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Application of a mapping tool to plan energy saving at a neighborhood scale

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Abstract

This study proposes the application of a model for the evaluation of the overall energy demand of existing urban neighborhoods, which can be useful when planning energy enhancement strategies at urban scale. The application of this model can be interconnected with the use of a GIS software tool, thus providing the opportunity to perform the energy mapping of city neighborhoods.

In the proposed model, the overall energy demand of existing urban neighborhoods is evaluated by considering the three most energy intensive sectors: buildings, transport and urban lighting. However, in this paper the application of the model is only focused on the assessment of the energy demand in the building sector.

The proposed methodology is applied to a neighborhood of the municipality of Catania in Southern Italy. The preliminary results are reported in this study: first, the existing energy consumption for space heating and electric appliances is assessed, then the effectiveness of a series of energy-saving strategies is considered, thus providing a tool to implement effective energy planning policies at urban scale.

Keywords: district, energy planning, energy savings, refurbishment

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1. Introduction

In the last decades the contrast to climate changes, mostly related to human activity, has clearly emerged as a basic priority [1]. The mapping of world's primary energy demand and of emissions has pointed out that urban areas are responsible of 75% of the overall consumption and of 60% of GHG. But, while being part of the problem, cities are also part of the solution [2], as they have the potential to reduce CO2 emissions significantly [3].

The recognition of cities as complex systems behaving more like "organisms" than "machines" is the basis for a change of paradigm in the analysis and the potential optimisation of energy flows [4]. As opposite to previous approaches, according to this paradigm urban areas are regarded as being organised in a bottom up structure, in which energy flows are determined by a limited number of sub-systems, such as buildings, transport, human activities and green areas [5-6], and by their interaction. In fact, the assessment of energy consumption is mostly developed with sectorial approaches, frequently focusing on the building sector [6-11]. On the other hand, interactions are not fully taken into account, though, occurring at different scales, they represent a key element of the system complexity. Therefore, limitations arise to the traditional approach, that sees the substantial independence of urban planning and energy policies, which implies the need for an integration of energy action planning and urban planning.

Within this perspective, Jones et al. [12] developed the Energy and Environment Prediction Model (EEPM) as an analytical tool to assess energy use and carbon emissions for different sectors in urban areas described by separate sub-models. More recently, Reiter and Marique [13] proposed an integrated method to evaluate energy consumption in suburban neighbourhoods of Walloon region. The model quantifies energy consumption associated to buildings, transport and public lighting, integrating the outcomes to determine the overall consumption of a neighbourhood.

Fichera et al. proposed a strategy to assess the overall energy demand of existing urban neighbourhoods, including the contribution of indoor space heating, household electricity consumption, outdoor lighting and transport [14]. The proposed methodology constitutes an analytical tool that aims at providing an estimation of the global energy demand of existing urban neighbourhoods, even when there is lack of reliable data. The applicability to urban neighbourhoods makes the model suitable for spatial planning applications. In fact, district level is widely considered the right scale for the implementation of energy and planning actions in sustainable town planning [5].

Moreover, the model may be further applied to configure urban energy scenarios through GIS modelling; in fact, combining urban energy mapping and scenario analysis allows to determine integrated planning – energy strategies and to support sustainable political choices on existent urban areas.

Starting from the more general methodology developed in [14], this paper only deals with indoor space heating, with the aim of showing how the proposed mapping tool can be used to study the effectiveness of energy saving strategies in this sector at a neighbourhood scale. In particular, the sub-model implements a mixed method, integrating aggregated statistical and individual building approaches as suggested by Dall'O et al. [7], that yields, through the linear regression of the data, the correlation between EP_H and S/V ratio for different construction periods of the examined building stock. In accordance to Ascione et al. [6], the implemented approach determines the energy performance of buildings by simplifying the national standard procedure and, on this basis, proceeds to the energy mapping of the urban area.

2. Methodology

The model for the calculation of the energy needs for space heating is based on the procedure outlined in the Italian standards UNI-TS 11300 [15, 16]. In particular, the standards contemplate a simplified procedure (*asset rating*), applicable to existing buildings with the purpose to determine a conventional performance level. According to the simplified procedure, the thermal energy needs for space heating can be calculated as in Eq. (1):

$$Q_{H,nd} = \underbrace{\left(Q_{H,tr} + Q_{H,ve}\right)}_{\text{Heat losses}} - \eta_{H,gn} \cdot \underbrace{\left(Q_{sol,w} + Q_{int}\right)}_{\text{Gains}} \quad (1)$$

Here, $Q_{H,tr}$ and $Q_{H,ve}$ are respectively the heat losses due to transmission and ventilation. On the other hand, $Q_{sol,w}$ quantifies the beneficial contribution of the solar gains penetrating through the glazed envelope. Finally, Q_{int} refers to internal gains, due to people, artificial lighting and electrical appliances.

Equation (1) implies that solar and internal gains cannot be entirely exploited to compensate for the heat losses. Indeed, walls and slabs will first absorb the radiant energy; then, they will partially re-emit heat by convection to the indoor air. The effective exploitation of the heat gains is assessed through the utilization factor $\eta_{H,gn}$; as a rule, the higher is the thermal capacity of the envelope components, the higher gets the utilization factor. In this paper, the utilization factor is set to $\eta_{H,gn} = 0.9$ for all the buildings belonging to the district, which is a reasonable approximation in existing residential buildings with relatively high heat capacity, and where the heat losses are significantly larger than the internal gains.

The single terms appearing in Eq. (1) are detailed in Eq. (2) to Eq. (5):

$$Q_{H,tr} = 0.024 \cdot HDD \cdot \left[\sum_j U_j \cdot S_{env,j} + \sum_k \psi_k \cdot L_k \right] = 0.024 \cdot HDD \cdot (1 + x_{tb}) \cdot \sum_j \left(U_j \cdot S_{env,j} \right) \tag{2}$$

$$Q_{H,ve} = 0.024 \cdot HDD \cdot (\rho_a \cdot c_a \cdot n \cdot V) \tag{3}$$

$$Q_{sol,w} = \left[\sum_i \phi_{sol,w,i} \right] \cdot t = \left[\sum_i S_w \cdot g_{gl} \cdot F_{sh} \cdot (1 - F_F) \cdot I_{sol} \right]_i \cdot t \tag{4}$$

$$Q_{int} = \left[\sum_k \phi_{int,k} \right] \cdot t \tag{5}$$

In particular, Eq. (2) adopts a simplified approach for the calculation of the heat losses due to thermal bridges, since their contribution is stated as a percentage x_{tb} of the heat losses through the external envelope surface. Usually, in poorly insulated existing buildings this percentage is lower than in highly insulated new buildings, unless appropriate measures are taken to correct thermal bridges. The value retained for x_{tb} will be specified in Section 3.

The ventilation rate occurring in Eq. (3) is set to $n = 0.3\ h^{-1}$ in residential buildings and $n = 1\ h^{-1}$ in schools and public buildings. The Heating Degree Days for the city of Catania correspond to HDD = 833 °C day, defined relative to a base outdoor temperature of 12°C. Consequently, Catania belongs to the climatic zone B; here, the national regulations about energy savings in residential buildings allow the operation of the space heating system only for 8 hours per day, from the 1st of December to the 31th of March, on a total of 121 heating days. This is relevant to the calculation of the duration *t* of the heating period.

Moreover, the calculation of the solar gains $Q_{sol,w}$ takes into account the total solar transmittance of the glazing (g_{gl}), the possible role of the shading devices (F_{sh}) and the surface occupied by the frame ($F_F = 0.2$). The sum in Eq. (4) is extended to all the windows on the outer envelope. In this paper, the total solar transmittance is diversified according to the glazing type most widespread in the different periods, see Section 3. On the other hand, the shading factor is universally set to $F_{sh} = 0.8$, which corresponds to the presence of light internal white curtains.

As regards the window surface, in this paper a quick methodology is adopted to compute its size. In fact, the ratio of the glazed surface to the net useful horizontal surface S_u, measured for the entire building, is supposed to comply with the minimum value imposed by the Italian Ministerial Decree 5/7/1975. Hence, $S_{w,tot} = 0.125 \cdot S_u$.

Furthermore, the glazed surface is distributed amongst the different orientations proportionally to the size of the corresponding façades, as described in Eq. (6):

$$S_{w,i} = \left(S_{env,i} / S_{env,tot} \right) \cdot S_{w,tot} \tag{6}$$

Finally, in Eq. (5) the average internal gains are as high as $\phi_{int} = 4$ W/m^2 in residential buildings and schools. This contribution is slightly higher ($\phi_{int} = 8$ W/m^2) in other public buildings, such as hospitals and churches.

As a final step, it is possible to state the Energy Performance index for space heating, corresponding to the primary energy consumption per unit useful surface and measured in [kWh m^{-2} y^{-1}]:

$$EP_H = Q_{H,nd} \Big/ \left(S_u \cdot \eta_g \right) \tag{7}$$

The overall efficiency η_g of the space heating system includes the efficiency of the heat generator and the heat losses due to distribution, emission and inaccurate control systems. Suitable values for this parameter are provided in Section 3. As a rule, the more recent is the dwelling, the higher gets the overall system efficiency. Moreover, it is relevant to underline that, according to the Italian Ministerial Decree 26/5/2015, in case of energy refurbishment the overall efficiency of the newly installed space heating system must keep above a certain threshold. For gas-fueled heat generators with hydraulic distribution network, the threshold efficiency is $\eta_g = 0.95/0.81 = 0.77$; this value will then be applied to the scenario after refurbishment.

This procedure is applied to all the buildings belonging to the district identified in Section 3. The Energy Performance index EP_H of each building will be then correlated to the ratio S/V of the outer building surface to the overall heated volume.

3. Case study

The model described in the previous section has been applied to the municipality of Catania. For its size and urban characteristics, Catania is representative of many cities in Southern Italy. More specifically, the neighbourhood of Nesima Superiore has been identified for testing the methodology, due to the variety of land-use and the characteristics of buildings (Fig. 1). The buildings within this district belong to many ages, and show several morphological and land-use types; examples of social housing, single-family houses and blocks can be found. The investigated area has an extension of 0.67 square kilometers.

Fig. 1. Map of Nesima Superiore neighbourhood (each building is colored according to its S/V ratio).

The methodology has been applied to 458 buildings, most of which are either residential buildings or mixed use buildings, while only 5.8% of the buildings are retail ones. Through a deep analysis of the city maps, the historical evolution of the urban system has been retraced. The results of this preliminary investigation highlight that 50% of the building stock has been built before 1964 and 35% between 1964 and 1985. Less than 1% of buildings dates from after the enforcement of the Decree 192/2005, which introduced severe regulations for the energy performance of buildings.

Based on the age of the buildings and besides according to the evolution of the Italian legislation on building energy saving, the U-value of each building element has been assigned, as reported in Table 1. The values are chosen in accordance with the outcomes of the Tabula research project [17].

Table 1. Thermal features of the building element (before refurbishment)

Age	Windows [W m^{-2} K^{-1}]	Walls [W m^{-2} K^{-1}]	Base floor [W m^{-2} K^{-1}]	Roof [W m^{-2} K^{-1}]	x_{th}	g_{gl}	F_{sh}	η_g
1924/60	5	2	2	1.3	1.1	0.85	0.7	0.5
1961/64	5	1.15	2	1.3	1.1	0.85	0.7	0.5
1965/76	5.7	1.15	2	1.3	1.1	0.85	0.7	0.5
1976/85	5.7	0.78	1.24	0.98	1.1	0.85	0.7	0.6
1986/91	5.7	0.78	1.24	0.98	1.2	0.85	0.7	0.6
1992/01	3.7	0.78	1.24	0.98	1.2	0.75	0.7	0.7
2002/07	2.7	0.6	0.9	0.7	1.2	0.67	0.7	0.75

The data in Table 1 indicate a lack of thermal insulation in the building envelope. The U-values are at least twice as high as the level of performance requested by the current legislation, which emphasizes the poor quality of the building envelope. The heating systems are also affected by low efficiency.

Now, the main strategy for energy refurbishment usually consists in minimizing thermal losses through the envelope, but it is also desirable to control the solar heat gains and to reduce cooling loads. However, refurbishment can also improve other important issues, such as noise insulation and fire security. In addition, the energy behavior of buildings has a strong influence on the urban heat island effect [18].

This preliminary study aims to evaluate which is the degree of energy saving that can be attained by means of an ordinary renovation of both the building envelope and the heating system. More specifically, the target is to satisfy the U-value imposed by the recent Italian regulations (Decree 26/5/2015) in case of energy refurbishment in the climatic zone B. In particular, the following upper threshold are set: U = 3.00 W m^{-2} K^{-1} for windows, U = 0.42 W m^{-2} K^{-1} for the base floor, U = 0.32 W m^{-2} K^{-1} for the roof. In practice, the thermal insulation of these building elements is upgraded by adding a suitable thickness of rock glass or rock wool (λ = 0.037 W m^{-1} K^{-1}).

More specifically, external façades will be upgraded through an External Thermal Insulation Composite System (ETICS), which also contributes to reduce the impact of thermal bridges, measured by the coefficient x_{th}. Of course, the higher is the initial U-value (see Table 1), the higher is the thickness of insulation needed. In the worst case (most aged buildings), one needs to adopt 80 mm of insulation for walls and base floor, and 100 mm for the roof.

Table 2 shows the U-values of the building elements that can be reached adopting the previous mentioned strategies. It is also interesting to remark that rock wool is particularly suited for sound insulation, due to its high density.

Moreover, window elements will be remodeled using thermal break aluminum frame and double-glazed with low emissivity coating. It is also necessary to underline that the material used to make the spacer is able to reduce the heat travels through a window edge (warm-edge spacers). To achieve a sound insulation of 40 - 44 dB, the outer glazing has a thickness of 9 millimeters; the inner glazing has a thickness of 6 millimeters. In addition to the gas filling, a PVC foil is also applied to further reduce noise transmission significantly.

Table 2. Thermal features of the building element (after refurbishment)

Age	Windows [W m^{-2} K^{-1}]	Walls [W m^{-2} K^{-1}]	Base floor [W m^{-2} K^{-1}]	Roof [W m^{-2} K^{-1}]	x_{th}	g_{gl}	F_{sh}	η_g
1924/60	2.8	0.39	0.39	0.30	1.05	0.67	0.7	0.77
1961/64	2.8	0.38	0.39	0.30	1.05	0.67	0.7	0.77
1965/76	2.8	0.38	0.39	0.30	1.05	0.67	0.7	0.77
1976/85	2.8	0.39	0.38	0.30	1.05	0.67	0.7	0.77
1986/91	2.8	0.39	0.38	0.30	1.05	0.67	0.7	0.77
1992/01	2.8	0.39	0.38	0.30	1.05	0.67	0.7	0.77
2002/07	2.8	0.37	0.38	0.31	1.05	0.67	0.7	0.77

4. Results and discussion

As a first result, Fig. 2 reports the Energy Performance index EP_H calculated for all the buildings within the district, according to the procedure described in Section 2. With the aim to simplify the analysis and in accordance to the available data, existing buildings have been clustered in three age macro-categories: 1924 to 1964; 1965 to 1985; 1986 to 2007. For each macro-category of buildings, a tendency line is defined, with an equation that satisfactorily correlates the data obtained through the proposed methodology.

It is interesting to observe that the oldest buildings, built between 1924 and 1964, show a ratio S/V in the range 0.3-0.6, with a few exceptions having S/V close to 0.8. The Energy Performance index is mostly concentrated between 90 and 170 kWh/m^2. On the other hand, the buildings belonging to the period 1965-1985 show a larger scattering for the ratio S/V, and the Energy Performance index is reduced by around 30%. Finally, the district contains just a few recent buildings (after 1986), with higher shape factors (S/V > 0.8) and relatively low energy consumptions, at least if compared with other less recent buildings having the same S/V ratio.

However, after the proposed energy refurbishment all buildings would show a very similar behavior, independently on their original year of construction. The tendency lines are almost coincident, and the Energy Performance index ranges from less than 10 kWh/m^2 for S/V = 0.25 to 30 kWh/m^2 for S/V = 1. A map showing the distribution of EP_H within the district is reported in Fig. 3.

It is important to remark that the results shown in Fig. 2 and Fig. 3 do not include the energy consumption for Domestic Hot Water, that usually impact for about 20-25 kWh/m^2 per year.

Another interesting outcome of the study is reported in Fig. 4. Here, the overall predicted energy consumption for the whole district is reported, both before and after the proposed refurbishment strategy, with a detail of the impact of the different macro-categories. The intervention on the entire district would potentially reduce the energy consumption for space heating by 88%, thanks to the improvement of the energy performance of both the envelope and the heating systems. Of course, such a dramatic reduction is also justified by the high share of buildings dating back to more than 50 years ago, which show a huge potential for improvement.

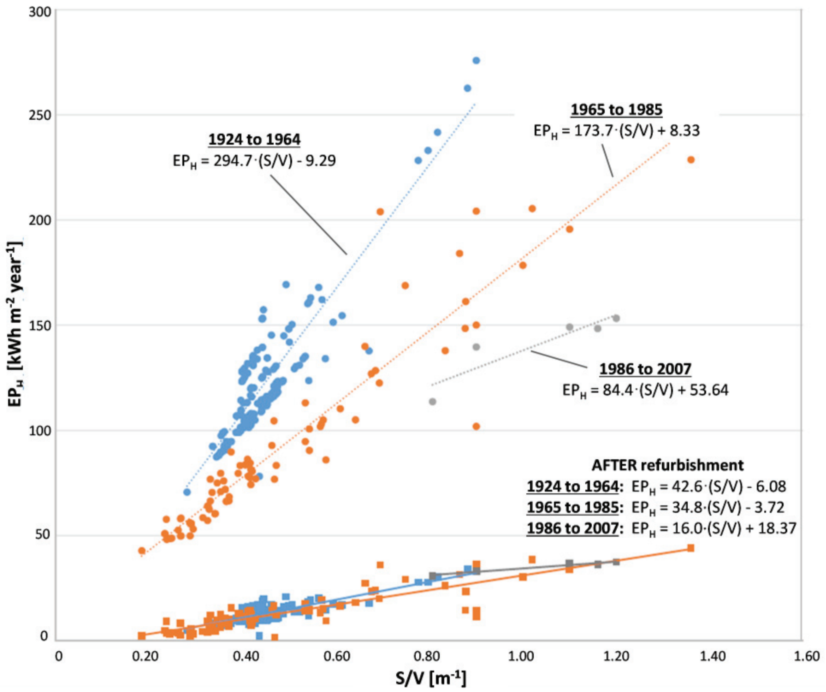

Fig. 2. Correlation between S/V ratio and energy performance (the dots refer to the real buildings in the district)

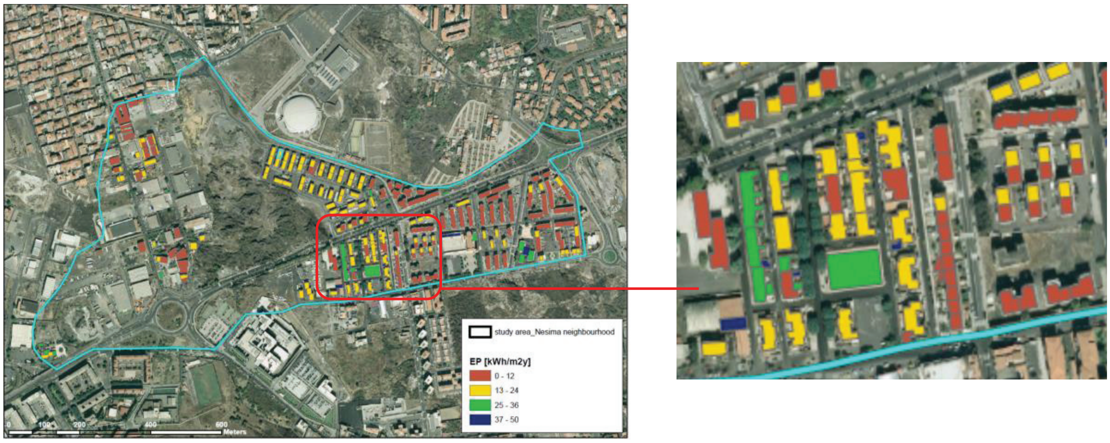

Fig. 3. Energy Performance index EP_H for the buildings within the district (after refurbishment).

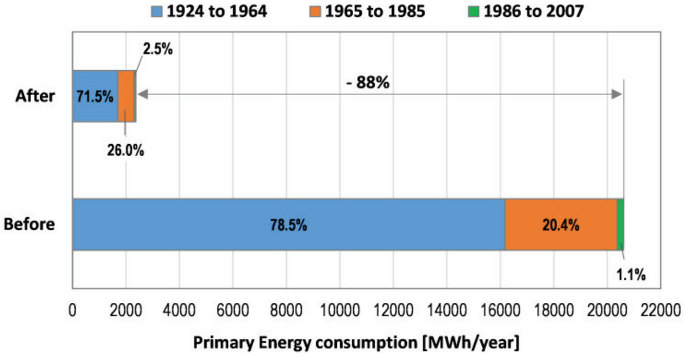

Fig. 4. Overall primary energy consumption at the district scale (before and after the proposed refurbishment)

Moreover, these results allow to obtain very interesting information about the potential contribution of building envelope and heating system renovation for achieving the Horizon 2020 objectives. In fact, the energy consumption of the building sector accounts for about 35% of the final energy consumption in Italy. This contribution is due to electrical and thermal energy uses, for which a proportion of about 40% to 60% in terms of primary energy has been calculated [19]. Therefore, the scenario of refurbishment that has been investigated may contribute to reduce by about 18% the global energy consumption of the district. Obviously, this result can be further increased by introducing more efficient heating and cooling systems, or through renewable energy systems.

Another very useful application of the model is its ability to perform the quick calculation of the energy needs of a district, via the regression equation shown in Fig. 2, only on the basis of synthetic data concerning the age of the building, the heated volume and the external surface of the building envelope.

Thus, since it is quite simple to introduce such data on a GIS platform, this model provides both the evaluation of the current energy consumptions and the estimate of the energy savings that can be obtained as a function of proposed refurbishment scenarios. In this perspective, the proposed model can represent a powerful support tool for implementation of effective energy planning policies at an urban scale. At the same time, interfacing the model in a GIS platform might allow further extension of the model potentiality through the interaction with other data bases, concerning, in particular, the availability of renewable sources, such as solar or wind resource.

5. Conclusions

This study proposes a methodology to assess the energy demand of neighborhoods, limited to the contribution of space heating. In particular, starting from a few data concerning the size of the buildings, their shape and the age of construction, it is possible to evaluate the primary energy consumption as a function of the ratio S/V, through regression lines that proved to have a satisfactory degree of correlation with the calculated data.

The results are represented by energy maps, developed with a GIS database support, which makes the model an essential cognitive tool for urban energy planning. In this sense, the proposed methodology can be used by urban planners to identify the most energy intensive areas within a city, and to assess easily and with reasonable approximation the effectiveness of suitable refurbishment strategies in the direction of the objectives set by Horizon 2020. Of course, the degree of approximation, determined by the methodology and by the use of regression lines, is consistent with what usually required to urban planners.

In this case study, the tool has been applied to a basic refurbishment strategy consisting in the substitution of the windows and in the envelope insulation up to the level required by current Italian laws. However, the tool can be applied also to other refurbishment solutions, such as cool roofs, shading devices, advanced window technologies, natural ventilation, etc. Further investigations in this direction will be discussed in future works.

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