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A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas

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ABSTRACT

This paper illustrates a GIS (Geographic Information System) based approach for assessing thermal and electric energy consumptions and usable solar energy potential of residential buildings in order to increase their independence from fossil fuels.

After integrating and simplifying previous researches, a methodology for estimating thermal energy needs, both for heating and hot water supply, and electric energy demand for assessing PV and solar thermal productivity is presented.

For each single building the decrease of non-renewable thermal and electricity needs has been estimated both considering possible installations of PV and solar thermal systems.

The described approach has been applied in two urban cells comparing the obtained results and testing its applicability in two different urban contest: a historical town centre and a new suburban district. The methodology has been proven to be suitable in both different contexts. On one hand, it has stated that new suburban districts are most suitable for solar potential exploitation, especially by means of PV. On the other hand, the obtained outcomes shows that a reduction of non-renewable thermal energy demand would have a greater impact on enhancing the buildings efficiency. The developed model should help local authorities for implementing energy management strategies in their urban areas.

1. Introduction

The assessment of residential buildings energy consumptions is one of the key aspect for the energy management of urban areas (Mattoni, Pagliaro, Gugliermetti, Bisegna, & Cellucci, 2015), considering the primary energy consumption (PEC) and the renewable energy fraction (Noussan & Nastasi, 2018). Among renewables, solar energy is commonly the first energy source used in buildings to improve their energy sustainability and to reduce their consumptions of fossil fuels.

In particular, residential buildings can use solar energy mainly with the installation of photovoltaic (PV) or solar thermal (ST) systems. In residential buildings PV arrays should be coupled with electric/gas heat pumps and Combined Heat and Power (CHP) for thermal management (Lo Basso, Nastasi, Salata, & Golasi, 2017). Furthermore, storage systems like hydrogen and CO_2 methanation process for solar energy storage (Castellani et al., 2017), as well as district heating and cooling (Dominković, Bačeković, Sveinbjörnsson, Pedersen, & Krajačić, 2017; Dominković, Bin Abdul Rashid et al., 2017) could be integrated for linking heat and electricity needs (Nastasi & Lo Basso, 2016, 2017).

Different methodologies should be used to evaluate the solar potential of urban areas (Ronzino et al., 2015); among them, Geographic Information Systems (GIS) have proved to be a useful tool for regional renewable energy potential estimation (Arnette & Zobel, 2011; Van Hoesen & Letendre, 2010) and an effective support for decision making in energy planning (Domínguez & Amador, 2007; Voivontas, Assimacopoulos, Mourelatos, & Corominas, 1998) at urban scale. As sustained by Diaz-Cuevas and Dominguez-Bravo (2015) GIS must play an important role in the development of a new model for the rational and integrated planning of renewable energies, facilitating the decision-making process from a territorial and landscaping perspective.

In particular ARGIS10 was used to perform a geostatistical analysis to assign the value of solar radiation resulting from each season (Rosas-Flores, Rosas-Flores, & Fernández Zayas, 2016).

Indeed, GIS helps to pinpoint and visualize buildings data for modelling energy consumption, supporting decision-making, at urban and regional scale (Torabi Moghadam, Toniolo, Mutani, & Lombardi, 2017).

Applying a GIS analysis at single building scale it is possible to

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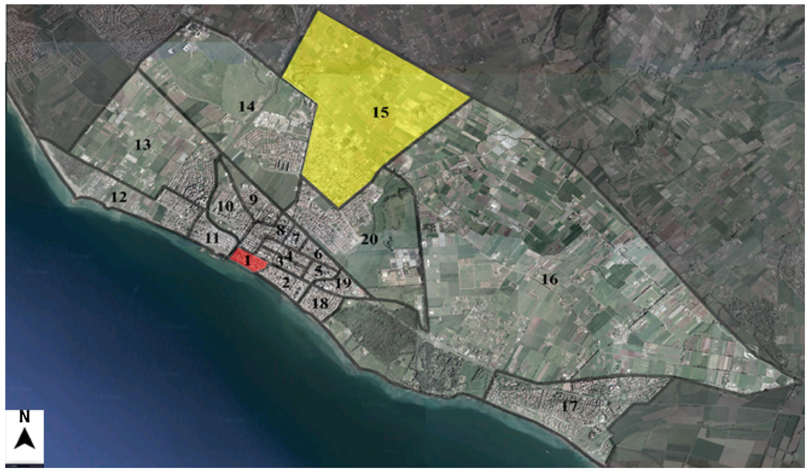

Fig. 1. Localisation of the two analysed urban cells of Ladispoli.

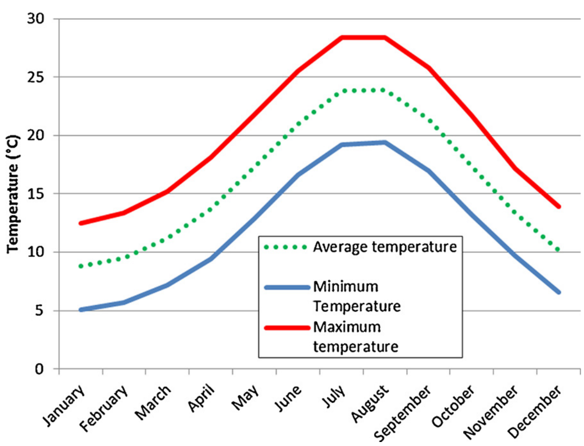

Fig. 2. Ladispoli climatic data (source: meteorological station of Torre Flavia).

assess the actual residential energy consumptions of an urban area.

Considering the RES penetration assessment in a city, the use of GIS methods to estimate available roof area for PV generation has become more and more established, opening up possibilities for city-scale analysis. Bergamasco and Asinari (2011) analyze vector maps to calculate building footprint area; however their final assessment for solar energy potential remains aggregated to the municipal scale. Brito, Gomes, Santos, and Tenedorio (2012) and Kodysh, Omitaomu, Bhaduri, and Neish (2013) used Light Detection and Ranging (LiDAR) data to estimate available roof area for PV installation. All these methods developed insolation maps clipped to residential areas. Also Kodysh et al. used LIDAR data and a GIS approach for estimating solar potential on multiple building rooftops for photovoltaic systems (Kodysh et al., 2013).

Considering previous researches on the assessment of thermal energy consumptions at urban scale, TABULA (Typology Approach for BUiLding stock energy Assessment) is a research project, funded by the Intelligent Energy Europe programme, whose main objective is the creation of a harmonized structure for European building typologies, considering the construction period and the size of each building (Florio & Teissier, 2015).

In this framework, the main aim of this research is to integrate, in a new approach, urban building energy consumptions assessment with the valuation of usable solar energy for the same buildings considering PV and ST systems, both at urban or sub urban scale.

In particular, the developed model is based on the integration of a GIS analysis with some findings of previous researches for the energy demand assessment at urban scale considering both thermal and electricity needs as well as with an estimation of the renewable energy that could be produced installing PV and ST systems.

Nowadays GIS software have been commonly used in urban areas for many purposes: assessing energy systems (Wu & Ning, 2018), estimating rooftop solar photovoltaic technical potential (Assouline, Mohajeri, & Scartezzini, 2018), analysing the environmental implications of buildings retrofits (García-Pérez, Sierra-Pérez, & Boschmonart-Rives, 2018), mapping buildings view factors (Gong et al., 2018), targeting and modelling urban energy retrofits (Gupta & Gregg, 2018), as well as estimating high spatial- and temporal-resolution anthropogenic heat discharge (Zheng & Weng, 2018).

The model has been applied in two areas of Ladispoli, a city of 26 Km^2 located in the Tirrenian coast of the centre of Italy whose population is about 41.100 inhabitants in 2017, considering both the town centre and new suburban districts.

2. Methods

The research method is based on the “urban cell” approach defined during a research bilateral project between Italy and Sweden called SoURCE “Sustainable Urban Cells” focused on the sustainable reshaping of urban areas considering a minimum core of the larger city’s model, conventionally called “urban cell” (Cumo, Astiaso Garcia, Calcagnini, Rosa, & Sferra, 2012). Each urban cell has between 1.000 and 3.000 inhabitants and is designed on the base of its main intended use, urban structure and building typology.

Table 1
Period and description of each identified building age class.

Age class acronym	Age class period	Age class description
ACI	< 1945	historic buildings and the beginning of the Twentieth Century buildings
ACII	1946–1972	building of the Postwar and the Reconstruction period
ACIII	1973–1990	buildings with energy performance requirements coherent with the first Italian regulations on energy efficiency
ACIV	1991–2005	buildings with energy performance requirements coherent with Law no. 10/1991
ACV	2006–2015	buildings with energy performance requirements coherent with the Legislative Decree no. 192/2005

Table 2
Thermal transmittance and construction period of identified roof / ceiling construction elements.

Roof/ceiling construction elements	U (W/m^2 K)	Construction period and insulation level
Ceiling with reinforced brick-concrete slab	0.30	after 2005 - high insulation
Ceiling with reinforced brick-concrete slab	0.69	1991–2005 - medium insulation
Pitched roof with wood structure and planking	0.95	1976–1990 - low insulation
Ceiling with reinforced brick-concrete slab	0.97	1976–1990 - low insulation
Pitched roof with brick-concrete slab	1.14	1976–1990 - low insulation
Ceiling with reinforced brick-concrete slab	1.65	1930–1975 - no insulation
Pitched roof with wood structure and planking	1.80	1921–1945 - no insulation
Flat roof with reinforced brick-concrete slab	1.85	1961–1975 - no insulation
Pitched roof with brick-concrete slab	2.20	1946–1960 - no insulation
Flat ceiling with hollow bricks and steel beams	2.48	1921–1945 - no insulation
Ceiling with reinforced concrete	2.66	1921–1945 - no insulation

Table 3
Thermal transmittance and construction period of identified floor construction elements.

Floor construction elements	U (W/m^2 K)	Construction period and insulation level
Concrete floor on soil	0.33	after 2005 - high insulation
Floor with reinforced brick-concrete slab	0.33	after 2005 - high insulation
Floor with reinforced brick-concrete slab	0.77	1991–2005 - medium insulation
Floor with reinforced brick-concrete slab	0.98	1976–1990 - low insulation
Floor with reinforced brick-concrete slab	1.30	1930-1975 - no insulation
Floor with hollow bricks and steel beams	1.81	1920–1945 - no insulation
Floor with reinforced concrete	1.95	1901–1930 - no insulation
Concrete floor on soil	2.00	Before 1975 - no insulation

Table 4
Thermal transmittance and construction period of identified walls construction elements.

Walls construction elements	U (W/m^2 K)	Construction period and insulation level
Masonry with lists of stones and bricks (40 cm)	1.61	Before 1930 - no insulation
Solid brick masonry (25 cm)	2.01	1900–1950 - no insulation
Solid brick masonry (38 cm)	1.48	1900–1950 - no insulation
Solid brick masonry (50 cm)	1.14	1900-1950 - no insulation
Hollow brick masonry (40 cm)	1.26	1950–1975 - no insulation
Hollow wall brick masonry (30 cm).	1.15	1930–1975 - no insulation
Hollow wall brick masonry (40 cm).	1.10	1930–1975 - no insulation
Hollow wall brick masonry (40 cm)	0.76	1976–1990 - low insulation
Hollow brick masonry (25 cm)	0.80	1976–1990 - low insulation
Hollow wall brick masonry (30 and more)	0.59	1991–2005 - medium insulation
Concrete masonry (also prefabricated, 30 cm)	0.79	1991–2005 - medium insulation
Honeycomb bricks masonry (high thermal resistance)	0.34	after 2005 - high insulation

Table 5
Thermal transmittance of identified windows construction elements.

Windows construction elements	U (W/m^2 K)
Low-e double glass, air or other gas filled, wood frame	2.20
Double glass, air filled, wood frame	2.80
Double glass, air filled, metal frame with thermal break	3.40
Double glass, air filled, metal frame without thermal break	3.70
Single glass, wood frame	4.90
Single glass, metal frame without thermal break	5.70

Table 6
Geometrical data and A/V ratio ranges of each identified building cluster. Data from Corrado et al. (2012).

Age class - building typology	Gross heated Volume [m^3]	Net floor area [m^2]	Gross floor area [m^2]	Number of floors	A/V ratio range
AC I - SFH	448–533	115–139		2	0.77–0.81
AC I - TH	428–500	112–123		2	0.49–0.51
AC I - MFH	2684–4388		647–1306	2	0.54–0.55
AC I - AB	3745–11029		1058–2880	4–5	0.35–0.47
AC II - SFH	583–679	156–162		2	0.73–0.75
AC II - TH	347–400	89–11		2	0.51–0.52
AC II - MFH	3074–3076		934–961	3–5	0.51–0.54
AC II - AB	5949–9438		1763–2869	4–5	0.46
AC III - SFH	725	199		2	0.72
AC III - TH	434	125		2	0.69
AC III - MFH	4136		1209	3	0.48
AC III - AB	12685		4125	6	0.37
AC IV - SFH	605	172		2	0.73
AC IV - TH	426	111		2	0.67
AC IV - MFH	3526		1120	3	0.54
AC IV - AB	9912		3271	6	0.43
AC V - SFH	607	174		2	0.72
AC V - TH	519	127		2	0.64
AC V - MFH	2959	829		3	0.54
AC V - AB	8199	2124		7	0.40

The method has been applied in two urban cells (UCs) of Ladispoli. In particular, 20 UCs have been identified in Ladispoli municipality area (Fig. 1); among theme, UC1 and UC15 have been selected as case studies.

UC1 includes the historical area of Ladispoli and it contains 98 buildings of different ages and typologies; it is large 6.5 ha and has about 1.400 inhabitants.

UC 15 includes 460 buildings mainly built in the last 20 years; it has 2280 inhabitants and is large 316 ha (70 ha of urban area and 246 ha of rural area).

As regard the climatic conditions, Ladispoli is located in “C” climatic zone with 1295 ° days, according with the national rules (Legislative Decree 311/2006). The degree-days are expressed as the annual sum, considering only the period when heating systems are allowed to work, of the daily differences between the conventional temperature attributed to the internal environment (20 °C for residential buildings) and the average daily outdoor temperature. In particular, Fig. 2 shows climatic data from the meteorological station of Ladispoli Municipality.

2.1. Energy demand assessment for heating/cooling and electricity

Among the different methods used in the previously mentioned researches, thermal energy consumptions have been assessed following the approach elaborated during the TABULA research project (Florio & Teissier, 2015), classifying the building stock on the base of their

Table 7
Roofs/ceilings, Floors, walls and windows construction elements of each identified building cluster.

Age class - building typology	Roofs/Ceilings	Floors	Walls	Windows
AC I - SFH	Pitched roof with wood structure and planking	Concrete floor on soil	Masonry with lists of stones and bricks (40 cm)	Single glass, metal frame without thermal break
AC I - TH	Flat ceiling with hollow bricks and steel beams		Solid brick masonry (25 cm)	Single glass, wood frame
AC I - MFH	Ceiling with reinforced concrete	Floor with reinforced concrete	Solid brick masonry (38 cm)	
AC I - AB	Flat ceiling with hollow bricks and steel beams	Floor with hollow bricks and steel beams	Solid brick masonry (50 cm)	Single glass, metal frame without thermal break
AC II - SFH	Pitched roof with brick-concrete slab	Concrete floor on soil	Solid brick masonry (38 cm)	Single glass, wood frame
AC II - TH	Flat roof with reinforced brick-concrete slab		Hollow brick masonry (40 cm)	
AC II - MFH	Ceiling with reinforced brick-concrete slab	Floor with reinforced brick-concrete slab	Hollow wall brick masonry (30 cm).	
AC II - AB			Hollow wall brick masonry (40 cm).	
AC III - SFH	Pitched roof with brick-concrete slab, slow insulation	Floor with reinforced brick-concrete slab, low insulation	Hollow wall brick masonry (40 cm), low insulation	Double glass, air filled, wood frame
AC III - TH	Pitched roof with wood structure and planking, low insulation			
AC III - MFH	Ceiling with reinforced brick-concrete slab, low insulation		Hollow brick masonry (25 cm), low insulation	Double glass, air filled, metal frame without thermal break
AC III - AB			Hollow wall brick masonry (40 cm), low insulation	
AC IV - SFH	Ceiling with reinforced brick-concrete slab, medium insulation	Floor with reinforced brick-concrete slab, medium insulation	Hollow brick masonry (40 cm), medium insulation	Double glass, air filled, wood frame
AC IV - TH				
AC IV - MFH			Hollow wall brick masonry (30 and more), medium insulation.	Low-e double glass, air or other gas filled, wood frame
AC IV - AB			Concrete masonry (also prefabricated, 30 cm), medium insulation	Double glass, air filled, metal frame with thermal break
AC V - SFH	Ceiling with reinforced brick-concrete slab, high insulation	Concrete floor on soil, high insulation	Honeycomb bricks masonry (high thermal resistance), high insulation	Low-e double glass, air or other gas filled, wood frame
AC V - TH				
AC V - MFH		Floor with reinforced brick-concrete slab, high insulation		
AC V - AB				

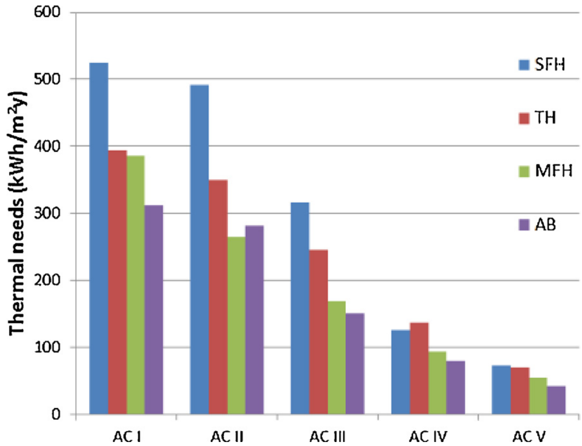

Fig. 3. Average thermal needs for each age class (AC) and building typology.

Table 8
Average electricity demand for each consumer typology according with Italian ISTAT database.

Consumer typology	Average electric consumptions (kWh/m^{2}y)
Residential	45
Hotel	90
Restaurant	30
Coffee shop	20
Grocery	35
Other shops	10

typologies and construction periods.

Each construction age class is related to an historical period characterized by specific geometrical and construction typologies with defined energy parameters.

Since no regulations on energy savings in buildings were in force in Italy before 1973, insulation materials were not used up to that year; hence, the thermal transmittance of any building envelope was only caused by its thickness and the materials of its components. At a later time, in 1991 and in 2005, there was a gradual increase of building thermal insulation levels, due to the enactment of respectively Law no.10/1991 and the Legislative Decrees no. 192/2005 and no. 311/2006.

Using the TABULA approach for the Ladispoli building stock, five construction age classes have been identified, as reported in Table 1.

For each considered period, the most common construction elements of the building envelopes have been identified and linked with respectively thermo-physical parameter values (Tables 2–5) reported in the construction elements analysis for the Italian building stock carried out within TABULA project (Corrado, Ballarini, & Corgnati, 2012). This project attributed an insulation level (high, medium or low) to each construction element of the Italian building stock, coherently with the national regulations on energy efficiency of buildings reported in Table 1: insulation materials have not been used before up to 1976 since no energy saving regulations for buildings were in force; low insulation level (e.g. Uwall ≈ 0.8 W/m^2 K) has been considered for building elements between 1976 and 1990; medium insulation level (e.g. Uwall ≈ 0.6 W/m^2 K) for building elements between 1991 and 2005; high insulation level (e.g. Uwall ≈ 0.3 W/m^2 K) for building elements after 2005 due to the following regulations: Legislative Decrees no. 192/2005 and no. 311/2006.

Moreover, four size classes have been identified, each one characterized by a specific building geometry:

- SFH *single-family house*: one or two floors single flats, detached o semi-detached houses (Compactness ratio: 0.72–0.82);
- TH *terraced house*: one or two floors single flats, terraced (Compactness ratio: 0.49–0.69);
- MFH *multi-family house*: small buildings up to 5 floors and 20 apartments (Compactness ratio: 0.48–0.55);
- AB *apartment block*: buildings with a higher number of floors and apartments (Compactness ratio: 0.35–0.47).

In particular, each size class is related to a defined rage of compactness ratio or A/V ratio, (ratio between the outdoor-exposed surface and the heated volume of the building), easily calculated for each of the TABULA reference buildings and main geometrical data (Corrado et al., 2012) (Table 6).

Consequentially, crossing construction age classes with building size classes, 20 building clusters have been identified (Table 7).

Average thermal needs in kWh/m^{2}year have been therefore assessed for each building size and construction age cluster considering the above described Ladispoli climatic context and the energy consumptions reported in the warehouse of the National Institute of Statistics (ISTAT, 2016a) (Fig. 3).

Then, assessing by local surveys and GIS tools both the number of floors and the respective surfaces of each building, it was possible to estimate its thermal energy demand.

For the energy demand assessment, the ISTAT database (ISTAT, 2016b) has been used to evaluate the average consumptions for each consumer typologies (Table 8).

Moreover, according with average electric consumptions of cooling systems, 10 kW h/m^{2}y have been added for each consumer provided with a cooling system.

Together with GIS workflows (Fiduccia, Pagliaro, Gugliermetti, & Filesi, 2017), local surveys (Bruhns, Steadman, & Herring, 2000; Guo et al., 2015) have been carried out in order to gather for each considered building additional data like the total surface, the presence of cooling systems, its typology and its age class (Figs. 4 and 5).

The total energy saved coming from the replacement of single glass windows with double ones have been therefore assessed implementing field data gathered in the GIS database with the thermal transmittance values of windows construction elements reported in Table 5.

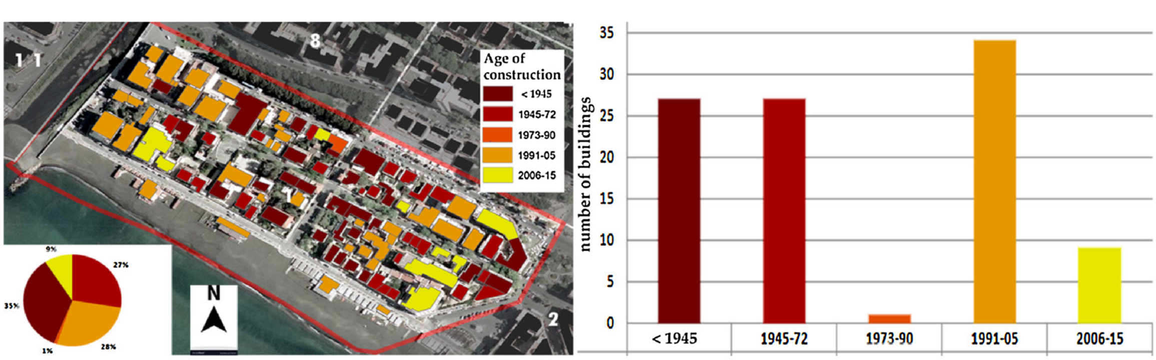

Fig. 4. Buildings age of construction of UC1.

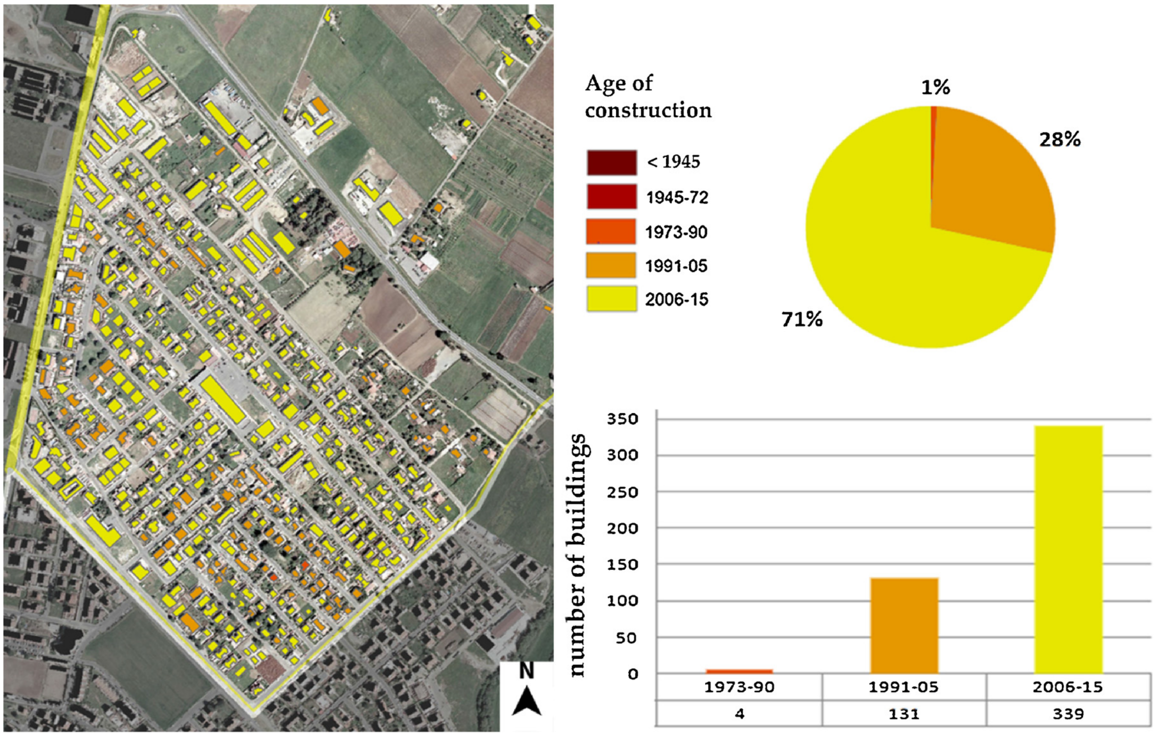

Fig. 5. Buildings age of construction of UC15.

Table 9
ST thermal characteristics.

η_0	a_1	a_2
0.783	3.88	0.0108

Where:
η_0 is the absorber optical efficiency.
$\mathbf{a}_1$ is the absorber linear dispersion coefficient $[\frac{W}{m^2K}]$.
$\mathbf{a}_2$ is the absorber quadratic dispersion coefficient $[\frac{W}{m^2K^2}]$.

Particularly in UC1, 14 of 98 (14%) of buildings have single glasses that could be replaced with double ones with a 10% average thermal energy saving for each building; on the other hand, 7 of 472 buildings (1.4%) in UC15 have single glasses whose replacement involves a thermal energy saving of 18% in the whole urban cell and an average thermal energy saving for each building of about 20%. The higher energy saving of UC15 is mainly caused by the more insulated building envelopes of this urban cell due to the more recent period of construction.

Implementing in the GIS database the ISTAT data about the average consumptions for each consumer typologies (ISTAT, 2016b), it is possible to assess that the 75% of the UC1 buildings and the 96% of UC15 ones can be classified as residential buildings.

2.2. Assessment of PV and solar thermal productivity

In order to assess the available surface on buildings' rooftops, a methodology split in different phase was carried out. The first step consisted in analysing the suitability of building rooftops for installation considering regulatory constraints, building barriers and minimum performance standards.

The criteria for classifying the suitability of the systems' installations are: historic and architectural constraints, roofs' slope, roof orientation and minimum available surfaces. In particular, in order to consider regulatory constraints, the Territorial Regional Landscaping Plan and the General Regulatory Plan of Ladispoli Municipality (available for consultation at Municipal offices) have been analysed and historic and architectural restrictions have been identified.

A GIS analysis has been carried out by means of ArcGIS Software for pinpointing the following three further limitations: roofs' slope, orientation and the surface with a minimum yearly solar radiation (Ouria & Sevinc, 2018). Particularly, buildings with pitched-roofs characterized by a slope not included in the 25–40° range have been discarded while flat roofs have been considered suitable for installation. Building orientation that has been assessed by means of the ArcGIS tool named "Calculate Metrics": only buildings oriented South (0°), precisely just the ones between South-East (−45°) and South-West (+45°) have been considered suitable for the installation. Finally, the solar potential assessment was carried out by means of the tools "Solar Area Radiation" and "Zonal statistics as table". Thus, the total building rooftops surfaces for a feasible installation have been identified. Surfaces with a yearly mean irradiation below 1200 kW h/m^2 (Moser, Vettorato, Vaccaro, Del Buono, & Sparber, 2014; Prina et al., 2016) have not been considered suitable. The last filter applied was the least suitable surface per building, establishing 10 m^2 and 2.5 m^2 as the minimum surfaces for installing respectively PV and ST systems.

Regarding PV for example, using PV GIS software the least surface was chosen assuming an overall PV nominal efficiency of 10% (Lo Basso, Rosa, Astiaso Garcia, & Cumo, 2018), thus 10 m^2 is the surface that can host a peak power of 1 kW_p that has been established as the least power to be considered for a reasonable investment.

The ST minimum size has been chosen to be 2.5 m^2 since it is the average minimum size available in the Italian market. ST efficiency has been evaluated at a monthly scale considering average value of outdoor temperature and irradiation (NASA Surface meteorology and Solar Energy - Location, n.d.). Solar collectors have been considered to produce water at a 60 °C temperature and the assessed ST parameters are the ones that can be typically found in the Italian market. Those values are evaluated by means of tests in accordance to EN 12975 referred to a glycole-water mix at 33.3% by volume, 75 l/s flow rate and Irradiation $G = 800\ \frac{W}{m^2}$, as shown in Table 9.

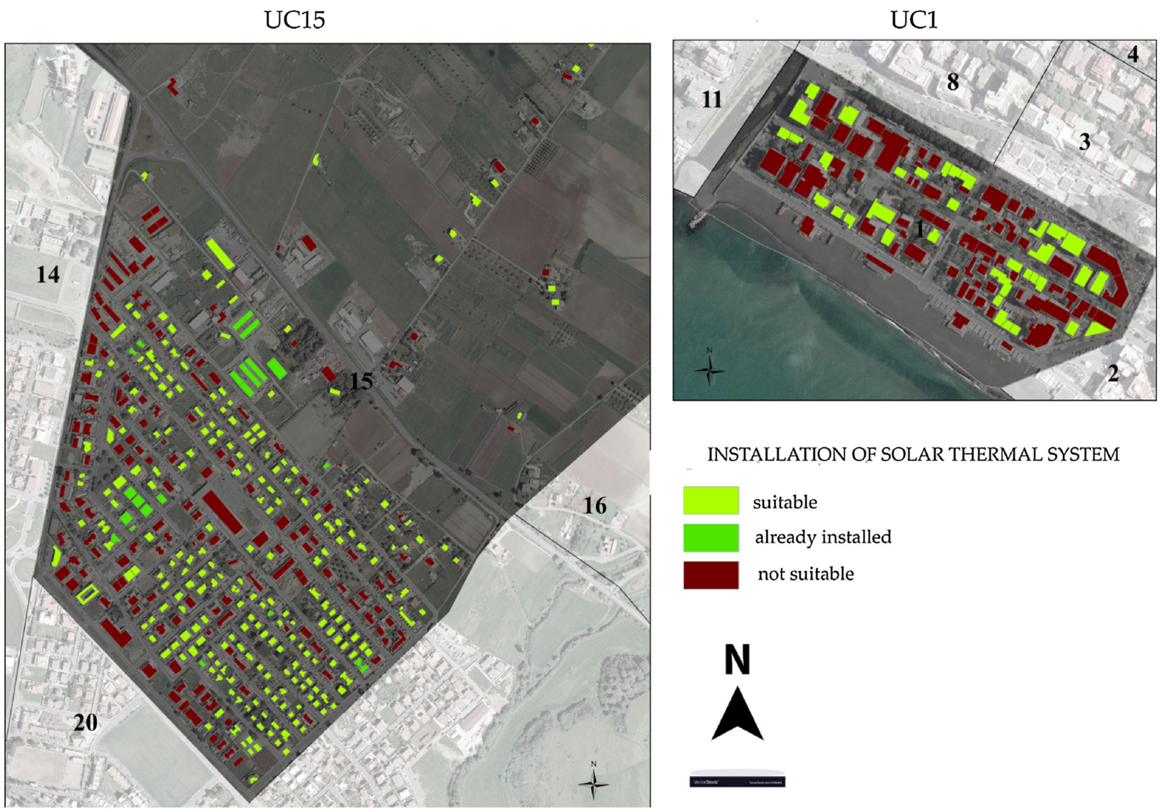

Fig. 6. Building suitability to an integrated installation of ST systems in UC1 and UC15.

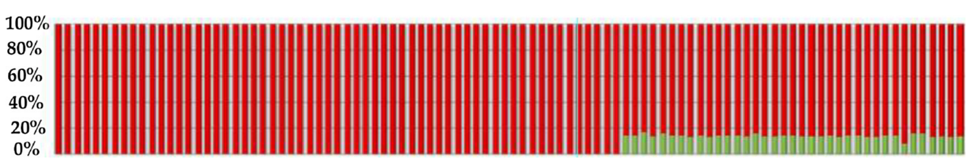

Fig. 7. The decrease of non-renewable thermal energy demand (% in red) due to ST system installation in suitable buildings of UC1 (in green % of thermal energy demand covered by ST).

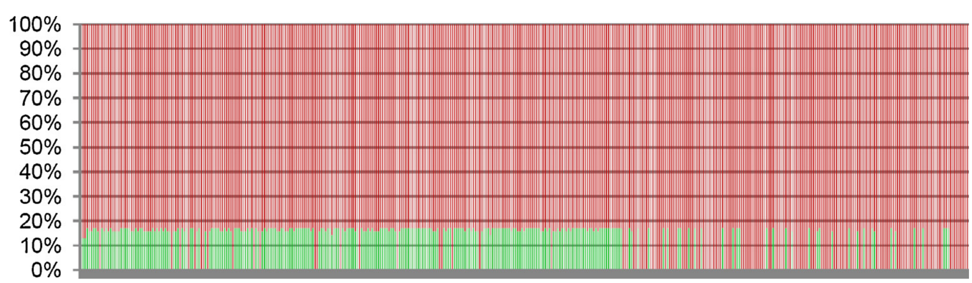

Fig. 8. The decrease of non-renewable thermal energy demand (% in red) due to ST system installation in suitable buildings of UC15 (in green % of thermal energy demand covered by ST).

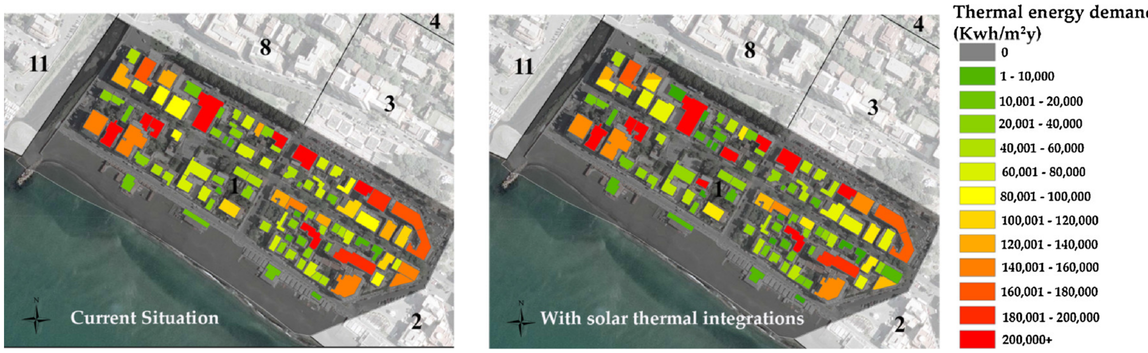

Fig. 9. UC1 thermal energy demand before and after ST integrations in suitable buildings.

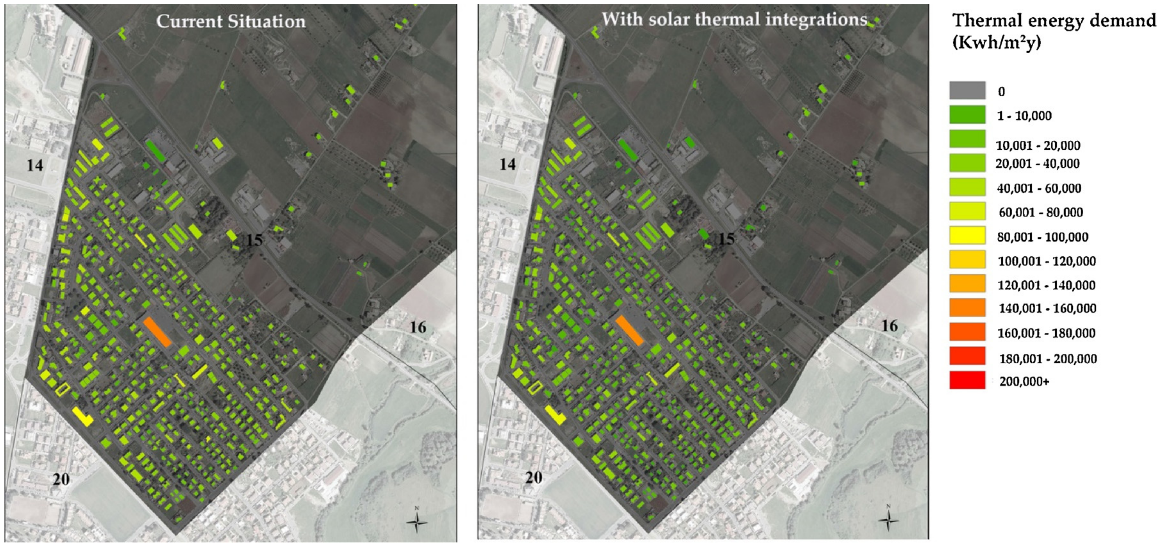

Fig. 10. UC15 thermal energy demand before and after ST integrations in suitable buildings.

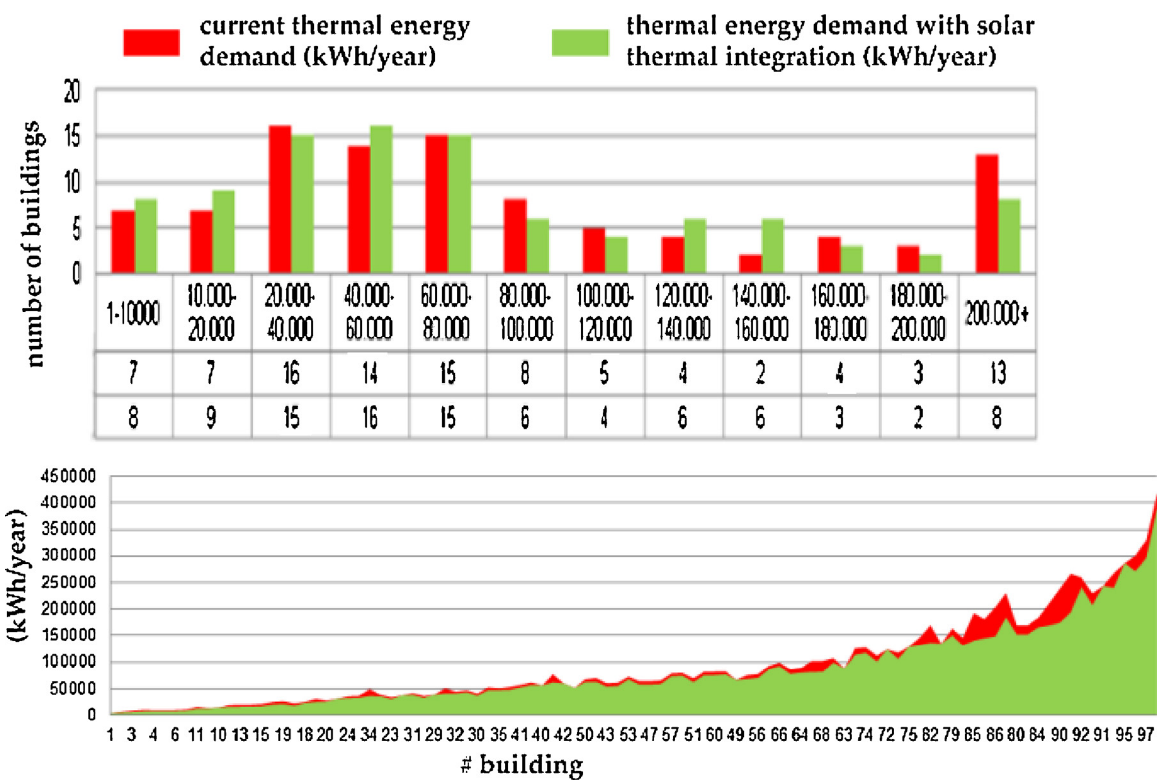

Fig. 11. Thermal energy consumption trends dividing UC1 buildings in energy consumption classes.

The yearly energy production has been therefore calculated starting from the suitable surfaces for each technology. Consequentially, the not renewable energy needs reduction potential was evaluated for each UC.

3. Results

3.1. Assessment to decrease the non-renewable energy demand for heating/cooling and electricity

Local surveys about roofs suitability for the installation of building integrated solar thermal systems pinpointed that ST systems could be installed only in the 27% of UC1 buildings, according with the suitability criteria described in paragraph 2.2. Among these criteria the main one for UC1 was the regulatory framework that limits system installations in the buildings of the historic town centre.

On the other hand, ST systems are currently installed in the 3% of UC15 building and this percentage could reach the 38% if these systems will be installed in the 35% of UC15 buildings that are suitable for an integrated installation (Fig. 6).

Figs. 7 and 8 show the decrease of thermal energy derived from non-renewable sources (in red) needed for each building in UC1 and UC15 respectively, due to ST system feasible installations. The percentage of thermal energy demand covered by ST systems is shown in green for each building of UC1 (Fig. 7) and UC15 (Fig. 8).

Figs. 9 and 10 show the thermal energy demand before and after the ST systems integration in suitable buildings of UC1 and UC15.

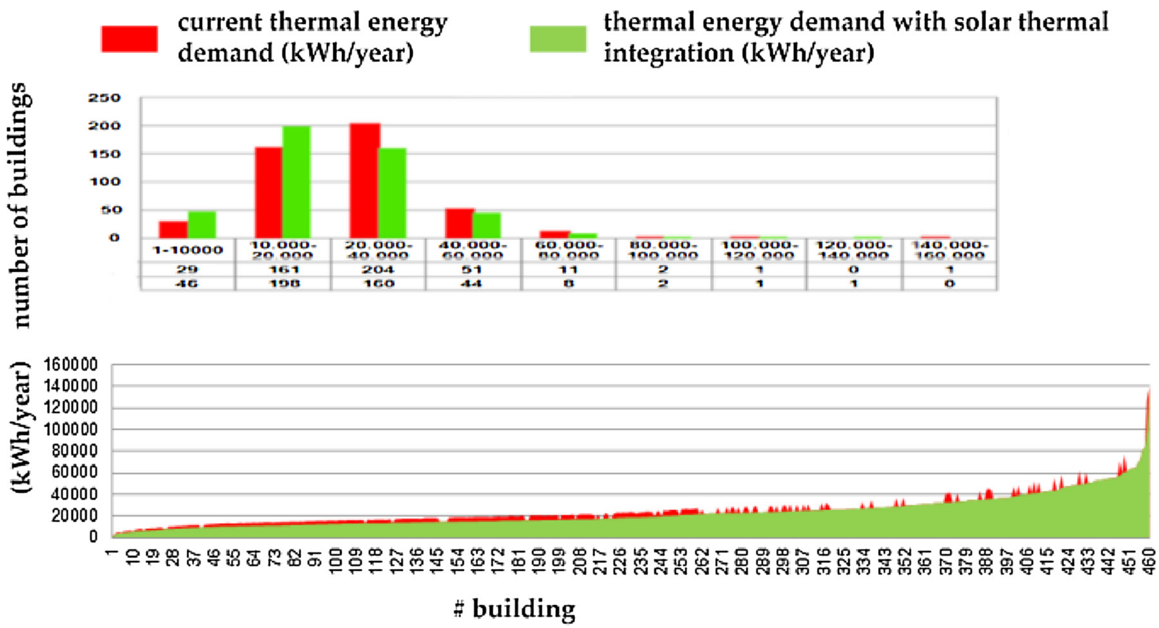

Fig. 12. Thermal energy consumption trends dividing UC15 buildings in energy consumption classes.

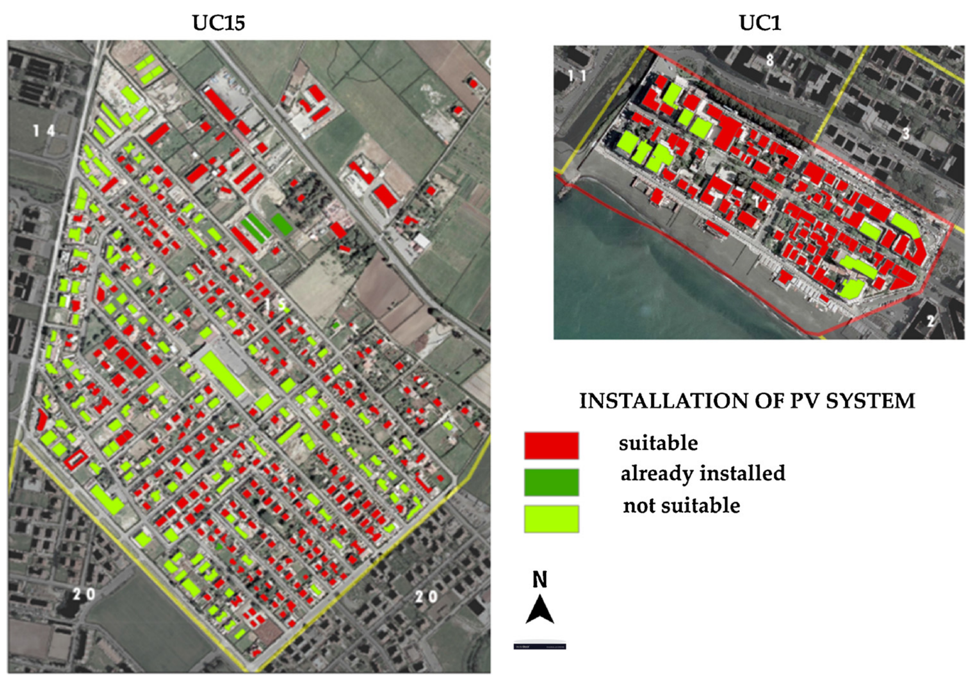

Fig. 13. Building suitability to an integrated installation of PV in UC1 and UC15.

Overall thermal energy saving in UC1 is about 27% due to the limited suitability of buildings roof to the installation of ST systems.

In particular, analyzing the thermal energy demand of each single building suitable to the installation of a ST system, thermal energy saving percentage in UC1 varies between 15% and 18%, while the energy saving of the whole urban cell is about 8%. On the other hand, energy saving in UC15 is 18% considering the whole UC energy consumptions, with values from 11 to 19% considering each single building suitable for installation.

Figs. 11 and 12 respectively show UC1 and UC15 energy consumption trends before and after ST installations. Energy saving percentages are lower in buildings with current low energy needs and much higher in buildings with high energy consumptions.

3.2. Assessment to decrease the non-renewable energy demand for electricity

The analysis developed identified that the 10% of the buildings have been considered suitable for installing a PV system according with the suitability criteria described in paragraph 2.2. In particular the disqualification of the 90% of the buildings mainly comes from the regulatory framework limits in the historic town centre as well as from constructive barriers that limits the available surface. Local surveys identified that PVs are not already installed in UC1 as shown in Fig. 14. Moreover, Fig. 13 shows that PV systems are installed in the 1% of UC15 buildings and another 33% of the edifices of this urban cell is suitable for further installations.

Figs. 14 and 15 show buildings non-renewable electricity demand

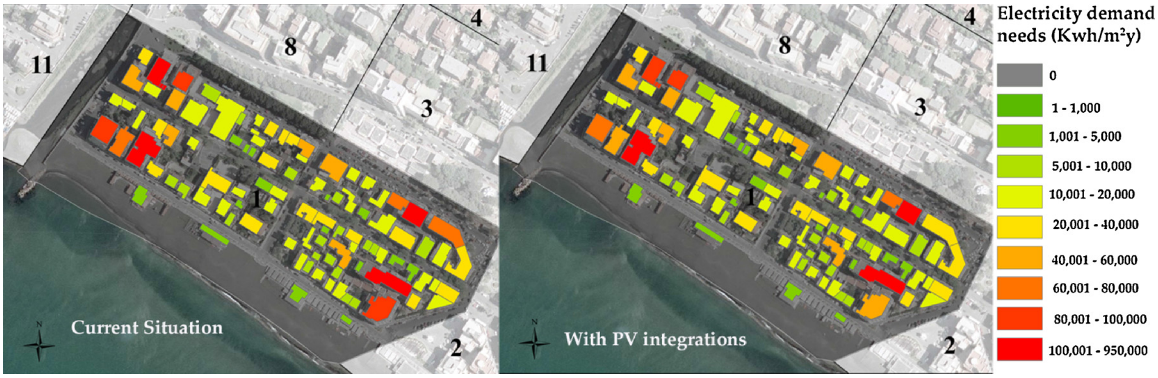

Fig. 14. UC1 non-renewable electricity demand before and after PV integrations in suitable buildings.

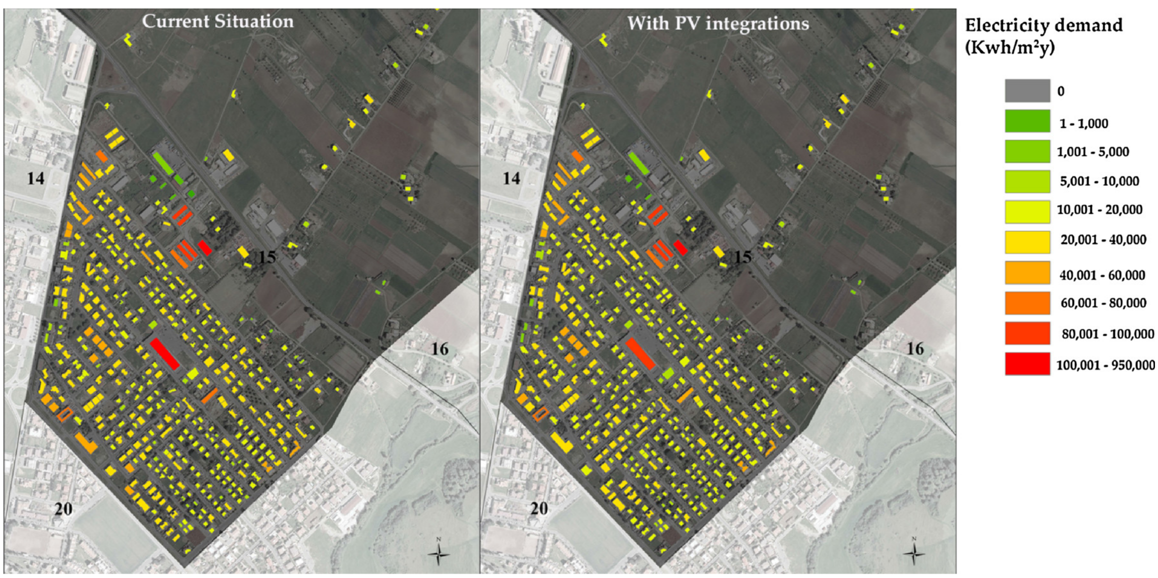

Fig. 15. UC15 non-renewable electricity demand before and after PV integrations in suitable buildings.

before and after PV systems integration in suitable buildings of UC1 and UC15.

Overall non-renewable electric energy savings in UC1 are about 7% due to the limited suitability of buildings roof to the installation of PV systems. On the other hand, energy saving in UC15 is 28% considering the whole UC energy consumption.

Figs. 16 and 17 respectively show UC1 and UC15 energy consumption trends before and after PV installations as well as the number of buildings for non-renewable energy consumption category. In UC1 energy saving percentages are lower in buildings with current low energy demands and much higher in the ones with high energy consumptions. On the other hand, in UC15 most of the buildings that mainly benefit from the PV introduction are the ones with average consumptions.

Table 10 summarizes the overall obtained results in order to facilitate the comparison between the analyzed UCs. Three relevant parameters have been considered: i) percentage of buildings that are suitable for the installation (in bracket the percentage of buildings where ST/PV systems are already installed); ii) non-renewable energy saved in the whole UC; iii) the difference between the percentage of the number of buildings with low-energy demand before and after the installation (ΔLEB_t, ΔLEB_e). The same parameters have been evaluated both for thermal and electricity demands. Buildings with low thermal energy demand are the ones with values lower than 60 MW h/y. On the other hand, buildings with electricity demands below 10 MW h/y have been considered as low-energy buildings.

As shown in Table 10, a recently built UC contains a higher number of buildings suitable to host both ST and PV installations. The most relevant factors that affect such value are i) the regulatory framework limits in the historic town centre and ii) the available surface per installation. The surface availability particularly affect the installation of PV systems. As a matter of fact, just the 10% of UC1 buildings are suitable for installations versus a percentage of 33% in UC15. Such values strongly affect the non-renewable energy that can be saved both for heating and electricity.

An interesting value to be analysed is the difference between the percentages of low-energy buildings before and after the installations. Such values represent the number of buildings that have moved to a low-energy consumption thanks to PV or ST installations. Regarding the ST installation in UC1, the percentage of low thermal energy demand buildings changes from 44.9% to 49% thus generating a variation of 4.1%. In UC15, the percentage of low thermal energy demand buildings change from a value of 96.74% to a value of 97.39% thus generating a variation equal to 0.65%. Thus, the number of buildings with a low thermal energy demand mainly changes in UC1 where buildings performance are worse even if the number of suitable buildings is lower. Regarding the PV systems installation, in UC1 no building moves into the class of low electricity demand. In UC15, the percentage of low electricity demand buildings change from a value of 14.62% to a value of 15.04% thus generating a variation equal to 0.42%. Thus, it can be stated that the installation of PV systems in UC15 would save a higher amount of non-renewable energy than the ST ones. In UC1, the two

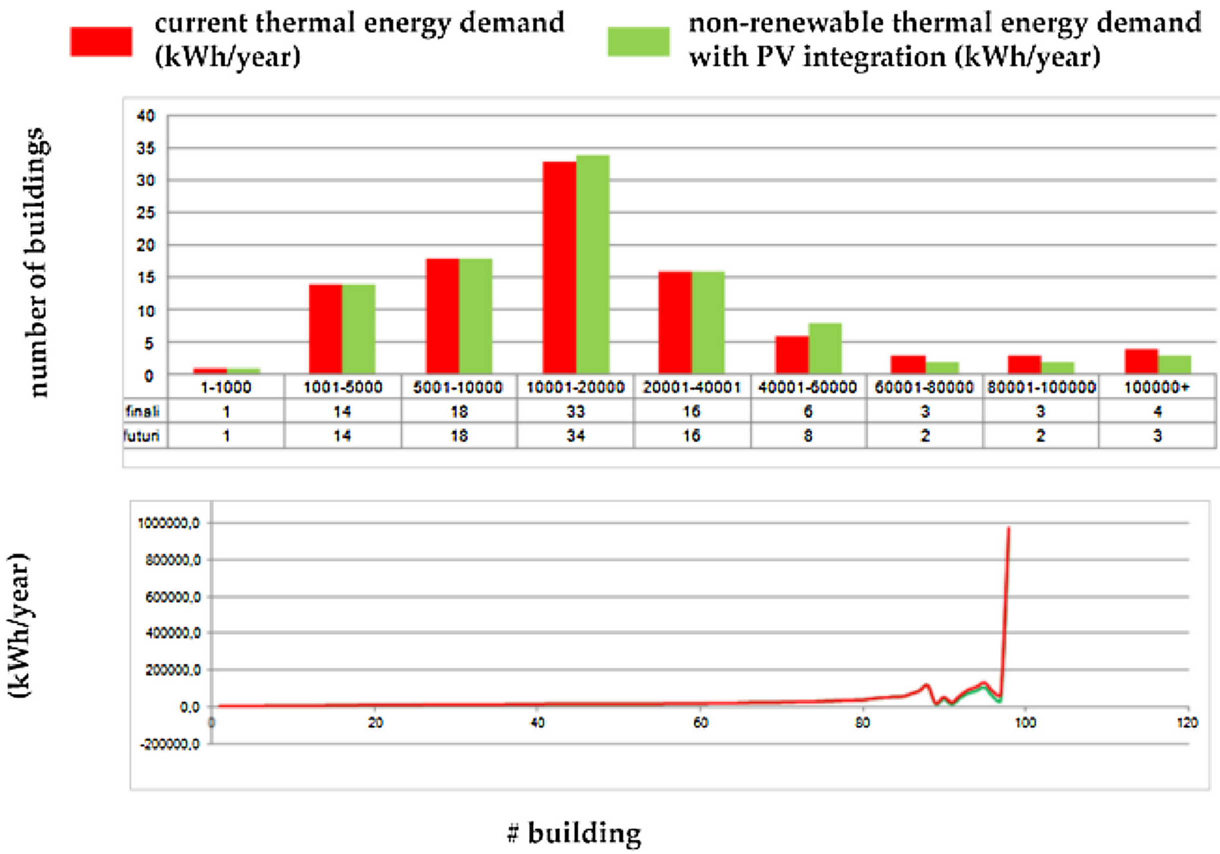

Fig. 16. Electric energy consumption trends dividing UC1 buildings in energy consumption classes.

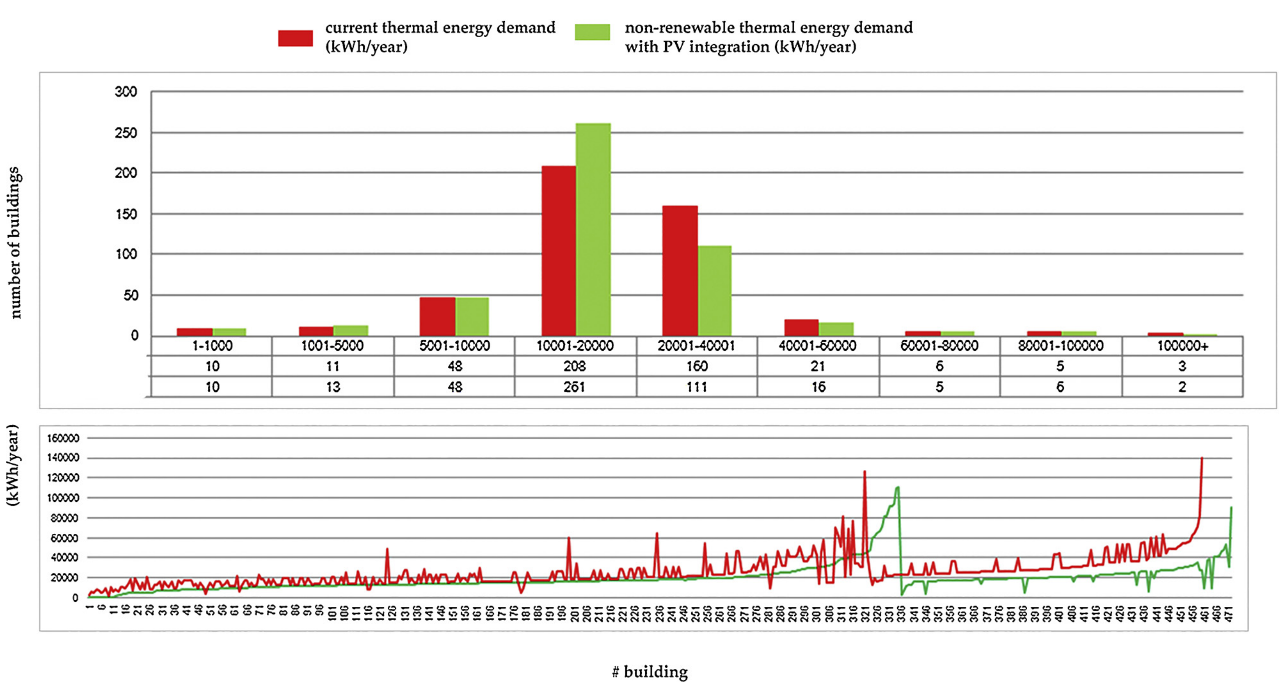

Fig. 17. Electric energy consumption trends dividing UC15 buildings in energy consumption classes.

technologies have almost the same impact but the installation of ST systems has a higher percentage impact on enhancing the thermal energy efficiency of buildings, respect the one caused by PV installation on the electricity sector. Particularly, PV installation reduce the non-renewable electricity demand exclusively in non-efficient buildings, but none of those can be considered efficient even after the installation.

4. Conclusions

This article presented a new approach to assess thermal and electric energy consumptions at the city scale, using GIS tools combined with a statistical treatment of urban criteria, and to estimate the decrease of non-renewable thermal energy and electricity demand with the feasible

Table 10
UCs comparison.

Parameter	UC1	UC15
% of buildings suitable for ST installation	27	35 (3)
Thermal non-renewable energy saved (%)	8	18
ΔLEB_t (Δ%)	4.1	0.65
% of buildings suitable for PV installation	10	33 (1)
Electrical non-renewable energy saved (%)	7	28
ΔLEB_e (Δ%)	0	0.42

installations of solar thermal or photovoltaic systems respectively.

The developed model should help in developing strategies of urban design and renewal as well as improving urban management and policy making since it can be adapted or reproduced for many other territories in Italy and in other similar countries.

To test the methodology, two case study applications have been considered on the urban area of Ladispoli. This applied study concluded that:

- the installation of PV systems would save a greater amount of non-renewable energy than ST ones in recently built suburban district. In an old urban district the two technologies have almost the same impact in terms of overall non-renewable energy savings;
- the installation of ST systems has a greater percentage impact on enhancing the thermal energy efficiency of buildings than the one caused by PV installations on the electricity sector in both UCs. Particularly, PV installations reduce the non-renewable electricity demand exclusively in non-efficient buildings and none of those buildings can be considered efficient even after the installation;
- historic buildings are most likely to host ST than PV. This is mostly due to available surface issues.

Finally, it can be concluded that the energy efficiency policies on new buildings are not enough to significantly decrease the energy consumptions of an urban cell, but they should include the restoration of the existing building stock that generates a substantial impact on the energy consumption reductions of a city.

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References

Arnette, A. N., & Zobel, C. W. (2011). Spatial analysis of renewable energy potential in the greater southern Appalachian mountains. *Renewable Energy, 36*(11), 2785–2798. http://dx.doi.org/10.1016/j.renene.2011.04.024.

Assouline, D., Mohajeri, N., & Scartezzini, J. (2018). Large-scale rooftop solar photovoltaic technical potential estimation using random forests. *Applied Energy, 217*, 189–211. http://dx.doi.org/10.1016/j.apenergy.2018.02.118.

Bergamasco, L., & Asinari, P. (2011). Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy). *Solar Energy, 85*(5), 1041–1055. http://dx.doi.org/10.1016/j.solener.2011.02.022.

Brito, M. C., Gomes, N., Santos, T., & Tenedorio, J. A. (2012). Photovoltaic potential in a Lisbon suburb using LiDAR data. *Solar Energy, 86*(1), 283–288. http://dx.doi.org/10.1016/j.solener.2011.09.031.

Bruhns, H., Steadman, P., & Herring, H. (2000). A database for modeling energy use in the non-domestic building stock of England and Wales. *Applied Energy, 66*(4), 277–297. http://dx.doi.org/10.1016/S0306-2619(00)00018-0.

Castellani, B., Gambelli, A., Morini, E., Nastasi, B., Presciutti, A., Filipponi, M., & Rossi, F. (2017). Experimental investigation on CO2 methanation process for solar energy storage compared to co2-based methanol synthesis. *Energies, 10*(7), 855. http://dx.doi.org/10.3390/en10070855.

Corrado, V., Ballarini, I., & Corgnati, S. P. (2012). *National scientific report on the TABULA activities in Italy*Retrieved fromhttp://episcope.eu/fileadmin/tabula/public/docs/scientific/IT_TABULA_ScientificReport_POLITO.pdf.

Cumo, F., Astiaso Garcia, D., Calcagnini, L., Rosa, F., & Sferra, A. S. (2012). Urban policies and sustainable energy management. *Sustainable Cities and Society, 4*, 29–34. http://dx.doi.org/10.1016/j.scs.2012.03.003.

Diaz-Cuevas, P., & Dominguez-Bravo, J. (2015). GIS, territory and landscape in renewable energy management in Spain. In M. Frolova, M. J. Prados, & A. Nadaï (Eds.). *Renewable energies and European landscapes*. Dordrecht: Springer.

Domínguez, J., & Amador, J. (2007). Geographical information systems applied in the field of renewable energy sources. *Compuers & Industrial Engineering, 52*(3), 322–326. http://dx.doi.org/10.1016/j.cie.2006.12.008.

Dominković, D. F., Bačeković, I., Sveinbjörnsson, D., Pedersen, A. S., & Krajačić, G. (2017). On the way towards smart energy supply in cities: The impact of interconnecting geographically distributed district heating grids on the energy system. *Energy, 137*, 941–960. http://dx.doi.org/10.1016/j.energy.2017.02.162.

Dominković, D. F., Bin Abdul Rashid, K. A., Romagnoli, A., Pedersen, A. S., Leong, K. C., Krajačić, G., ... Duić, N. (2017). Potential of district cooling in hot and humid climates. *Applied Energy, 208*, 49–61. http://dx.doi.org/10.1016/j.apenergy.2017.09.052.

Fiduccia, A., Pagliaro, F., Gugliermetti, L., & Filesi, F. (2017). *A GIS-Based model for the analysis of ecological connctivity. International Conference on Computational Science and Its Applications*600–6012.

Florio, P., & Teissier, O. (2015). Estimation of the energy performance certificate of a housing stock characterised via qualitative variables through a typology-based approach model: A fuel poverty evaluation tool. *Energy and Buildings, 89*, 39–48. http://dx.doi.org/10.1016/j.enbuild.2014.12.024.

García-Pérez, S., Sierra-Pérez, J., & Boschmonart-Rives, J. (2018). Environmental assessment at the urban level combining LCA-GIS methodologies: A case study of energy retrofits in the barcelona metropolitan area. *Building and Environment, 134*, 191–204. http://dx.doi.org/10.1016/j.buildenv.2018.01.041.

Gong, F.-, Zeng, Z.-, Zhang, F., Li, X., Ng, E., & Norford, L. K. (2018). Mapping sky, tree, and building view factors of street canyons in a high-density urban environment. *Building and Environment, 134*, 155–167. http://dx.doi.org/10.1016/j.buildenv.2018.02.042.

Guo, S., Yan, D., Peng, C., Cui, Y., Zhou, X., & Hu, S. (2015). Investigation and analyses of residential heating in the HSCW climate zone of china: Status quo and key features. *Building and Environment, 94*, 532–542. http://dx.doi.org/10.1016/j.buildenv.2015.10.004.

Gupta, R., & Gregg, M. (2018). Targeting and modelling urban energy retrofits using a city-scale energy mapping approach. *Journal of Cleaner Production, 174*, 401–412. http://dx.doi.org/10.1016/j.jclepro.2017.10.262.

ISTAT (2016a). *Statistiche ISTAT–Censimento della popolazione (population census)*. Retrieved fromhttp://dati-censimentopopolazione.istat.it/Index.aspx.

ISTAT (2016b). *Statistiche ISTAT–Energia, consumo per uso domestico (energy, residential energy need)*. Retrieved fromhttp://dati.istat.it/Index.aspx?DataSetCode=DCCV_CNSENRG.

Kodysh, J. B., Omitaomu, O. A., Bhaduri, B. L., & Neish, B. S. (2013). Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems. *Sustainable Cities and Society, 8*, 31–41. http://dx.doi.org/10.1016/j.scs.2013.01.002.

Lo Basso, G., Nastasi, B., Salata, F., & Golasi, I. (2017). Energy retrofitting of residential buildings—how to couple combined heat and power (CHP) and heat pump (HP) for thermal management and off-design operation. *Energy and Buildings, 151*, 293–305. http://dx.doi.org/10.1016/j.enbuild.2017.06.060.

Lo Basso, G., Rosa, F., Astiaso Garcia, D., & Cumo, F. (2018). Hybrid systems adoption for lowering historic buildings PFEC (primary fossil energy consumption)–a comparative energy analysis. *Renewable Energy, 117*, 414–433. http://dx.doi.org/10.1016/j.renene.2017.10.099.

Mattoni, B., Pagliaro, F., Gugliermetti, L., Bisegna, F., & Cellucci, L. (2015). A territorial based strategy for the distribution of sensor networks in smart cities. *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC),* 653–658. http://dx.doi.org/10.1109/EEEIC.2015.7165242.

Moser, D., Vettorato, D., Vaccaro, R., Del Buono, M., & Sparber, W. (2014). The PV potential of south Tyrol: An intelligent use of space. *Energy Procedia, 57*, 1392–1400. http://dx.doi.org/10.1016/j.egypro.2014.10.130.

NASA Surface meteorology and Solar Energy. Retrieved from https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi.

Nastasi, B., & Lo Basso, G. (2016). Hydrogen to link heat and electricity in the transition towards future smart energy systems. *Energy, 110*, 5–22. http://dx.doi.org/10.1016/j.energy.2016.03.097.

Nastasi, B., & Lo Basso, G. (2017). Power-to-gas integration in the transition towards future urban energy systems. *International Journal of Hydrogen Energy, 42*(38), 23933–23951. http://dx.doi.org/10.1016/j.ijhydene.2017.07.149.

Noussan, M., & Nastasi, B. (2018). Data analysis of heating systems for buildings–a tool for energy planning, policies and systems simulation. *Energies, 11*(1), http://dx.doi.org/10.3390/en11010233.

Ouria, M., & Sevinc, H. (2018). Evaluation of the potential of solar energy utilization in Famagusta, Cyprus. *Sustainable Cities and Society, 37*, 189–202. http://dx.doi.org/10.1016/j.scs.2017.10.036.

Prina, M. G., Cozzini, M., Garegnani, G., Moser, D., Filippi Oberegger, U., Vaccaro, R., ... Sparber, W. (2016). Smart energy systems applied at urban level: The case of the municipality of Bressanone-Brixen. *International Journal of Sustainable Energy Planning and Management, 10*, 33–52. http://dx.doi.org/10.5278/IJSEPM.2016.10.4.

Ronzino, A., Osello, A., Patti, E., Bottaccioli, L., Danna, C., Lingua, A., ... Rasconà, G. (2015). The energy efficiency management at urban scale by means of integrated modelling. *Energy Procedia, 83*, 258–268. http://dx.doi.org/10.1016/j.egypro.2015.12.180.

Rosas-Flores, J. A., Rosas-Flores, D., & Fernández Zayas, J. L. (2016). Potential energy saving in urban and rural households of Mexico by use of solar water heaters, using geographical information system. *Renewable and Sustainable Energy Reviews, 53*, 243–252. http://dx.doi.org/10.1016/j.rser.2015.07.202.

Torabi Moghadam, S., Toniolo, J., Mutani, G., & Lombardi, P. (2017). A GIS-Statistical approach for assessing built environment energy use at urban scale. *Sustainable Cities and Society, 37*, 70–84. http://dx.doi.org/10.1016/j.scs.2017.10.002.

Van Hoesen, J., & Letendre, S. (2010). Evaluating potential renewable energy resources in Poultney, Vermont: A GIS-based approach to supporting rural community energy planning. *Renewable Energy, 35*(9), 2114–2122. http://dx.doi.org/10.1016/j.renene.2010.01.018.

Voivontas, D., Assimacopoulos, D., Mourelatos, A., & Corominas, J. (1998). Evaluation of renewable energy potential using a GIS decision support system. *Renewable Energy, 13*(3), 333–344. http://dx.doi.org/10.1016/S0960-1481(98)00006-8.

Wu, D., & Ning, S. (2018). Dynamic assessment of urban economy-environment-energy system using system dynamics model: A case study in Beijing. *Environmental Research, 164*, 70–84. http://dx.doi.org/10.1016/j.envres.2018.01.029.

Zheng, Y., & Weng, Q. (2018). High spatial- and temporal-resolution anthropogenic heat discharge estimation in Los Angeles county, California. *Journal of Environmental Management, 206*, 1274–1286. http://dx.doi.org/10.1016/j.jenvman.2017.07.047.