Multi-functional Integrated System for Energy Retrofit of Existing Buildings: A Solution Towards nZEB Standards

N. Aste[a], R. S. Adhikari[a], C. Del Pero[a], F. Leonforte[a]*

[a] Department of Architecture, Built environment and Construction Engineering, Politecnico di Milano, Via Bonardi 9, 20133 Milano, Italy

Abstract

The present work is aimed at assessing the energy performances of a multi-functional integrated system designed to cover the HVAC needs using renewable energy sources (RES), with a specific focus on residential buildings. In detail, within the system design, RES are represented by building integrated photovoltaics (BIPV) and aerothermal energy. The heating, cooling and DHW demand is in fact satisfied by a reversible and high efficiency air-water heat pump with continuous power modulation, optimized for the specific purpose, directly fed in direct current (DC) from the PV. The eventual surplus of PV production can be stored in form of thermal energy thanks to a dedicated storage system for providing heating, cooling or DHW production in the periods when there is no/low solar radiation. Moreover, the system is able to minimize the peak power demand of electricity, according to the match between PV electricity generation and usable/storable thermal energy demand. The results of the energy simulations on a case study residential building demonstrate the effectiveness of the proposed system towards nZEB standards.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Energy retrofit, multi-functional HVAC system, modular heat pumps, photovoltaics, nZEB

Nomenclature

AC	Alternate Current
BIPV	Building integrated photovoltaics
COP	Coefficient of Performance
DC	Direct Current
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
HP	Heat Pump
nZEB	Nearly Zero Energy Building
TMY	Typical Meteorological Year
U	Thermal trasmittance [W/m^2K]

* Corresponding author. Tel.: +39-02-2399 3891
E-mail address: fabrizio.leonforte@polimi.it

1876-6102 © 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.608

1. Introduction

The building sector in Europe is responsible for 41% of final energy consumption, 27% of which is attributable to the residential sector (within which approximately 80% is due to space heating and DHW). Furthermore, it has to be noted that a major item is the constantly increasing demand (3.14% annually) for air conditioning in the summer, which occurs mainly in the Central and Southern European countries (68% of the EU total demand) [1]. Latter data can also be interpreted considering climate change, the increase in the levels of required comfort and the gradual raising of thermal insulation level of buildings envelope, which could even cause overheating in areas with warmer summers.

The goal to reduce energy consumption by 80% in 2050 fixed by the EU [2] is supported by the definition and implementation of the nearly Zero Energy Building (nZEB) targets. In fact, in recent years buildings energy efficiency registered a continuous improvement, thanks to the introduction of new standards firstly promoted by the EPBD (Energy Performance of Buildings Directive). However, the overall improvement is offset by the low renewal rate of existing building stock, estimated about 1% annually, compared with a target of 2.5% necessary to redevelop the entire building stock by 2050 [3].

In order to achieve the nZEB standard, it should be noted that a significant increase in energy efficiency of existing buildings cannot be simply achieved by means of envelope works (e.g. external thermal insulation and/or windows replacement) but rather by combining these with the adoption of high performance system solutions for HVAC, that also include the installation of renewable energy sources.

Among various RES, PV is currently the more competitive and versatile technology for building applications [4] and, usually, a nZEB-oriented building cannot disregard the installation of BIPV systems [5].

Nowadays, PV technology is close to full maturity as regards the modules [6], but considerable margins of improvement can be identified in the methods to properly use the produced electricity, for example by combining PV with electrical HVAC and reducing conversion losses through the use of DC-powered equipment.

In this sense, in the outlined systemic perspective, the electrically-powered HVAC plant characterized by the best potential is represented by reversible heat pumps for heat, cold and DHW production [7].

Furthermore, in order to allow the storage of surplus self-production and to implement load shifting (essential to avoid grid overloading), the system must be connected to a thermal and/or electric storage. The latter can also increase the interaction with the grid, for example by providing distributed storage.

As regards the existing residential building stock, it is considered that a significant energy retrofit potential lies in the multi-storey residential buildings, realized in the second half of the last century, which account for about 20% of the European existing building stock [8]. Within this category, the most common types are on average represented by 4-5 floors linear condominium buildings [9], which ratio between roof surface and floor area makes them suitable to cover most of the energy needs through photovoltaics.

To this end, the present work is focused on the assessment of a multi-functional integrated system designed to cover the HVAC needs from solar energy and to be applied especially within energy retrofit interventions of existing buildings.

2. System configuration

In the proposed system design, the heating, cooling and DHW demand is satisfied by a reversible and high efficiency air-water heat pump (HP), with continuous power modulation, directly fed in DC from the PV system integrated in the building envelope. That way it is possible to completely avoid energy losses due to DC/AC conversion. The eventual surplus of PV production can be stored in form of thermal energy thanks to a dedicated storage system for providing heating, cooling or DHW production in the periods when there is no/low solar radiation. In detail, such configuration is constituted by:

- a direct current air-water electric heat pump (HP) with continuous power modulation and optimized for the integrated operation with PV systems; the proposed HP is also equipped with a desuperheater, in order to generate DHW both in heating and cooling mode.
- high-efficiency thermal storages for hot and chilled water;
- an advanced power management and control system, able to optimize the whole operation of the configuration and to allow the interaction among the PV system, the HP and the grid.

Since the configuration is based by air-to-watr heat pump, it is characterized by a high performance level particularly in moderate climates, and also is cheaper than other alternatives, such as geothermal HP.
A concept scheme of the proposed configuration in winter operating mode is shown in Fig.1.

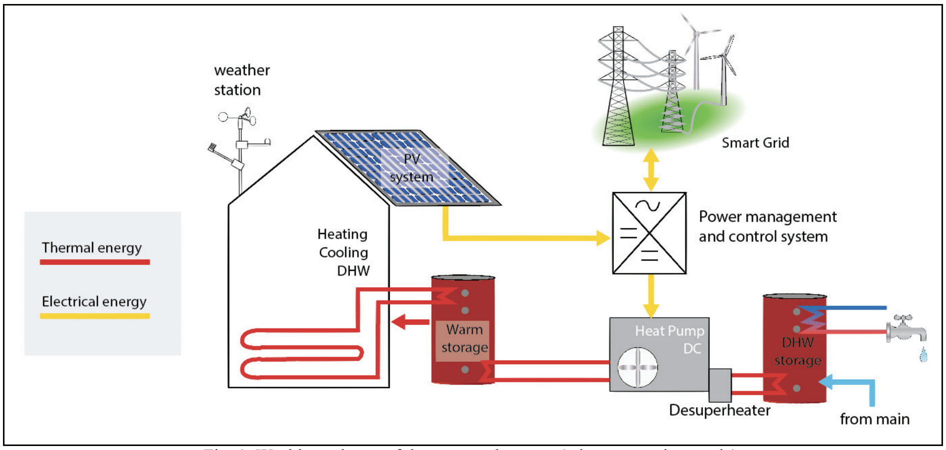

Fig. 1. Working scheme of the proposed system (winter operating mode).

According to the specific control logic, the heat pump is always in operation during the periods when the PV system generates electricity: if no thermal load is provided by the building, the electricity is stored in form of thermal energy in the storage systems or, if the latter is full, converted to AC and exported to the grid. The HP is also active when the thermal energy provided by the storage tank is lower than the building energy demand.

3. Application to a case study

In order to assess the energy saving potential of the proposed system, its application on a reference building was simulated through dynamic simulations carried out with EnergyPlus and TRNSYS [10]. The case-study application is represented by an existing 4-storey residential building located in Reggio Emilia in Italy, which can be considered a location representative of the typical European temperate climatic condition. The installation of the HVAC system is supposed to be coupled with energy retrofit interventions on the building envelope, such as insulation of opaque surfaces and windows replacement, and the substitution of the existing radiators with a radiant floor. The main features of the building before and after the energy retrofit are summarized in Table 1.

Table 1. Representative parameters of the of the building

General data of the building	Features before the retrofit	Features after the retrofit
Location: Bagnolo in Piano Reggio Emilia, Italy.	Envelope: brick cavity walls; U= 0.7 W/m^2 K	Envelope: brick cavity walls with thermal insulation; U= 0.23 W/m^2 K
Construction period: 1985 Net surface: 636 m^2 Gross volume: 1.900 m^3	windows with single glass; U= 4 W/m^2 K	windows with double glass; U= 2.2 W/m^2 K
Housing units: 12 S/V = 0.7 $S_{windows}/S_{opaque}$=25%	HVAC systems: Traditional gas boiler and radiators	HVAC systems: Multifunctional integrated system with radiant floor

The estimated thermal energy demand of the building before the retrofit is approximately 100,000 kWh (69,000 kWh for heating, 11,000 for cooling and 20,000 for DHW).

The main climatic data for the reference site, summarized in Table 2 and used in the simulation, are taken from the Typical Meteorological Year (TMY) of Meteonorm database [11-13].

Table 2. Representative parameters of the reference climatic context.

Site	Reggio Emilia
Latitude	44°
Heating Degree-Days	2542
Cooling Degree-Days	391

Max. temp. [°C]	33.6
Min. temp. [°C]	-9.0
Annual global irrad. on horiz. plane [kWh/m^2]	1141

Building energy simulations were carried out assuming internal gains equal to 4.5 W/m^2 and 0.5 W/m^2 respectively in heated and unheated zones and an air exchange rate equal to 0.5 h^{-1}; the hourly energy demands for heating, cooling and DHW production were calculated by means of dynamic simulations through EnergyPlus software. The monthly values are reported in Fig.2.

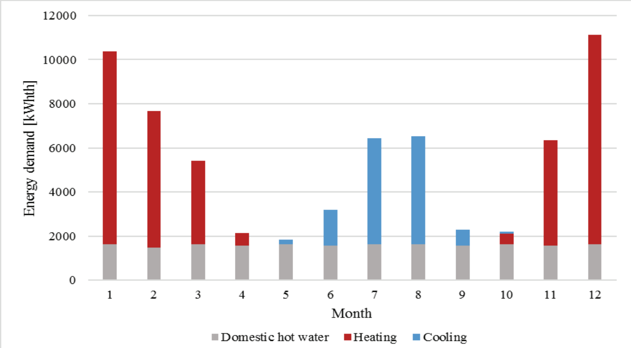

Fig. 1. Energy demand for heating, cooling and DHW for a multi-storey building in Reggio Emilia.

According to simulations results, the thermal energy demand after the retrofit of the envelope is 62,300 (34,000 kWh for heating, 12,300 for cooling and 20,000 for DHW). On such basis the HVAC system was sized in order to satisfy the peak power of the building in design-day condition, with a maximum thermal power in heating mode equal to 16 kW. A high-insulated water tank of 2000 litres is provided to store DHW and a second tank of 4000 litres is used as a storage for heating/cooling fluid. The heat pump is then coupled with a 10 kW peak power PV system. The size of the storages was defined in order to minimize the electricity fed into the grid and to maximize the self-consumption by the heat pump, as subsequently discussed in section 4. The size of the PV plant was set to annually supply an amount of electricity equal to that needed for HVAC and DHW purposes. The main features of the system are summarized in Table 3.

Table 3. Main system parameters

Parameters	Measuring units	Value
Slope of PV module	-	30°
PV module azimuth		0°
Peak power of the array	kW	10
Heat pump type		Air-to-Water
Heating capacity of the heat pump	kW	15
Cooling capacity of the heat pump	kW	16
COP of the heat pump (7°C-35°C)	-	5.5
EER of the heat pump (35°C-16°C)	-	5.8

It should be mentioned that the above-reported reference values of COP and EER already take into account that the pump is powered in DC.

Subsequently, the described system configuration was modelled in TRNSYS with Type 505 and Type 94 which represents respectively the water-to-air heat pump and the PV plant, using as an input the hourly thermal energy demand obtained through EnergyPlus simulations.

Additional used components are Type 4 (storage tank), Type 110 (circulation pump), Type 653 (radiant floor), and some other subsidiary components such as Type 2 (ON/OFF Differential Controller), Type 14 (Time Dependent Forcing Function) and Type 9 (Data Reader For Generic Data Files).

4. Results and discussions

According to the simulation results shown in Fig. 3, it can be observed that during winter season the electricity needed for heating and DHW is higher than the PV production, which is almost entirely consumed on-site (only 3% of the winter PV production is fed to the grid). The logic of the power management and control system allows to take advantage of the air-water HP potential, limiting its operation only to daytime when higher external air temperatures exist, reaching its maximum COP, and PV production is available. The thermal storages allow indeed to decouple over time the heat demand from the electricity production, also reducing the peaks of power requested from the grid.

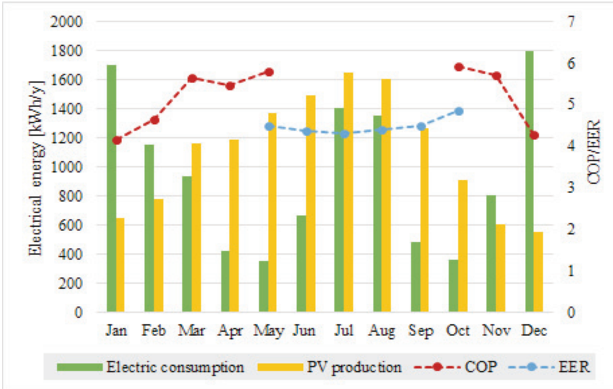

Fig. 3. Electric energy consumption of the HP, PV energy production and mean monthly COP/EER

During summer period and in the mid seasons, a part of the PV production will be used by the HP for DHW production. Given the type of HP proposed in the present study, the DHW production allows to totally recover the evaporation heat, producing free cooling energy that can be used when necessary.

If the cooling demand is higher than the free share obtained from the DHW production, the HP will work in cooling mode according to availability of renewable electricity, storing the chilled water for delayed operation.

It was estimated that, in the identified application context, about 65% of the electricity produced in summer, spring and autumn by PV is self-consumed on-site in DC, strongly reducing the interaction with the grid and maximizing the affordability of the whole system. The remaining share of electricity is fed into the grid.

An example of hourly energy fluxes during one week of March is shown in Fig. 4. As already said, the HP works only during daytime in order to maximize the self-consumption of PV energy. In the considered week, 68% of the thermal energy provided by the HP is used instantaneously, while the remaining part is stored in the water tanks and used during the night in order to completely cover the heating and DHW demand. It can be also observed that during the days of less availability of solar radiation, PV is not able to produce sufficient electricity to operate the HP in order to completely recharge the thermal storage. However, the thermal energy stored in previous days is enough to cover all the energy demand.

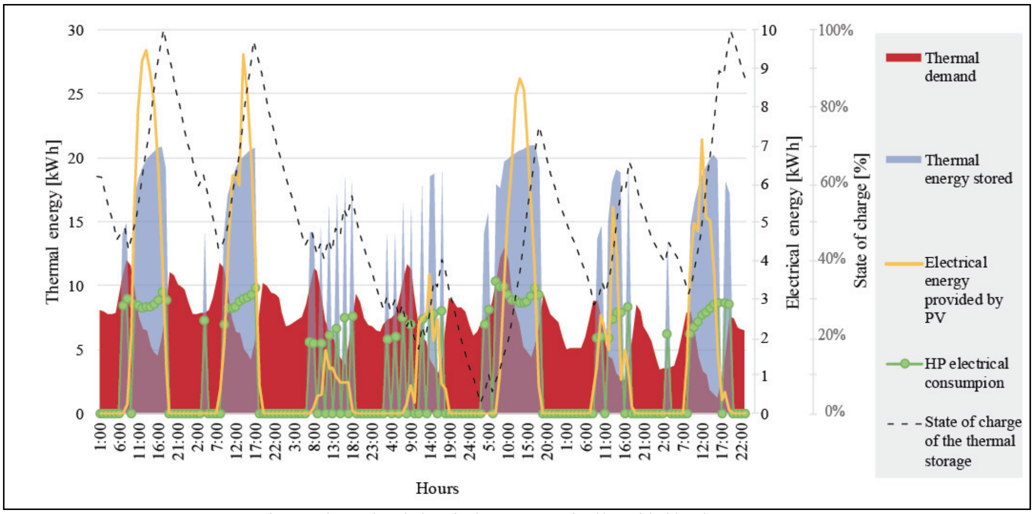

Fig. 4. Thermal and electrical energy required/provided by the system

Finally, considering the yearly energy balance (evaluated on hourly basis), the PV plant covers completely the HP yearly electrical consumption (Table 3). In addition, about 72% of the yearly PV electricity production is self-consumed instantaneously on-site. In this respect the proposed system allows a significant reduction of the impact on the electric grid related to installed PV power and electric load due to the presence of the HP in substitution of a traditional gas boiler.

Table 3. Yearly electrical energy balance

	Electrical energy balance [kWh]
Overall electric consumption (H, C and DHW)	12,640
PV production	13,231
PV self-consumption	9,590
Energy fed into the grid	3,641
Energy from the grid	3,050

For the energy saving potential calculations, the analysed technical configuration was compared with the most widespread technology used in Italy for space heating and DHW [14], which is the natural gas boiler. Previously calculated energy consumptions are referred to electrical energy, therefore, heating, cooling and DHW needs are converted into primary energy consumption, using the average efficiency of the national power generation system, equal to 46% [15], corresponding to the typical fuel mix used for electricity production in Italy. The comparison doesn't take into account the energy consumption for cooling since the efficiency of the modern direct-refrigerant system typically used for air conditioning in dwellings was prudentially assumed the same of the one achievable with the proposed configuration . The gas boiler adopted for the comparison is characterized by an efficiency of 97% (condensation gas boiler).

The achievable annual primary energy savings related to heating and DHW are reported in Table 4. These values also include the energy consumption due to auxiliaries.

Table 4. Primary energy consumption and energy saving potential

	Primary energy consumption [kWh]	Energy saving potential [kWh]
Gas boiler (H and DHW)	64,437	-
Heat pump (H and DHW) + PV	7,634	56,803

It can be observed that the proposed system allows to achieve an energy saving equal to 90% compared to a condensing boiler. In addition, it must be noted that during the summer the DHW production by the integrated system can be considered almost totally free thanks to possibility to recover energy from the condenser of the HP which operate in cooling mode.

5. Conclusions

The work is focused on the energy performance estimations of a multi-functional HVAC system. The results show that the proposed system has a large potential for energy retrofit in existing buildings and is also suitable for new buildings, especially in the climates characterized by both heating and cooling demands. The obtainable energy potential from the proposed system is estimated up to 90% with respect to conventional HVAC system, showing clearly the effectiveness of the integrated solution towards nZEB standards. Moreover, it allows a significant reduction of the impact on the electric grid related to the increasing diffusion of PV power and electric heat pumps.

6. Copyright

Authors keep full copyright over papers published in Energy Procedia

References

[1] JRC. Heat and cooling demand and market perspective. Joint Research Centre, European Commission; 2012. http://publications.jrc.ec.europa.eu/repository/handle/JRC70962

[2] ECF. Roadmap 2050: a practical guide to a prosperous low carbon Europe, European Climate Foundation; 2010. www.roadmap2050.eu

[3] BPIE. Europe's buildings under the microscope - A country-by-country review of the energy performance of buildings, Buildings Performance Institute Europe; 2011. www.bpie.eu

[4] BPIE. Principles for nearly Zero-Energy Buildings- Paving the way for effective implementation of policy requirements, Buildings Performance Institute Europe; 2011. www.bpie.eu

[5] ECOFYS. Towards nearly zero–energy buildings: Definition of common principles under the EPBD. Project number: BESDE10788; 2013. http://www.nezeh.eu/assets/media/fckuploads/file/Reports/2.nzeb_full_report.pdf

[6] Torgal FP, Mistretta M, Kaklauskas A, Granqvist CG, Cabeza LF (ed.). Nearly Zero Energy Building Refurbishment-A Multidisciplinary Approach ; 2013, Springer.

[7] IEA. Technology Roadmap Energy - efficient Buildings: Heating and Cooling Equipment, International Energy Agency; 2011. http://www.iea.org/publications/freepublications/publication/buildings_roadmap.pdf

[8] TABULA . First Tabula Synthesis Report, Use of building Typologies for Energy Performance Assessment of National Building Stocks, TABULA project (Typology Approach for Building Stock Energy Assessment); 2010. http://episcope.eu/iee-project/tabula
[9] iNSPiRe. Renovating the existing building stock across Europe, iNSPiRe project (Infrastructure for Spatial Information in Europe); 2014. www.inspirefp7.eu/renovating-the-existing-building-stock-across-europe-bsria-webinar-and-building-stock-analysis
[10] University of Wisconsin-Madison. Solar Energy Laboratory and S. A. Klein. TRNSYS, A transient system simulation program; 1979.
[11] Remund J,.Quality of Meteonorm Version 6.0, Europe 6 1.1.; 2008. www.meteotest.ch/fileadmin/user_upload/Sonnenenergie/pdf/2008WREC_mn6_qual_paper.pdf
[12] Cros S, Mayer D, Wald L. The availability of irradiation data. International Energy Agency, Vienna, Austria, Report IEA-PVPS T 2; 2014
[13] Kaplanis S. New methodologies to estimate the hourly global solar radiation; Comparisons with existing models, *Renewable Energy* 2006 ; 31: 781-790.
[14] Aste N, Del Pero C, Adhikari RS, Marenzi G. Effectiveness and weaknesses of supporting policies for solar thermal systems—A case-study, *Sustainable Cities and Society* 2015; 14:146-153.
[15] AEEG. Delibera EEN 3/08: Aggiornamento del fattore di conversione dei kWh in tonnellate equivalenti di petrolio connesso al meccanismo dei titoli di efficienza energetica; 2008.

Biography

Claudio Del Pero is a researcher of the Architecture, Built Environment and Construction Engineering Department. He is actively involved in research and advisory activities related to energy efficiency of the built environment and to the exploitation of renewable energy sources, with particular reference to the topics of PV technology and distributed energy generation.