

PAPER • OPEN ACCESS

Smart use of mechanical ventilation for energy retrofit of residential dwellings

To cite this article: S Pedrazzi *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 052032

View the [article online](#) for updates and enhancements.

You may also like

- [Respiratory mechanics to understand ARDS and guide mechanical ventilation](#)
Tommaso Mauri, Marta Lazzeri, Giacomo Bellani *et al.*
- [Effects of different ventilation strategies on exhaled nitric oxide in geriatric abdominal surgery](#)
Yinghua Cui, Xin Pi, Changsong Wang *et al.*
- [Profile of fluid balance in the first 48 hours and duration of mechanical ventilation in pediatric intensive care unit](#)
P L andriamuri and D L aridamurian



ECS Toyota Young Investigator Fellowship

For young professionals and scholars pursuing research in batteries, fuel cells and hydrogen, and future sustainable technologies.

At least one \$50,000 fellowship is available annually.
More than \$1.4 million awarded since 2015!

 Application deadline: January 31, 2023

Learn more. Apply today!

The advertisement features a dark background with a glowing globe and futuristic interface elements. The ECS TOYOTA logo is prominently displayed in the top right corner.

Smart use of mechanical ventilation for energy retrofit of residential dwellings

S Pedrazzi¹, C Ferrari¹, G Allesina¹, A Muscio^{1,*}

¹EELab – Dip. di Ingegneria “Enzo Ferrari” – Univ. di Modena e Reggio E., Italy

* alberto.muscio@unimore.it

Abstract. Residential buildings of Italy built during the last century usually show very poor energy performance. The only retrofit action widely implemented on their envelope is substitution of windows. These are very seldom coupled with mechanical ventilation, however, so their high air tightness induces serious problems of moisture condensation and mold formation – unless they are left open and their usefulness nullified. In this work, a smart combination is simulated of single flow mechanical ventilation, in itself essential to control indoor air quality and ventilation heat loss, with a relatively inexpensive sunspace built on an existing balcony, aimed to behave as a preheating chamber of the inlet cold air in winter. Moreover, mechanical ventilation is combined with an electric heat pump for hot water production, in which the outlet air flow of warm exhaust air is introduced to improve the coefficient of performance of the heat pump in the cold seasons. Energy savings allowed by such smart yet simple combination of existing technologies are discussed.

1. Introduction

A smart and energy efficient use of mechanical ventilation can be done with regard to energy retrofit of existing condominium buildings built in Italy during the second half of the last century. These are a large part of the existing residential dwellings and usually show very poor energy performance [1]. Easy to implement retrofit actions such as installing condensing boilers and also improving the control sub-system by means of self-regulating thermostatic valves applied to radiators have been widely implemented, but they are not enough to improve drastically the energy performance because this is mainly influenced by heat loss through the uninsulated building envelope [2]. Insulation of roofs and walls is rare since it is expensive and also difficult to apply, therefore substitution of windows is the only retrofit action commonly implemented on the building envelope. On the other hand, it is seldom suggested by window producers to complement new windows with mechanical ventilation, so their high air tightness often induces serious problems of moisture condensation and mold formation, unless windows are left open and their usefulness thus nullified by ventilation heat loss [3]. A mechanical ventilation system could counter such issue by controlling indoor air quality, humidity above all, as well as by limiting the air flow rate and, with this, ventilation heat loss [4,5]. Nonetheless, double flow ventilation with heat recovery is generally promoted by designers and installers, but then users are discouraged by its installation cost and invasiveness [6]. Less inexpensive single flow systems, in which air is pulled in through simple wall vents (usually regulated on temperature or humidity), then it flows and is distributed in the indoor spaces, and it is eventually extracted from bathroom and kitchen by one or more fans, are very seldom proposed [5].

In this work, a smart combination is simulated of single flow mechanical ventilation, in itself essential to control indoor air quality and ventilation heat loss, with a relatively inexpensive sunspace built on an existing balcony at inlet, and with an electric heat pump for domestic hot water production at outlet. The sunspace is aimed to behave as a preheating chamber of the inlet flow of fresh air in winter and it is easily removable in summer. Moreover, sending the outlet flow of warm exhaust air to



the heat pump permits to improve significantly, in the cold and intermediate seasons, its coefficient of performance (*COP*), that is the ratio of heat transferred to the hot water and electric energy supplied to the heat pump by the grid. Energy savings allowed by such smart yet simple combination of existing technologies are discussed here.

2. Coupling single flow mechanical ventilation with a sunspace built on a balcony

Retrofit of the envelope of condominium buildings may be difficult due to the numerous thermal bridges that occur in the architecture of many countries and must be corrected, above all thermal bridges due to the reinforced concrete slab of balconies, which usually crosses the wall structure and the insulation layer. All apartments above the ground floor have balconies in most condominium buildings of Italy and other countries. Field measurements and calculations have shown that their impact on heating energy needs may be up to 34% in retrofitted buildings of Eastern Europe [7], whereas simulations have shown that their impact on the heating energy consumption is 5-13% in Canada [8]. On the other hand, the cost of thermal bridge correction has been shown to be important in Italy, and the cost-benefit analysis generally not favorable [9].

Instead of retrofitting the balcony area to reduce heat loss through walls and windows, and the consequent need of thermal energy for winter heating, the heat loss can be offset with solar energy that is gained by enclosing in a sunspace the volume above the balcony. Indeed, passive sunspaces have been shown to be an appropriate and effective system all over Europe during the cold period of the year [10-12], and their use has been widely considered for retrofitting purposes, for both cold climates [13-15] and warm ones [16-19]. Most studies, however, have been focused on relatively expensive and heavyweight solutions, using insulated and airtight glazing, nor ventilation of the sunspace has been frequently considered. Nonetheless, a solution as simple as roll-up transparent plastic (*e.g. PVC*) sheets, mounted along the balcony perimeter and easily removable in the hot season, or in case of severe wind conditions, can be used to enclose the air volume between two superposed balcony slabs. Moreover, the lack of thermal insulation and the weak air tightness of the roll-up sheets can be counterbalanced by using the sunspace as a pre-heating chamber for a single flow mechanical ventilation system. The potentialities of this approach to energy retrofit of existing condominium buildings have already been investigated by means of a simplified calculation method, substantially validated with measurements on a small scale model of ventilated sunspace [20].

Entering into details, solar radiation passing through the plastic sheets is absorbed by the wall and the balcony floor, then it is partly released by convection to the air in the sunspace, and partly transmitted indoor through the wall. The combined result of heat gains and heat transfer processes is a decrease of the net heat loss through the wall, but most of the absorbed solar energy is transferred to the air in the sunspace and then lost in the external environment due to the very weak insulation provided by the plastic sheets and to air leakage. On the other hand, enclosing the sunspace with double pane low-emittance glazing with metal frame can be very expensive, often not allowed by building codes, and it can also overburden the balcony with the cantilevered mass of glazing and frame. Instead, the effectiveness of the sunspace can be maximized by extracting from it the warm air and then introducing such air into the inhabited rooms, that is by using the sunspace as a preheating chamber of a single flow mechanical ventilation system designed to ensure the air change per hour (*ACH*) value required in the indoor environment. The warm air extracted from the sunspace is substituted by colder external air that can enter through, for example, a line inlet along all or part of the lower balcony perimeter. This also makes an accurate sealing of the sunspace unnecessary as air leakage would be needed to allow the entering airflow. Moreover, insulation of the wall and substitution of windows facing the balcony are made superfluous. In some cases, the performance can be analogous to that provided by substituting the glazed elements, applying an insulation layer to the wall and also correcting the thermal bridges [20], yet all this is achieved without permanent changes in the aesthetics, or reduction of the available balcony floor area. In Italy, the cost of such retrofit can be as low as about 1'500 € for the roll-up plastic sheets, and approximately the same for a single-flow mechanical ventilation system – which should not be considered an additional cost, however, as ventilation would generally be needed to ensure air quality and prevent mold growth. The overall cost

of insulating the wall, retrofitting a glazed door and a window, and applying a however poor correction of the balcony thermal bridge can be calculated in excess of 5'000 €.

A simplified, steady-state thermal balance can be built of a ventilated sunspace, including solar energy transmitted through the transparent plastic sheets and absorbed by the irradiated surfaces of the opaque wall, heat needed to warm up the cold air entering the sunspace, heat transmitted to the outdoor environment through the plastic sheets, and heat transmitted to the indoor spaces through opaque wall elements, glazed window elements, and linear thermal bridges along the balcony line or around the perimeter of the glazed elements. The increased heat rate transmitted through the envelope elements in the balcony area is obtained from the following thermal balance:

$$\dot{Q}_c = \frac{T_e + \left(\frac{R_c'' U_c}{U_w A_w + \sum_b \psi_b L_b + U_c A_c} + \frac{1}{U_s A_s + \rho_a c_{p,a} \dot{V}_a} \right) \tau_s \alpha_c I_{sol} A_c - T_i}{\frac{1}{U_w A_w + \sum_b \psi_b L_b + U_c A_c} + \frac{1}{U_s A_s + \rho_a c_{p,a} \dot{V}_a}} \quad (\text{W}) \quad (1)$$

where

A_c	surface of the opaque wall element (m ²)	U_c	thermal transmittance of the opaque wall element (W/(m ² °C))
A_s	surf. of the sunspace transparent envelope (m ²)	U_s	thermal transmittance of the sunspace transparent envelope (W/(m ² °C))
A_w	overall surface of glazed elements (m ²)	U_w	thermal transmittance of glazed elements (W/(m ² °C))
$c_{p,a}$	air specific heat at constant pressure (J/(kg °C))	\dot{V}_a	volume flow rate (m ³ /s)
I_{sol}	solar irradiance onto a vertical wall surface, average value (W/m ²)	α_c	solar absorptance of the opaque wall surface (0 < α_c < 1)
L_b	length of a thermal bridge (e.g. the balcony width) (m)	ρ_a	air density (average value) (kg/m ³)
R_c''	surface resistance at the opaque component outer surface (m ² °C/W)	τ_s	solar transmittance of the sunspace envelope (0 < τ_s < 1)
T_e	external (outdoor) ambient temperature (°C)	ψ_b	linear trans. of a thermal bridge (W/(m °C))
T_i	internal (indoor) temperature (°C)		

Space averages are considered for temperatures. The additional heat rate related to the fraction of energy need for ventilation saved thanks to preheating in the ventilated sunspace must also be considered to obtain the overall benefit:

$$\dot{Q}_v = \rho_a c_{p,a} \dot{V}_a (T_s - T_e) \quad (\text{W}) \quad (2)$$

where the temperature T_s inside the sunspace can be evaluated by the following relationship:

$$T_s = \frac{A_c \tau_s \alpha_c I_{sol} (1 - R_c'' U_c) + (U_s A_s + \rho_a c_{p,a} \dot{V}_a) T_e + (U_w A_w + \sum_b \psi_b L_b + U_c A_c) T_i}{U_s A_s + \rho_a c_{p,a} \dot{V}_a + U_w A_w + \sum_b \psi_b L_b + U_c A_c} \quad (^\circ\text{C}) \quad (3)$$

More details on the simplified thermal model outlined above are given in [20]. A dynamic simulation of the ventilated sunspace would indeed be needed to forecast its actual performance, possibly coupled with a dynamic model of the whole apartment in which the extracted air must be introduced. Nonetheless, the forecasts provided by equations (1)-(3) have been substantially confirmed by measurements on a small scale model of a sunspace, with 1:2.65 scale reduction [20].

Figure 1 shows the monthly heat gain/loss allowed in the different months of the heating season by an unshaded ventilated sunspace built on a balcony having size similar to balconies of common Italian apartments: width 5 m, depth 1.2 m, and distance between upper/lower balcony slabs around 3 m. The heat gain/loss (in red) is compared with those obtained: with the same sunspace but unventilated (yellow); without the sunspace and with wall/window elements in the balcony area uninsulated (blue); without the sunspace but with well insulated wall/window elements (grey). Considering an internal height from floor to ceiling equal to 3 m, a typical apartment of Italy with floor surface area $A_{floor} \approx 100$ m² has internal ventilated volume $V_{indoor} \approx 300$ m³. In the Italian calculation method for energy performance of buildings a minimum value of air change per hour $ACH = 0.3$ vol/h is suggested for

residential buildings, so a volume flow rate of 90 m³/h has been considered. Moreover, conventional monthly averaged data on outdoor temperature and solar radiation can be used [21].

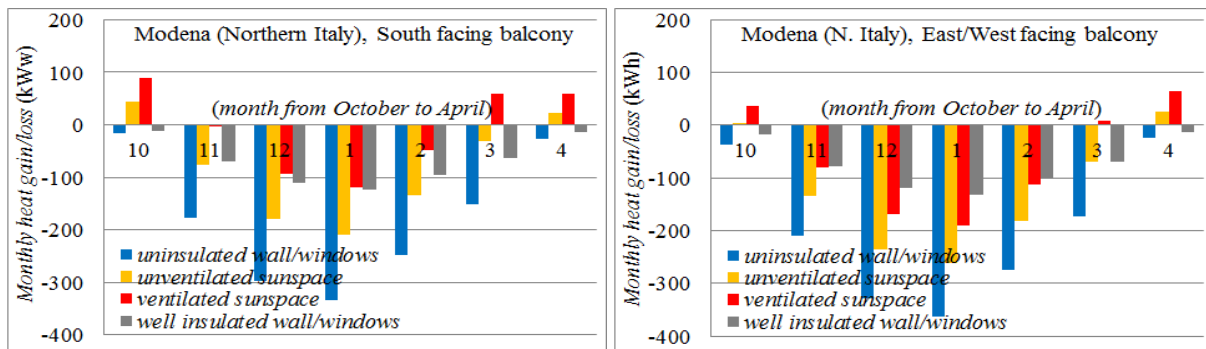


Figure 1. Monthly net heat gain/loss (positive/negative) for a ventilated sunspace with $ACH = 0.3$ vol/h facing South (left) or East/West (right), compared to an unventilated sunspace, to uninsulated wall and windows of the balcony area, and to insulated ones (Modena, Northern Italy).

Summing up the results over the heating season (conventionally from October 15 to April 15 in the considered location), the thermal energy saving yielded by a South facing ventilated sunspace is relatively high, equal to 1192 kWh compared to a balcony area with uninsulated wall/window elements and thermal bridges, and equivalent to 67% of the heat loss for ventilation. It is 960 kWh, or 54% of the heat loss for ventilation, for an East/West facing ventilated sunspace. The thermal energy saving can be translated into a primary energy saving if the efficiency of the heating system is given. For example, a hydronic heating system with natural gas boiler can have global efficiency around 80-90%, and the conversion factor into primary energy for natural gas is 1.05 in Italy, therefore the primary energy saving is quantitatively obtained increasing by 17-31% the thermal energy saving.

3. Coupling single flow mechanical ventilation with a heat pump for hot water production

The amount of hot water needed daily in an apartment may significantly change between different users. However, average or reference values are provided by national and international calculation standards. In Italy, for the already considered typical apartment with floor surface $A_{floor} \approx 100$ m², the standard value for the daily need of hot water is $V_{w,day} \approx 143$ L/day $\equiv 0.143$ m³/day [22]. Hot water is assumed to have inlet temperature $T_{w,in}$ equal to the annual average temperature of ambient air in the considered location (e.g. $T_{w,in} = 13^\circ\text{C}$ for Modena, Northern Italy), whereas the temperature $T_{w,out}$ at which hot water is delivered to the end users is assumed to be 40°C .

Energy need $Q_{w,day}$ for production of the daily amount of hot water $V_{w,day}$ (calculated in m³) is:

$$Q_{w,day} = \rho_w c_w V_{w,day} (T_{w,out} - T_{w,in}) / \eta_d \quad (\text{J}) \quad (4)$$

where water density is $\rho_w = 1000$ kg/m³, water specific heat is $c_w = 4183$ J/(kg°C), and distribution efficiency η_d due to heat loss in the distribution ducts can be assumed between 88% and 92% [17], depending on the level of duct insulation – but it can be much lower if a recirculation loop with poor insulation is installed to allow immediate availability of hot water in apartments far from the boiler site. For the typical apartment with $A_{floor} \approx 100$ m², on has $Q_{w,day} = 17.6$ MJ/day $\equiv 4.9$ kWh/day with $\eta_d = 92\%$, but in excess of 32 MJ/day $\equiv 9$ kWh/day with $\eta_d < 50\%$.

Being known the coefficient of performance (COP) of the considered heat pump, often including the effects of heat loss from an embedded water reservoir, and being given the conversion factor $f_{P,el}$ of electric energy into primary energy for the considered country (e.g. $f_{P,el} = 2.42$ in Italy), the primary energy needed for hot water production in a single day is

$$E_P = f_{P,el} Q_{w,day} / COP \quad (\text{J}) \quad (5)$$

An analysis of the market of heat pump boilers for hot water production in single apartments or small buildings has shown the availability of a wide range of commercial products, featuring single element or split layout, refrigerant R134a or, less frequently, R410a. The eat rate to the heated water ranges from 600 W to 2.2 kW, with COP around 2.5-3.0 in reference conditions. The air flow rate is

such that the temperature drop in the air flowing through the evaporator is around 10°C. A hot water reservoir is always included, with volume of from 80 L to 500 L.

Manufacturers of heat pumps for hot water production usually provide the *COP* for a given outlet temperature of the hot water $T_{w,out}$ and, above all, as a function of the inlet temperature of the air $T_{a,in}$. They also suggest to obtain the inlet air from the inhabited environment and to return it back, if its lower temperature does cause an increased energy need for ambient heating, or otherwise to discard the cooled air in the external environment. In the latter case, the heat pump behaves like a single flow mechanical ventilation system, or it can be combined with it. In case the mechanical ventilation system provides an insufficient flow of exhaust indoor air, this can be mixed with a supplementary flow of outdoor air in order to obtain the reference (*i.e.* desired) air flow rate to the heat pump. The inlet air will thus have a lower temperature than the exhaust indoor air:

$$T_{a,in} = T_{a,indoor} \dot{V}_{a,indoor} / \dot{V}_{a,desired} + T_{a,outdoor} \left(1 - \dot{V}_{a,indoor} / \dot{V}_{a,desired}\right) \quad (6)$$

The advantage of matching a heat pump for hot water production and a single flow mechanical ventilation system is the difference between primary energy $E_{P,outdoor}$ needed by the heat pump while using only outdoor air, and primary energy $E_{P,ACH}$ needed by the combined system:

$$\Delta E_P = E_{P,outdoor} - E_{P,ACH} = f_{P,el} Q_{w,day} \sum_{month} N_{day,month} \left(\frac{1}{COP_{month,outdoor}} - \frac{1}{COP_{month,ACH}} \right) \quad (7)$$

The advantage is mostly evident in the colder seasons, whereas during summer it may sometimes be convenient to bypass the ventilation system and supply outdoor air to the heat pump.

A commercial heat pump for hot water production has been selected as representative of the large set of analyzed devices. It features R134a refrigerant, a 215 L hot water reservoir, and *COP* vs. inlet air temperature as in Figure 2, declared for $T_{w,in} = 10^\circ\text{C}$, $T_{w,out} = 51^\circ\text{C}$, minimum airflow rate 320 m³/h. Due to the size of the device, it is assumed to serve two similar apartments. Analogous commercial products are available with smaller size, adequate to a single apartment, as well as larger ones.

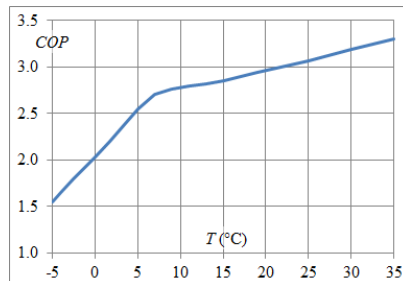


Figure 2. Reference individual heat pump for hot water production: *COP* vs. inlet air temperature.

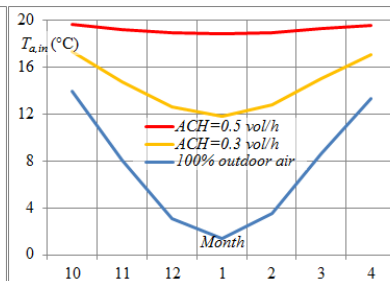


Figure 3. Air temperature at the heat pump inlet for different flow rates of exhaust air (data for Modena, Northern Italy).

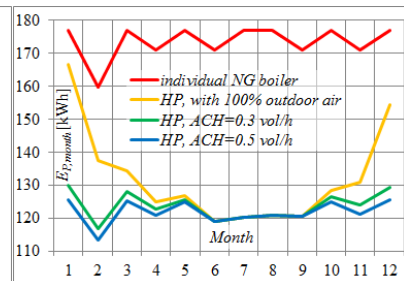


Figure 4. Monthly primary energy need with a NG boiler and a heat pump (data for Modena, Northern Italy).

As already mentioned, a minimum value of air change per hour (*ACH*) equal to 0.3 vol/h is suggested in Italy for residential buildings, however a higher value of 0.5 vol/h can be obtained applying other design standards. With *ACH* from 0.3 vol/h to 0.5 vol/h, in the already considered typical apartment with floor area $A_{floor} \approx 100 \text{ m}^2$ and internal ventilated volume $V_{indoor} \approx 300 \text{ m}^3$ the air flow rate can range from 90 m³/h to 150 m³/h, therefore slightly lower than the minimum flow rate of 160 m³/h required for the considered heat pump. Given the (monthly averaged) outdoor temperatures [21] in the heating season, Figure 3 shows the inlet air temperature obtained by using only outdoor air, or mixing this with the flow rate of indoor air at $T_{indoor} = 20^\circ\text{C}$ as resulting from the considered *ACH*.

The mechanical ventilation system and the heat pump can be combined by means of a three-way small plenum with a vent open to let outdoor air enter the plenum, another vent through which the exhaust air is introduced in the plenum by the mechanical ventilation system, and a third vent through which the airflow to be sent to the heat pump is extracted from the plenum. The use of *ACH* = 0.3 vol/h yields savings of 98 kWh of primary energy, that is a 11.4% reduction of the primary energy needed in the heating period while the heat pump uses only outdoor air. In the same period, the use of

$ACH = 0.5$ vol/h would yield savings of 117 kWh of primary energy, that is a 13.6% reduction. These savings are calculated with respect to an already efficient electric heat pump, which by itself would allow significant savings of primary energy compared to a common natural gas (NG) boiler, as high as 498 kWh/year, or 31.4% of primary energy over the whole year, if an individual boiler is installed in the apartment and distribution heat loss is such that $\eta_d = 92\%$. Savings in excess of 2248 kWh/year, or 58.7% of the yearly need of primary energy, are obtained if the boiler is centralized and the distribution ducts are poorly insulated, with $\eta_d < 50\%$. Monthly data of the calculated primary energy need are shown in Figure 4. The NG boiler has been assumed to have generation efficiency $\eta_{gn} \approx 90\%$, whereas the conversion factor into primary energy is 1.05 in Italy for natural gas.

4. Conclusive remarks

Combining a single flow mechanical ventilation system with a sunspace built on a balcony at its inlet, and with an electric heat pump for hot water production at its outlet, can provide significant savings in terms of primary energy need, as well as an improved air quality. The proposed combined system can be quickly implemented as a retrofit solution for residential buildings, possibly independent for each apartment of a same condominium building, with relatively low cost and invasiveness. Indeed, in an actual implementation, it is important to set up a control method, e.g. by sensors of the air properties, that takes care simultaneously of ventilation, indoor air quality and energy efficiency requirements.

References

- [1] Nemry F, Uihlein A, Colodel CM, Wetzel C, Braune A, Wittstock B, Hasan I, Kreißig J, Gallon N, Niemeier S, Frech Y 2010 *Energy Build.* **42** 976
- [2] Zheng D, Yu L, Wang L, Tao J 2019 *J. Cleaner Prod.* **208** 1587
- [3] Laukkarinen A, Kero P, Vinha J 2018 *J. Build. Eng.* **19** 592
- [4] Kamendere E, Zogla G, Kamenders A, Ikaunieks J, Rochas C 2015 *Energy Procedia* **72** 27
- [5] Allesina G, Mussatti E, Ferrari F, Muscio A 2018 *Energy and Build.* **158** 406
- [6] Ai ZT, Mak CM 2016 *Build. and Env.* **108** 12
- [7] Ilomets S, Kuusk K, Paap L, Arumägi E, Kalamees T 2017 *J. Civil Eng. Manag.* **23** 96
- [8] Ge H, McClung VR, Zhang S 2013 *Energy Build.* **60** 163
- [9] Evola G, Margani G, Marletta L 2011 *Energy Build.* **43** 2385
- [10] Mihalakakou G 2002 *Renew. Energy* **26** 415
- [11] Hilliaho K, Mäkitalo E, Lahdensivu J 2015 *Energy Build.* **99** 87
- [12] Ulpiani G, Giuliani D, Romagnoli A, di Perna C 2017 *Energy Build.* **152** 194
- [13] Hilliaho K, Kovalainen V, Huuhka S, Lahdensivu J 2016 *Energy Build.* **125** 27
- [14] Hilliaho K, Köliö A, Pakkala T, Lahdensivu J, Vinha J 2016 *Energy Build.* **128** 458
- [15] Grudzińska M 2016 *Build. Services Eng. Res. Tech.* **37** 555
- [16] Asdrubali F, Cotana F, Messineo A 2012 *Energies* **5** 1864
- [17] Aeleneia D, de Azevedo Leal H, Aelenei L 2014 *Energy Procedia* **48** 1436
- [18] Albatici R, Passerini F, Pfafferott J 2016 *Energies* **9** 365 pp 1-12
- [19] Kotti S, Teli D, James PAB 2017 *Procedia Env. Sciences* **38** 306
- [20] Allesina G, Ferrari C, Muscio A, Pedrazzi S 2019 *Ren. Energy* **141** 541
- [21] UNI 2016, *UN 10349-1:2016* (in italian)
- [22] UNI 2014, *UNI/TS 11300-2:2014*