Simulation of the Annual Energy Demand of Buildings through Averaged Monthly and Hourly Calculation Methods: a Comparative Analysis

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Abstract

In Italy, with reference to assessment of energy performance of buildings, the legislation currently in force still provides for the use of averaged monthly calculation methods. In anticipation of a gradual transition to more accurate calculation methods based on dynamic evaluations, it is of fundamental importance to know the differences in prediction of these different methods (averaged monthly and hourly calculation), with particular reference to those indicated in the European technical standards.

With this study, the authors want to push forward the knowledge by using the results of simulations obtained on a sample of single-family and offices buildings. This study is part of a wider research activity aimed at the comparative analysis of the energy demand of new buildings, using averaged monthly and hourly calculation methods.

Introduction

The energy efficiency of buildings is one of the most important issues that are being debated in recent years worldwide (Koulamas, 2018). The production of fossil fuel energy entails extremely heavy side effects on the environment and the climate, with the emission of local pollutants harmful to human health and greenhouse gases, responsible for global warming and in turn for environmental changes. In Europe, this aspects have led Member States to adopt, especially in the last decade, a series of European policies in order to stem the consequences. The European Directive 2010/31 EPBD (Energy Performance of Buildings Directive, recently modified by the Directive 2018/844) was issued with the aim of improving the energy performance of the civil constructions sector. The EPBD introduced at national level a mechanism of comparative analysis with the purpose of determining optimal level of cost to be used for the formulation of energy prescriptions in the constructions sector: it requires Member States that the minimum energy performance requirements of buildings are defined to achieve optimal cost levels through balanced choices (Fantozzi, 2019; Blumberga, 2016; Corrado, 2016a; Becchio, 2015). NZEB buildings (Nearly Zero Energy Buildings), represent a fundamental element of the EPBD Directive. Member States shall

ensure that from 1st January 2021 all new buildings will be NZEB and from 1st January 2019 all new public buildings will be NZEB (Attia, 2017; Buso, 2017; Corrado, 2016b), although in Italy this latter prescription is still rather disregarded. As a result of the European Directive 2010/31 EPBD, in Italy the energy classification system for buildings has also changed, moving from a system with 8 performance levels, from G to A+ (Fantozzi, 2009) to a 10 levels system, from G to A4 (Italian Ministry of Economic Development, 2015a).

The thermal behavior of a complex system, as in the case of a building, is strictly dependent on the variability of the surrounding environmental conditions. In particular, the heat flow transmitted through the building envelope depends on the oscillations of the internal conditions of the building (mainly determined by the characteristics of building occupancy and building systems management) and, at the same time, by the fluctuations of the external climatic conditions, such as temperature and solar radiation. In order to numerically analyze these effects, it is necessary to resort to dynamic evaluations, taking into consideration the effects of the thermal capacity of the materials that constitute the envelope and the partitions of the investigated building. Through the models of dynamic analysis, the variability of the external climatic conditions is described using climate data on an hourly basis and the variability of the environmental conditions inside the building is determined through the imputation of employment and management data (Silenzi, 2018; Cornaro, 2015; Caruso, 2013).

In the present study, the energy performance of different buildings were assessed using averaged monthly and hourly calculation methods. The results, obtained locating the buildings in different Italian climatic zones, were compared in terms of heating and cooling primary energy demands. In addition the impact of different ventilation rates were analyzed for office buildings.

Material and Methods

In the present study two different types of buildings were analyzed: single-family and office buildings. The main geometric characteristics of the analyzed buildings are shown in Figure 1.

Figure 1: Schematic representation of the analysed buildings: a) plan, main geometric characteristics and 3-D South-East view for the residential building; b) plan, main geometric characteristics and 3-D South-West view for the office building.

These buildings can be considered as representative of typologies rather widespread in Italy, as indicated in (Corrado, 2014). The residential building has the shape of a regular parallelepiped, with an unconditioned attic, an insulated roof and an unconditioned space inserted in the volume (e.g. garage, see Fig. 1a). The office building has the same shape of the residential one, even if with very different dimensions, has an insulated roof without attic (see Fig. 1b) and it has unconditioned spaces inserted in the volume. The values of the thermal transmittances of the opaque and transparent elements of the building envelopes are those indicated for the “reference building” in function of the climatic zones as defined in Italian rules (Italian Ministry of the Economic Development, 2015), they are shown in Table 1.

Table 1: Thermal transmittances of opaque and transparent building elements.

Building element	U (W/m ² K)				
	Climatic zone				
	B	C	D	E	F
OVW	0.43	0.34	0.29	0.26	0.24
OHR	0.35	0.33	0.26	0.22	0.20
OHF	0.44	0.38	0.29	0.26	0.24
WIN	3.00	2.20	1.80	1.40	1.10
PAR	0.80				

Legend– OVW=Opaque Vertical external Walls; OHR=Opaque Horizontal or inclined Roofing elements; OHF=Opaque Horizontal ground Floors, WIN=Windows, PAR=Partition elements between conditioned spaces.

Note– The Italian territory is divided in six climatic zones (from A, hottest, to F, coldest) in function of the heating degree-days according to cited Italian rules.

The U values of Table 1 are inclusive of the effect of the thermal bridges and, therefore, in the energy simulations ideal buildings without thermal bridges were considered. In order to take into account the properties of thermal storage of the building elements, essential in time varying heat transfer conditions (Fantozzi, 2014; Leccese, 2018; Leccese 2019), the effective distribution of the capacitive and resistive layers of each opaque building element was modeled in the software. In particular for the opaque vertical external walls, traditional brick walls were chosen (thermal conductivity of the brick 0.68 W/mK, thickness 30 cm), with external thermal insulation in polystyrene (thermal conductivity 0.034 W/mK, variable thickness, depending on the climatic zone, to reach the thermal transmittance values indicated in Tab. 1). These walls are finished with layers of internal and external plaster (thermal conductivity 0.80 W/mK, thickness of each layer 1.5 cm), adequate convective (h_c) and radiative (h_r) surface heat transfer coefficients were used (h_c equal to 2.5 and 20 W/m²K, h_r equal to 5.13 and 4.14 for internal and external surfaces respectively) according to the technical standard EN ISO 13789.

All the analyzed buildings are equipped with a reversible air-to-water electric heat pump with modulating compressor. Both the residential and the office buildings have a single heat generator. In compliance with the energy coverage from renewable sources envisaged by (Italian Ministry of Economic Development, 2011), a photovoltaic solar system was considered for both types of building.

For the office building, moreover, the characteristics of the mechanical ventilation and lighting systems were included. The selection of technical features for the heating/cooling system and for the photovoltaic solar system was conducted in such a way all the analyzed buildings comply with the current requirements for the Nearly Zero Energy Buildings (NZEB) defined by Italian legislation (Italian Ministry of Economic Development, 2015b).

Simulating the energy performance of a building using the hourly calculation method, the information regarding the occupation profile is very important. In the present study, the simple occupation profiles shown in Figure 2 were considered; they were hypothesized valid for the whole year. During the occupation periods, the following set-point temperatures were considered for the air-conditioning system (in case of both residential and office buildings): 20 °C for the winter season, 26 °C for the summer season. Moreover, the internal gains were calculated as indicated in the technical standard UNI/TS 11300-1, by using Equations (1) and (2), in case of residential and office buildings respectively, for the determination of the thermal power Φ_i (W):

$$\Phi_i = 7.987 \cdot A_f - 0.0353 \cdot A_f^2 \quad (1)$$

$$\Phi_i = 6 \cdot A_f \quad (2)$$

where A_f (m²) is the building net floor area.

Figure 2: Building occupation profiles used in the simulations: a) residential building; b) office building.

In order to evaluate the energy demand due to the ventilation, the calculation method indicated in the technical standard UNI/TS 11300-1 was employed by using different values of the air flow rates. In the case of residential buildings, natural ventilation due to windows opening was considered. The air flow rate was evaluated considering a standardized user's behavior, characterized by a constant value of air changes per hour $n=0.5 \text{ h}^{-1}$. In the case of office buildings, the presence of mechanical ventilation systems were considered with constant value of air flow rate $g=1.05 \text{ m}^3/\text{s}$, evaluated according the technical standard UNI 10339. To investigate the effect of different ventilation rates, in addition to the above mentioned value of the air flow rate ($g=1.05 \text{ m}^3/\text{s}$, Scenario 1), two other ventilation scenarios have been hypothesized for the office buildings, characterized

respectively by $g=1.61 \text{ m}^3/\text{s}$ (Scenario 2) and $g=2.25 \text{ m}^3/\text{s}$ (Scenario 3). These latter values were obtained according to the technical standard EN 15251, considering "very low polluted building" and "low polluted building" categories respectively. For all mechanical ventilation systems in offices, the presence of a heat recovery unit with an efficiency $\epsilon=0.7$ was also considered.

In order to evaluate the energy demand due to the lighting in the office buildings, the indications contained in the technical standard EN 15193 were followed, in particular a value of the specific electric power installed for artificial lighting purposes $P=10 \text{ W/m}^2$ was used.

For each building five climatic zones of the Italian national territory were considered and for each of them three significant locations were analyzed, obtaining 30 models to be simulated (15 for each building type). In the choice of locations, the most representative winter climatic zones (from B to F) were considered (the climate zone A was disregarded, affecting just 0.04 % of the population). The significant locations are indicated in Table 1 and they were selected using the following criteria: Location 1 is the provincial capital with a number of heating degree-days (HDD) closer to the average value of the related climatic zone, weighted with respect to the population; Location 2 is the provincial capital with a number of HDD closer to the maximum value of the zone; Location 3 is the town with a maximum number of HDD of the zone. For the climatic zone F, the first two locations coincide, therefore a town with a number of HDD equal to the average value of the zone weighted with respect to the population was chosen.

Table 2: Considered climatic zones, locations and related number of heating degree-days (HDD).

Climatic zone	ID	Location	HDD
B	1B	Reggio Calabria	772
	2B	Crotone	899
	3B	Saponara (ME)	900
C	1C	Lecce	1153
	2C	Catanzaro	1328
	3C	Caltagirone (CT)	1399
D	1D	Terni	1650
	2D	Forlì	2087
	3D	Castiglione del Lago (PG)	2099
E	1E	Rovigo	2466
	2E	Aosta	2850
	3E	Casina (RE)	2999
F	1F	Belluno	3043
	2F	Calascio (AQ)	3454
	3F	Sestriere (TO)	5165

Note – For the towns that are not provincial capital, the abbreviations of belonging provincial capitals are indicated in the brackets.

Energy performance simulations

The thermal behaviors of the buildings in the sample are simulated using the commercial software *Termolog EpiX9* (Logical Soft) certified by the Italian Thermotechnical Committee as required by (Italian Ministry of Economic Development, 2015a). It performs energy simulation according to the technical standards

UNI/TS 11300 (averaged monthly calculation method) and EN ISO 52016 (hourly calculation method). The simulation of the thermal behavior of each building was preceded by a preparatory phase, in which preliminary simulations were carried out using averaged monthly calculation method, until all the conditions indicated for a NZEB by the Italian legislation was achieved. It is important to observe that in Italy, to consider a building as NZEB, it is necessary for it to show higher energy performance than its *reference building* (Italian Ministry of Economic Development, 2015b). Unlike most European countries (Attia, 2017), no fixed performance thresholds are fixed for a NZEB in Italy. The *reference building* is identical to the actual one in terms of geometry (shape, volume, net surface, surfaces of the construction elements and components), orientation, territorial location, intended use and boundary situation and it has predetermined thermal characteristics of the envelope and energy efficiency of the systems. Furthermore for a NZEB, coverage must be guaranteed with energy produced by renewable sources, of the following amounts: 50% of the energy demand for domestic hot water production and 50% of the sum of the energy demands for domestic hot water production, heating and cooling. In Table 3, the values of the nominal thermal power and of the overall seasonal efficiencies obtained by averaged monthly calculation method are shown. The values are able to comply with the NZEB requirements.

Table 3: Nominal thermal powers and overall seasonal efficiencies of the reversible heat pumps used.

	W_{HP} (kW)	$\eta_{u,h}$ (-)	$\eta_{u,c}$ (-)	$\eta_{g,h}$ (-)	$\eta_{g,c}$ (-)
Residential buildings	4.0	0.81	0.81	3.00	2.50
Office buildings	60.0				

Legend– W_{HP} =Nominal thermal power of the heating/cooling system; $\eta_{u,h}$ and $\eta_{u,c}$ =Seasonal efficiency of utilization subsystems in heating and cooling mode respectively; $\eta_{g,h}$ and $\eta_{g,c}$ =Seasonal efficiency of the reversible heat pump in heating and cooling mode respectively.

Results and Discussion

The results of the primary energy demand evaluation for heating and cooling in the case of residential buildings are shown in the bar charts of Figure 3 and 4 respectively. The results obtained using averaged monthly and hourly calculation methods are compared in the bar charts. The comparison is done using the primary energy demand because this is the parameter on which the performance indicators, introduced for the energy classification of buildings, are based on.

Analyzing the results shown in Figure 3 it is possible to observe that the primary energy demand for heating obtained using the hourly calculation method are rather similar to those obtained using the averaged monthly method, with percentage deviations in the range from 1.5% (Lecce, ID 1C, Tab. 2) to 12.5% (Belluno, ID 1F, Tab.2). Exceptions are the localities of Calascio (ID 2F) and Sestriere (ID 3F), particularly cold locations (with HDD values higher than 3400) for which the deviations between the two calculation methods become significant

(see Figure 3). As it might be expected, the primary energy demand for heating, for localities contained within the same climatic zone, tends to increase with the HDD value with both calculation methods. Also in this case there are two exceptions, the localities of Castiglione del Lago (ID 3D) and Calascio (ID 2F), whose different behavior can be explained by the particular climatic data characterizing the two localities, which were derived from the technical standard UNI 10349. The consideration on the increase of primary energy demand for heating with the increase in of HDD value cannot be generalized to localities belonging to different climatic zones, since these (in order to meet the NZEB requirements) have different thermal insulation levels (see the different values of thermal transmittances shown in Table 2). In any case, for the analyzed residential NZEBs, excluding the localities of Calascio e Sestriere, the primary energy demand for heating varies from a minimum of 3960 kWh (Reggio Calabria, ID 1B) to a maximum of 10800 kWh (Belluno) in the case of averaged monthly method, and from a minimum of 3029 kWh to a maximum of 8810 kWh in the case of hourly calculation method. Considering the net floor area of the building ($A_f = 94.5 \text{ m}^2$), the aforesaid primary energy values lead to energy performance indicators for heating (EP_H) that vary from 40.9 kWh/m²year to 114.3 kWh/m²year using the averaged monthly method, and from 32.05 kWh/m²year to 93.2 kWh/m²year using the hourly calculation method.

Analyzing the results shown in Figure 4 it is possible to observe that the behavior related to the primary energy demand for cooling is very different from that for heating. The percentage deviations between the results obtained with the two different calculation methods become more significant, they reach an average value of about 80%, with a maximum value higher than 200% obtained for Calascio. In this case the locality of Sestriere was left out of the discussion, as it shows a negligible primary energy demand for cooling using both calculation methods.

Figure 5 shows the values of the percentage deviations obtained in the evaluation of primary energy for cooling using the two different calculation methods, in function of the HDD values. As it is possible to point out from Figure 5, these deviations show an increasing trend with the HDD values, the increasing trend can be considered with a good approximation ($R^2=0.879$) as linear (see the regression equation in Figure 5). Important to note that for HDD values lower than 1000, the hourly calculation method leads to results in terms of primary energy demand for cooling lower than those obtained using the averaged monthly method, for values of HDD higher than 1000 the opposite occurs (values of the primary energy demand for cooling higher if obtained using hourly calculation method with respect to those obtained using averaged monthly method, see Fig. 5). For the analyzed residential NZEBs, excluding the locality of Sestriere, the primary energy demand for cooling varies from a minimum of 115 kWh (Calascio) to a maximum of 1464 kWh (Reggio Calabria) in the case of averaged

Figure 3: Primary energy demand for heating in the case of single-family residential buildings with different locations.

Figure 4: Primary energy demand for cooling in the case of single-family residential buildings with different locations.

Figure 5: Percentage deviation of the primary energy demand for cooling between averaged monthly and hourly calculation methods in function of HDD for the analysed residential buildings.

monthly method, and from a minimum of 413 kWh (Belluno) to a maximum of 1158 kWh (Reggio Calabria) in the case of hourly calculation method. These primary energy values lead to energy performance indicators for cooling (EP_C) that vary from 1.2 kWh/m²/year to 15.5 kWh/m²/year using the averaged monthly method, and from 4.4 kWh/m²/year to 12.3 kWh/m²/year using the hourly calculation method.

The results of the primary energy demand evaluation for heating and cooling in the case of office buildings are

shown in the bar charts of Figure 6 and 7 respectively. The results obtained using averaged monthly and hourly calculation methods are compared in the bar charts.

Analyzing the results shown in Figure 6 it is possible to observe that, as in the case of residential buildings, the primary energy demand for heating obtained using the hourly calculation method are rather similar to those obtained using the averaged monthly method. The percentage deviations between the results obtained using averaged monthly and hourly calculation methods are, in

this case, in the range from 2.4% (Forlì, ID 2D) to 20.0% (Castiglione del Lago). Exceptions are all the localities of the climatic zone F (with HDD values higher than 3000), for which the deviations between the results obtained using the different calculation methods are very significant. Exactly as in the case of residential buildings, the primary energy demand for heating, for localities contained within the same climatic zone, tends to increase with the HDD value with both calculation methods, with the two exceptions of Castiglione del Lago and Calascio. Actually, in the case of using the

hourly calculation method, it is possible to observe a small reduction of the primary energy demand for heating, passing from the locality of Crotone (ID 2B) to the locality of Saponara (ID 3B), phenomenon that is not observable from the results obtained using the averaged monthly calculation method. The reduction in the primary energy demand for heating observed between some localities belonging to different climatic zones, e.g. between Forlì and Rovigo (ID 1E), it can be explained again through the different thermal insulation levels necessary to meet the NZEB requirements (see Tab. 2).

Figure 6: Primary energy demand for heating in the case of office buildings with different locations.

Figure 7: Primary energy demand for cooling in the case of office buildings with different locations.

Figure 8: Difference in the useful energy demands ($Q_{H,S2}-Q_{H,S1}$ and $Q_{H,S3}-Q_{H,S2}$) in function of HDD for the analysed office buildings.

For the analyzed office NZEBs, neglecting the localities belonging to the climatic zone F, the primary energy demand for heating varies from a minimum of 1380 kWh (Reggio Calabria) to a maximum of 42041 kWh (Casina, ID 3E) in the case of averaged monthly method, and from a minimum of 2743 kWh to a maximum of 44445 kWh in the case of hourly calculation method. Considering the net floor area of the building ($A_f = 1600 \text{ m}^2$), the aforesaid primary energy values lead to energy performance indicators for heating (EP_H) that vary from $0.86 \text{ kWh/m}^2\text{year}$ to $26.28 \text{ kWh/m}^2\text{year}$ using the averaged monthly method, and from $1.71 \text{ kWh/m}^2\text{year}$ to $27.78 \text{ kWh/m}^2\text{year}$ using the hourly calculation method.

Analyzing the results shown in Figure 7 it is possible to observe that the values of the primary energy demand for cooling, obtained using the averaged monthly method, are strongly higher than those obtained using the hourly calculation method for all the analyzed localities. The percentage reductions of primary energy demand (passing from averaged monthly method to hourly method) have an average value of about 60%. The values of the percentage reduction, found for all the considered localities, are rather constant, they are contained in the range between 55% (Casina, ID 3E) and 70% (Catanzaro, ID 2C). Considering the type of analyzed building, with large windowed surfaces (see Fig. 1), the differences so marked in the evaluation of the primary energy demand for cooling can be attributed in significant part to the different way of evaluating the solar gains of the two calculation methods. The hourly calculation method, using data with a very frequent step (each hour) if compared to the use of monthly average data, allows evaluations of the actual impact of the solar gains with greater accuracy with respect to the averaged monthly calculation method. This aspect must be taken into adequate consideration by the legislator, especially in a perspective of transition from the calculation method currently in force in Italy for the energy certification of buildings (based on averaged monthly data) to innovative methods based on dynamic simulations (e.g based on hourly data, as that in EN ISO 52016).

In order to evaluate possible effects due to the increase in the ventilation rate when hourly calculation method is used, the useful energy demands (Q_H , kWh/year) for heating were evaluated considering the Scenario 1 ($Q_{H,S1}$), the Scenario 2 ($Q_{H,S2}$) and the Scenario 3 ($Q_{H,S3}$), characterized by the ventilation rates defined in the previous Section. The choice to compare the useful energy demand for this evaluation was made to not consider any effects related to the performance of the heating system. Figure 8 shows the increases in the useful energy demands for heating that are obtained by passing from Scenario 1 to Scenario 2 ($Q_{H,S2} - Q_{H,S1}$) and from Scenario 2 to Scenario 3 ($Q_{H,S3} - Q_{H,S2}$), in function of the HDD values. As can be seen from Figure 8, both increases show trends in function of HDD values that can be reasonably approximated to linear.

Conclusive remarks

To calculate the energy demand of a building in an accurate way, the dynamic approaches generally produce more accurate results if compared with those obtained using steady-state approaches. Obviously the possibility of keeping in due consideration the inertia properties of the building elements offers to the designers the possibility of more detailed evaluations, particularly useful in rather efficient buildings such as NZEB. In this study the energy performances of NZEBs (intended for residences and offices) located in different Italian climatic zones were analyzed. The analysis was conducted using both averaged monthly and hourly calculation methods. From the obtained results it was possible to show how, the two methods provide similar estimations (with the exception of some locations with high values of degree-day) of the primary energy demands for winter heating. Great attention must instead be placed on summer cooling, for which the two forecasting methods provide significantly different estimations of primary energy demands.

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