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Abstract— **This work presents a place-based methodology which, through a statistical analysis, defines bottom-up models for the evaluation of the spatial distribution of energy consumption of residential buildings at urban scale. The objective of this work was to identify the main variables on which energy consumption depends, characterize the residential building stock according to these variables with a place-based assessment. To identify the characteristics of residential buildings that most influence energy consumption, the results of a questionnaire on more than 700 dwellings in Rome were used. Through significant linear regressions, energy performance of buildings for space heating, space cooling, domestic hot water production and electricity were estimated using municipal technical maps and data from the national census on population and buildings. Finally, the results of this work were validated by the consumption reported by the Sustainable Energy and Climate Action Plan for the Metropolitan City of Rome with a relative error of 3% for space heating.**

Keywords—energy models, linear regression, statistical bottom-up models, place-based assessment, residential buildings.

I. INTRODUCTION

The energy and environmental challenges of most countries can start to reach the energy sustainability in cities. Indeed, cities are the most critical areas with a high intensity of energy consumptions and low renewable energy resources. The solution proposed by the European and international policies is to reduce consumption with energy efficiency actions and to use more the available renewable energy sources. This solution would also make it possible to solve the environmental impact of the energy production from fossil fuels and, at the same time, lowering energy costs and favouring the energy independence of the territories.

The EU Climate and Energy Package, the Renewable Energy Directive Recast and the Covenant of Mayors initiative with the Sustainable Energy and Climate Action Plans (SECAP) are working in this direction but each territory, each city is different, and it is necessary to have tools and models to be able to evaluate the strengths, weaknesses, opportunities, and threats related to each energy scenario.

The work presented here is part of this research, with the aim of planning the optimization of energy demand and supply for a large city like Rome; to produce energy where there is an energy demand, it is necessary to evaluate the spatial distribution of energy consumption. This work starts from the analyzes already made for the cities of Torino (IT), Settimo Torinese (IT), other Italian cities, Frankfurt (DE), Geneva (CH) and Gran Mendoza (AR) with bottom-up and top-down models to evaluate the energy consumptions of buildings with a place-base assessment [1, 2, 3].

This work is developed through the presentation of: (i) a place-based methodology, (ii) some bottom-up models for the evaluation of the energy consumptions of residential buildings, (iii) the case study of the twenty districts of the Metropolitan City of Rome and (iv) the results of the application of these models with a Geographic Information System (GIS).

II. MATERIAL AND METHODS

In this paragraph, the databases and the methodology used for this work is explained. A place-based analysis was fundamental to represent the residential building heritage of a large city like Rome with its spatial distribution.

Starting from data on a questionnaire about the energy performance and characteristics of various residential buildings, some bottom-up models were developed. Then, these models were applied with a Geographical Information System (GIS) to the whole City of Rome. The results of this work were compared with the data of the Sustainable Energy Action Plan (SEAP) and the Sustainable Energy & Climate Action Plan (SECAP) for the twenty districts of the Metropolitan City of Rome.

A. Energy and residential buildings database

A specific questionnaire survey has been elaborated and spread to analyse energy consumptions of residential buildings. Specifically, data gathering includes the following parameters [4, 5]:

1. Building features: orientation, location, surfaces, building envelope thermal transmittances, air flow exchange rate, occupancy profile, shading devices;
2. Building technological systems for: space heating and cooling, domestic hot water (DHW) production, solar collectors, photovoltaic modules;
3. Electrical devices and appliances: refrigerator, oven, washing machine, vacuum cleaning, iron, hairdryer and personal care devices, lighting systems, television, audio/video devices, other appliances.

The questionnaire has been built in Excel spreadsheets based on “Visual Basic for Applications” with data about more than 700 dwellings.

The construction year of the buildings has been classified in 11 classes, implementing from the official classification of the Italian population ISTAT (National Institute of Statistics) census with additional classes identified coherently with the Italian law on energy savings and buildings’ energy requirements (years: 1976, 1991, 2005, 2008, 2010, 2015).

Figure 1 highlights that a significative portion of the building stock was built before the first Italian law about energy efficiency in building, Law 373/1976. Furthermore, Figure 2 represents the frequency of the dwellings size divided in five classes, coherently with the number of people living in each dwelling (~3 inh/dw). The average size is equal to 107 m^2 and the most common class is 50-85 m^2. A huge portion of the considered dwellings has only one floor (i.e., 91%), while 5% occupies two floors and 3% three floors. Table I shows the thermal transmittances of envelope components depending on the construction period of buildings in climate zone D.

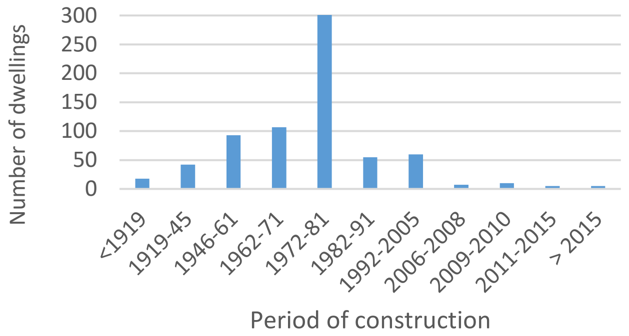


Fig. 1. Period of construction of the analyzed dwellings.

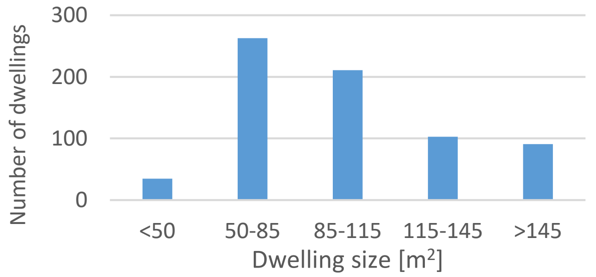


Fig. 2. Size of the analyzed dwellings.

Table I. Thermal transmittance U values by the period of construction of buildings and for the Italian climate zone D.

U W/m²/K	Buildings' construction period										
	< 1919	19–45	46–61	62–71	72–81	82–91	91–2005	06–08	08–10	10–15	<2015
Walls	1.3	1.2	1.2	1.2	1.0	1.0	0.8	0.50	0.40	0.36	0.36
Roofs	1.3	1.3	1.3	1.3	1.1	0.9	0.8	0.46	0.35	0.32	0.28
Floors	1.1	1.2	1.2	1.2	0.9	0.6	0.6	0.46	0.41	0.36	0.36
Windows	5.2	5.1	5.0	5.0	5.0	5.0	3.0	3.10	2.80	2.40	2.10

Table II. Retrofit interventions per building's component.

Construction period	Retrofitted building component			
	Walls	Roofs	Floors	Windows
before 1919	0%	0%	0%	41.7%
1919–1945	4.8%	4.8%	7.1%	69%
1946–1961	10.2%	13.6%	1.7%	78%
1962–1971	12.7%	11.1%	4.8%	46%
1972–1981	14.8%	14.8%	5.7%	50%
1982–1991	9.5%	11.1%	6.3%	42.9%
1991–2005	21.3%	18.7%	12%	17.3%
2006–2008	0%	0%	0%	0%
2008–2010	33.3%	16.7%	0%	33.3%
2010–2015	50%	50%	37.5%	25%
after 2015	0%	0%	0%	0%

Table II shows the percentage of dwellings by period of construction that have undergone to retrofit interventions. The most recurrent retrofit intervention is the replacement of windows, carried out in 270 dwellings (38% of the total).

B. Bottom-up and top-down assessment

Bottom-up models were based on the statistical analysis of the data collected by a questionnaire. On the first step, the data were divided in two classes: the buildings that were not be retrofitted and those that did at least one intervention of energy retrofit, such as the substitution of the windows, thermal insulation of the walls, floor or roof.

Afterwards, it was important to understand which variables influence the energy consumption for space heating (H), space cooling (C), domestic hot water (DHW) production and electricity (E). Once it was defined the variables that present good correlations with energy performance index, the analysis was focused on the type of correlation: linear correlation, linear correlation per building typology or multiple linear correlation.

The reliable correlations were chosen when: the signs of the coefficients are as expected from theory, R^2 is close to 1 with a good significance. The R^2 is the coefficient of determination meaning how the variation of the dependent variable can be explained by the variation of independent variables; the significance was evaluated with the significance F test meaning that the whole regression is statistically significant, while the p-value <5% means how each dependent variable is statistically significant for the regression.

Finally, these correlations have been applied at the residential buildings of the 20 districts of Rome with a Geographic Information System (GIS). Then their energy performances have been compared with the SEAP [6] and SECAP [7] data for the Metropolitan City of Rome.

The adopted databases and methodology are represented in Figure 3.

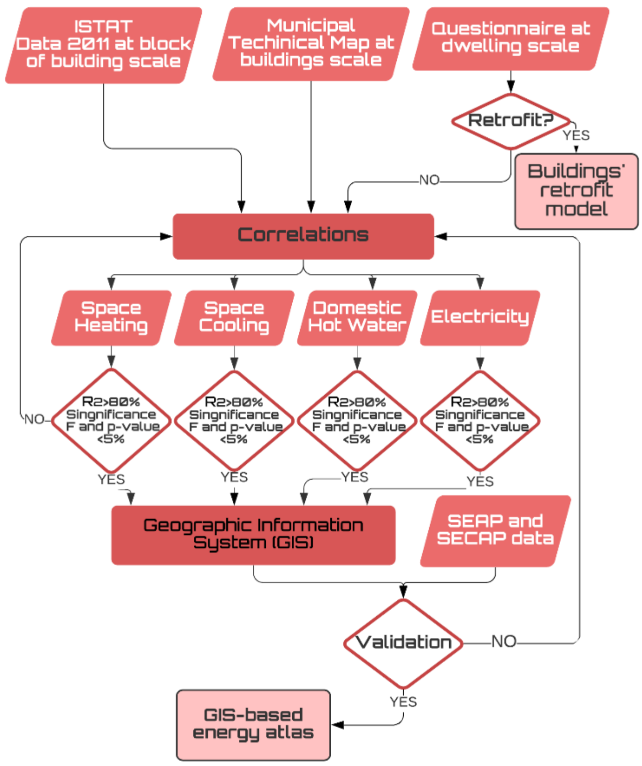


Fig. 3. Structure of the place-based methodology adopted with the identification of energy performance (EP) models for residential buildings stock in Rome.

III. The Case Study of Rome

The city of Rome is the Italian Capital, located in the Centre of Italy, in Lazio Region. The city has 2,778,662 inhabitants on a territory of 1,287.4 km^2. It is divided in 20 districts, numbered from I to XX (in Figure 4), excluding the XIV that in 1992 became the Municipal of Fiumicino airport. The ISTAT information about the inhabitants was related with the information about the gross volume of residential buildings evaluated by the technical map with GIS to have better correlations with the spatial distribution of the population.

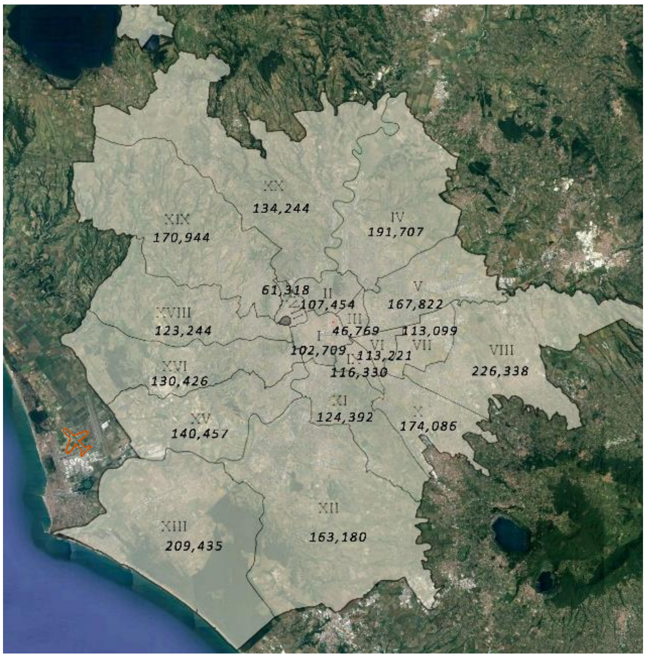


Fig. 4. The case study of the 20 districts of the Metropolitan City of Rome (with the number of inhabitants).

Rome is located in the Italian climatic zone D with 1,643°C at 20°C of heating degree days (HDD) and 143°C at 26°C of cooling degree days (CDD). The residential buildings are 137,021 and the 71% were built before 1980, mainly previously the first Italian law on the energy efficiency. For this reason, Rome building heritage presents a low energy efficiency level. The energy performance index (EP) of residential buildings for space heating $EP_{H.avg}$ is equal to 106 $kWh/m^2/y$, with the energetic class below the D [6], while the EPg is extimated to be equal to 119 $kWh/m^2/y$ [7]. The last data on the energy consumption for the residential buildings, for space heating is reported in the PAESC with 15,405 GWh and 9,489 $kton_{CO2}$ of greenhouse gas emissions in 2015. The same data for DWH and electricity are reported in the SEAP for the year 2009 [6] where the consumptions for DHW are equal to 1,500 GWh and for electricity about 8,465 GWh.

IV. Results and Discussion

The results show that about 50% of the analysed buildings carried out at least one retrofit intervention. To ensure that the model can better represent the Rome's buildings heritage, it was chosen to englobe in the non-retrofit data also the dwellings with windows substitution, because of the lower impact on the global energy performance of buildings. In this way, the analysed data grow up to 582 that represent the 83% of the completed questionnaires (in Table III).

Then, the correlation function was used to identify the main energy-related variables considering all data in the questionnaires. The higher correlations with primary energy per unit of gross volume are reported in Table IV. For every typology of primary energy, the resulting energy-related variables were (for electricity the consumptions have been multiplied by the conversion factor in primary energy of 1.95):

- *Space Heating H: surface-to-volume ratio S/V and period of construction*
- *Space Cooling C*: no correlations because, on average, only the 57% has cooling systems and for the 33% of rooms;
- *DHW*: inhabitants/m^3 and EP_E because of the high use of electric boilers (no correlation with the use of thermal solar collectors, only in 14 dwellings)
- *Electricity E*: inhabitants/m^3, EP_{DHW} and EP_C because of the high use of electric boilers for DHW production and heat pump for space cooling (no correlation with the use of photovoltaic modules, only in 9 dwellings).

Table III. Average and median values of energy performance index in primary energy for space heating (H), domestic hot water (DHW), space cooling (C) and electricity (E).

Energy Performance	**EP_H**	**EP_{DHW}**	**EP_C**	**EP_E** (with cooling system)
N. of dwellings (for no-retrofit model)	530	649	369	369
Average (kWh/y)	5874	3695	3683	12,128
Median (kWh/y)	4859	3764	2854	11,848
Average ($kWh/m^3/y$)	15.23	10.4	10.4	35.3
Median ($kWh/m^3/y$)	14.01	9.7	6.7	32.0

Table IV. Correlations of energy-related variables with EPs.

Correlations with:	**kWh/m^3**			
	EP_H	**EP_{DHW}**	**EP_C**	**EP_E**
Inhabitants density (inh/m^3)	0.02	**0.93**	0.25	**0.65**
Period of construction	**-0.33**	-0.09	-0.02	-0.10
S/V (m^2/m^3)	**0.76**	0.17	0.14	0.19
Thermal solar panels	-0.04	0.00	-0.31	-0.04
Photovoltaic modules	-0.18	0.02	-0.04	-0.13
EP_{DHW} (kWh/m^3)	0.04	1.00	0.29	**0.69**
EP_C (kWh/m^3)	0.16	0.29	1.00	**0.83**
EP_E (kWh/m^3)	0.13	**0.69**	**0.83**	1.00

Analyzing the main energy-related variables and the relative correlations, the following single and multiple linear regressions (respectively LR and MLR) were chosen for:

- Space heating: multiple linear regression with period of construction (PC) and surface-to-volume ratio (S/V); a second model considers linear regression with surface-to-volume ratio per period of construction;
- Space cooling: theoretical correlations with CDD-HDD considering the average efficiencies of space heating and cooling systems and the percentage of cooled buildings and rooms within buildings.
- DHW: linear regression with inhabitants/m^3
- Electricity: multiple linear regression with EP_{DHW} and inhabitants/m^3.

Considering the data from the municipal technical map and Istat 2011 census data about population and buildings, the GIS variable that works better is the gross volume of residential buildings for the evaluation of spatial distribution of buildings, inhabitants and consumption. This variable was defined by census section and was used for the place-based spatial distribution of most the data.

A. Energy models for space heating

Once the variables with higher correlation were defined, a multiple linear regression analysis was carried out considering the surface-to-volume ratio S/V and the period of construction PC of residential buildings. In this model, the period of construction was simulated with coefficients proportional to the consumptions for space heating [8, 9]. The results of space heating consumptions per unit of gross volume are reported in Figure 5 and Table V.

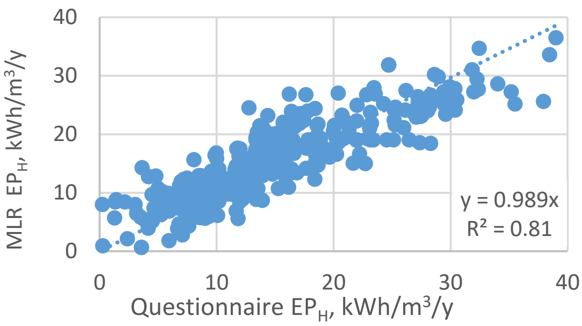


Fig. 5. Comparison between data calculated and indicated on the questionnaire of the annual energy performance index EP_H per unit of gross volume ($kWh/m^3/y$).

Table V. Multiple linear regression data and significance of the MLR on energy performance indicator for space heating per unit of gross volume ($kWh/m^3/y$).

Intercept	PC coeff.	S/V coeff.	F	Significance F
4.84	-12.21	36.15	690.88	**5.2367E-148**
p-value	**9.98689E-49**	**3.1723E-136**		

Since the significance F and p-values assume a value lower than 5%, it means that all the variables chosen for the regression are statistically significant.

Consequently, to better estimate the energy performance for space heating, the residential buildings were subdivided in different classes for period of construction and surface-to-volume ratio, like reported in the Table VI. This subdivision was done considering the different Italian laws on the energy savings (i.e., Law 373/76, Law 10/91, Decree 192/2005 and subsequent amendments and additions) and a significant number of dwellings in the various classes (with 10-72 buildings per class or about 30 buildings per class). In this work, the energy performance indexes and buildings characteristics were grouped in 4 classes of S/V, as reported in Table VI.

Table VI. Subdivision of buildings in classes for period of construction and surface-to-volume ratio.

Construction period	Surface-to-volume ratio S/V, m^2/m^3			
	Class I	Class II	Class III	Class IV
Before 1945	<0.25	0.25-0.45	>0.45	-
1946–1971	<0.23	0.23-0.45	>0.45	-
1972–1981	<0.23	0.23-0.45	0.45-0.52	>0.52
1982–1991	<0.25	0.25-0.52	>0.52	-
1991–2005	<0.25	0.25-0.40	>0.40	-
After 2005	<0.30	0.30-0.52	>0.52	-

To avoid the anomalous data affecting the model, a statistical analysis was previously performed to evaluate the normal distribution of energy performance data (verified with the Chi^2 and KS tests in Figure 6); thus, to exclude anomalous data out of range "average ± 2 times the standard deviation".

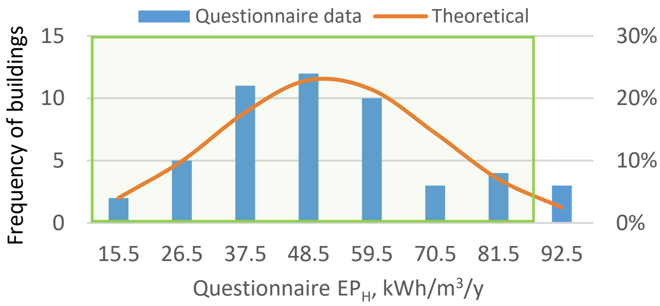


Fig.6. Normal distribution for space heating considering the class of buildings with 0.25<S/V<0.45 m^{-1} and 1972<PC<1981 (validated with Chi^2 and KS tests). Green lines represent the right range "average ±2 times the st. deviation".

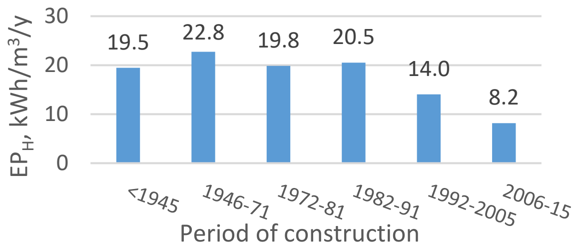


Fig.7. Average energy consumption data for space heating per period of construction of residential buildings in Rome.

Subsequently, for each class of buildings, average, median and standard deviation of energy performance index per gross volume were calculated (Figure 7). For the period "1946-71" higher values can be observed, as reported in literature [8, 9].

A further improvement of the model is reported in the Figure 8 with the LRs of the EP_H for different PCs at urban scale construction; with these LR_S the final result has a lower error. In Figure 8, it is possible to notice that the higher consumptions are expected for higher values of S/V and for the periods of construction "1946-71".

To complete the analysis the same evaluations are reported also for the retrofitted buildings. These results are presented in Figure 9; in this case, the PC "2006-15" is absent because these buildings do not need retrofit interventions.

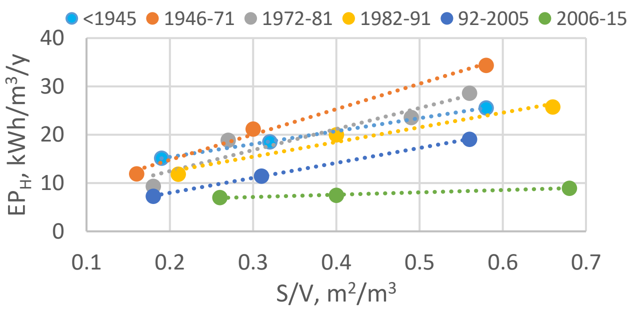


Fig.8. Linear regressions for EP_H index on space heating per unit of gross volume and period of construction (PC).

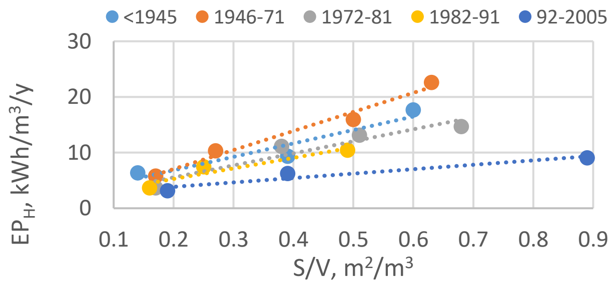


Fig.9. Linear regressions for EP_H index on space heating of retrofit buildings per unit of gross volume and PC.

B. Energy models for domesti hot water (DHW) production

The higher correlation variables for the EP_{DHW} are the following:

- Number of inhabitants per gross volume of residential building (i.e., inhabitants density): Inh/m^3 and
- Electrical consumptions EP_E kWh/m^3/y.

The dependence on electricity consumption can be explained by the fact that almost all the dwellings of the questionnaire database have an electric boiler and very few buildings have a photovoltaic system. For this reason, only the level of occupancy was considered for the linear regression. Table VI and Figure 10 represent the results of the DHW consumption model. The significance of this model is high with low significance F and low p-value.

After the regression analysis, the validity of the model was confirmed by some tests on residuals: the homogeneity of error variances or residuals and the independence of errors from the values of the independent variable. This analysis can be observed in Figure 11 with a constant variance of errors (residuals) independent by the value of inhabitants/m^3.

Table VI. Linear regression data and significance of the LR on energy performance indicator for DHW per unit of gross volume (kWh/m^3/y).

Intercept	Inh/m³ coeff.	F	Significance F/p-value
1.36	940.62	4368.72	**2.33E-287**

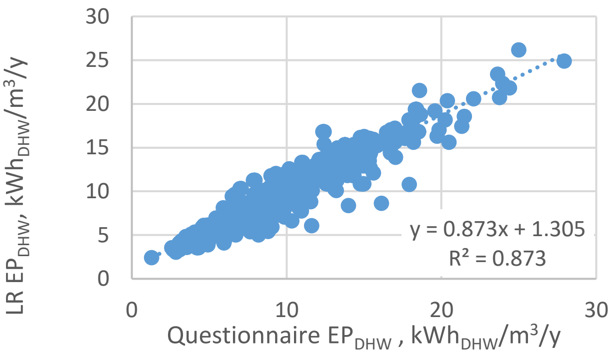


Fig. 10. Comparison between data calculated and indicated on the questionnaire of the energy performance index EP_{DHW} per unit of gross volume (kWh$_{DHW}$/m^3/y).

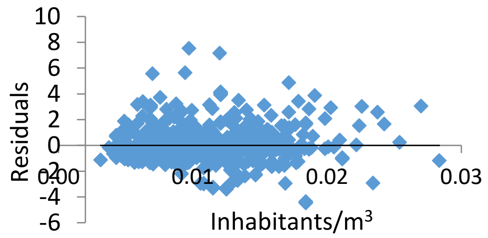


Fig. 11. Test on residuals of EP_{DHW} LR: the low error variances or residuals and the independence of errors from the values of the independent variable.

C. Energy models for electricity (E)

The model to estimate the energy performance for electricity was calculated with a multiple linear regression. In this case the variables that have a good correlation with energy performance index for electricity EP_E are:

- EP_C for space cooling [kWh/m^3/y]
- EP_{DHW} for domestic hot water [kWh/m^3/y]
- Inhabitants per gross volume of building: Inh/m^3.

Since, EP_{DHW} is influenced by the number of inhabitants/m^3, this last variable was not taken into account.

In Figure 12 the comparison between the EP_E data from questionnaire and the EP_E calculated with the multiple linear regression is presented. In the application of this model, it must be considered that only a percentage of dwellings and rooms within the dwellings were cooled; another model was calculated not considering this consumption for space cooling. In Figures 13 and Tables VII and VIII the validity of EP_E model, was confirmed by the tests on residuals with quite constant errors variance for the independent variables.

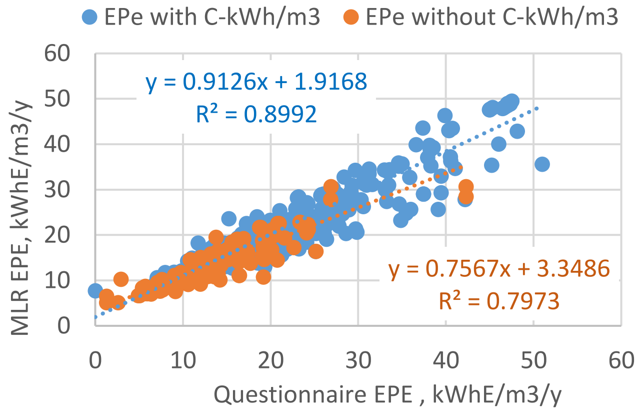


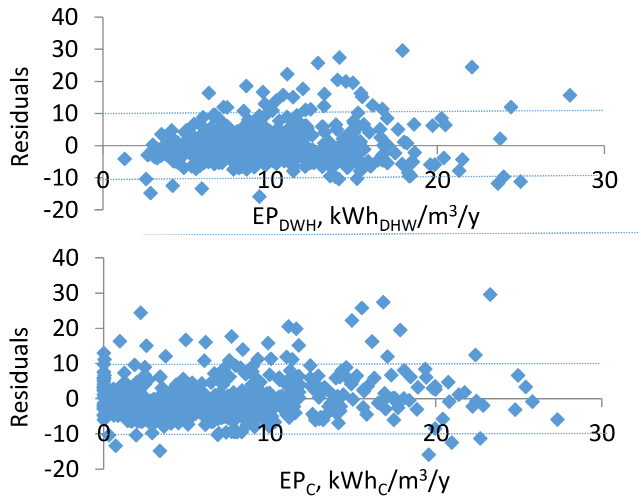
Fig. 12. Comparison between data calculated and indicated on the questionnaire of the annual energy performance index EP_E with and without cooling systems (kWh$_E$/m^3/y).

Table VII. Multiple linear regression data and significance of the MLR on energy performance index for Electricity per unit of gross volume with cooling systems (kWh$_E$/m^3/y).

Intercept	EPDHW kWh/m³ coeff.	EPC kWh/m³ coeff.	F	Significance F
2.605	1.175	0.509	3211.4	**1.445E-248**
p-value	**3.6452E-122**	**8.0452E-187**		

Table VIII. Linear regression data and significance of the LR on energy performance index for Electricity per unit of gross volume without cooling systems (kWh$_E$/m^3/y).

Intercept	EPDHW kWh/m³ coeff.	F	Significance F
3.578	1.127	593.16	**4.984E-56**
p-value	**4.984E-56**		



Figg. 13. Test on residuals of EP_E MLR: the homogeneity of error variances or residuals and the independence of errors from the values of the independent variables.

D. Energy models for space cooling (C)

To build a model for space cooling, a different approach was used because of the bad correlations among the variables and the EP_C. Probably this is due to the low presence of cooling systems and their use only for some rooms of the dwellings. For this reason, it was found a correlation among the heating and cooling degree days (HDD and CDD) to compare space heating and space cooling energy demand. The Italian Standard UNI 10349-3:2016 reports the degree days for the City of Rome; in Table VIII the 1643 HDD at 20°C and 143 CDD at 26°C are reported with a CDD/HDD ratio of about 9%.

Table VIII. HDD at 20°C and CDD at 26°C for Rome.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
372	309	266	73	-	-	-	-	-	46	224	353	**1643**
-	-	-	-	7	14	56	61	5	-	-	-	**143**

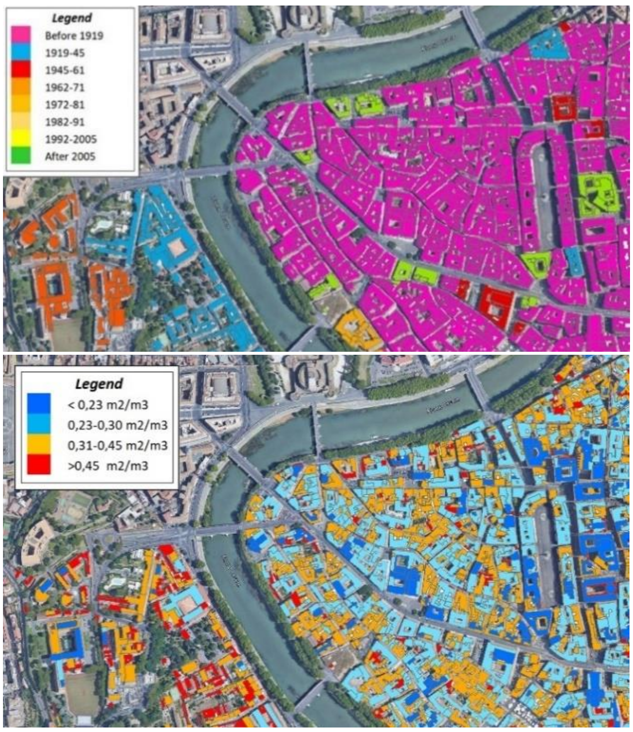
Subsequently, the energy consumption for space cooling Qc was estimated considering the typical seasonal efficiencies of heating and cooling systems (i.e., η_H=0.69 and EER=3.0). Finally, to obtain the energy performance index, the energy consumption was multiplied by the conversion factor to primary energy of 1.95 of electricity for non-renewable energy sources and then divided by the gross volume of buildings.

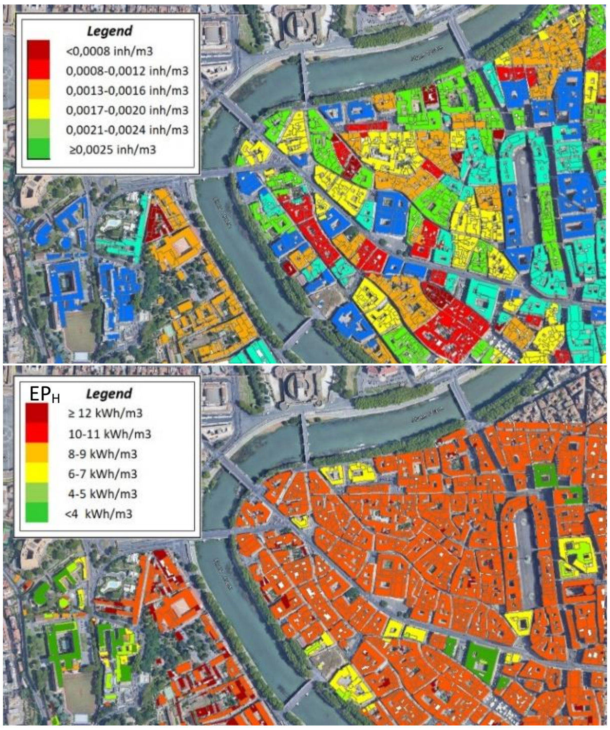
E. Place-based assessment of bottom-up models

The energy performance models were applied to each residential building in Rome using a GIS tool and the data from the Technical Map and the ISTAT 2011 Census. In Figures 14 it is possible to observe the result of the application of the place-based energy models with their spatial distribution considering the real characteristics of each single building.

F. Validation of energy consumption models

Finally, the results of the place-based energy model at municipal scale were compared with energy consumption data of SECAP for the year 2015 and SEAP for 2009. In particular, the space heating primary energy reported in SECAP for the year 2015 was 15,405 GWh and the result of this simulation is 15,023 GWh with a relative error of about 3%.





Figg. 14. The energy-related characteristics of buildings: inhabitants/m^3, period of construction and surface-to-volume ratio S/V used to evaluate the energy performance of buildings per unit of gross volume EP_H.

V. Conclusions

Each city and each territory have certain physical, technological, climatic and use features that characterize its energy consumption. The energy models here presented allows a place-base application of buildings' consumption model at urban scale considering their specific characteristics and using existing municipal technical maps and population census data.

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