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A mixed methodology for defining a new spatial decision analysis towards low carbon cities

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Abstract

Cities play a leading role in economic development, security, sustainability, and climate change. The fact that the built environment energy consumption contributes to a huge amount of CO2 emissions has a significant impact on the public agenda. Consequently, the emergence of the low carbon city concept has enhanced the necessity for a both quantitative and qualitative evaluation of related energy strategies and policies. Support decision maker's tools can play an essential role for sustainable and effective land use governance, in particular, geo-referencing territorial data. This paper proposes a mixed approach method, integrating GIS Urban Energy Mapping, Stakeholders Analysis, and Multi-Criteria Decision Analysis whit the aim at defining urban energy saving scenarios in two sides which includes (a) the development of an energy consumption model of the building stock that is able to explore a number of possible futures scenarios based on GIS and give a representative picture of the actual energy consumption state and performance of urban systems (b) and the pre-selection of evaluation criteria based on environmental, economic, and social sustainability pillars. The expected result is the development of spatial decision support tool able to support urban planners, policy makers and built environment stakeholders in their efforts to plan, design and manage low carbon cities in their future strategic decisions by visualizing scenarios analysis. This paper is part of an ongoing Smart City research, a national cluster project, called Zero Energy Buildings in Smart Urban Districts (EEB).

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Keywords: "Multicriteria Analysis; Urban Energy Consumption; GIS; Sustianble Development Indicators

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1. Introduction

Cities play a prominent role in sustainable development for different causes, particularly, more than half of the word population settle in urban areas and expecting to have this number enhanced to 64-69%, or 5.6-7.1 billion by 2050 [1]. Moreover, urban sprawl and the way that cities are growing and operating have an immense detrimental impact on environment and its energy demand [2]. Interestingly, urban areas account for about two-thirds of the world's energy [3]. Almost always, the most considerable source of greenhouse gas (GHG) emissions comes from either energy use in transportation or building sector [1].

Although built environment sector is very challenging (i.e. multiple stakeholders with varied and conflicting preferences and interests), provides cities with low-cost and short-term opportunities for emissions reductions first and foremost through the energy performance improvement. The European Commission emphasizes that emissions in this area could be reduced by about 90% by 2050, which is greater than average share value over the long-term [4]. This fact highlights the significance of attaining the objective of the recast Directive on energy performance of buildings that new buildings built from 2021 onwards will have to be nearly zero-energy buildings [5].

The rise of climate change, since the late 80's, on the public agenda and more recently of the concept of "Low carbon city" have emphasized the need for quantitative assessment of mitigation and adaptation strategies [6,1]. Energy policy in EU is based on three balancing components: competitiveness, sustainable development, and security of supply fundamental strategies [7,8].

Needless to say, there is a wide consensus on the concept of sustainable development that refers to three intersecting pillars: environmental, social and economic [9]. Furthermore, the rising attention to the institutional dimension, highlights the importance of policies, regulation, governing structures, urban protocols and sustainability principles for supporting cities in the transition towards sustainable development [10,11,12].

One of the most effective sustainable assessment tools in the development of models process, and support any decision that might be made at the present or in the future is Multi-Criteria analysis (MCA) [13]. Sustainable criteria lead to simplify and aggregate technical and social science information available to policy makers and stakeholders, and consequently, they help to set targets [14]. In the building sector, particularly, energy consumption is influenced by the spatial organization. Accordingly, many different approaches and tools are developed for the spatial representation of energy demand, supply and CO2 emissions such as a Geographical Information Systems (GIS) [15, 16,17,18,19,20].

This paper proposes a GIS-based simulation model for testing how different scenarios and building typologies affect energy performance and carbon emissions. In particular, a "mixed approach" methodology is suggested, which aims at defining urban energy saving scenarios, including (a) the development of an energy consumption model of the building stock that is able to explore a number of possible futures scenarios based on GIS and give a representative picture of the actual energy consumption state and performance of urban systems (b) and the pre-selection of evaluation criteria based on environmental, economic, and social sustainability pillars. The expected result is the development of spatial decision support tool ale to support urban planners, policy makers and built environment stakeholders in their efforts to plan, design and manage low carbon cities in their future strategic decisions by visualizing scenarios analysis.

The rest of the paper is organized as follows: Section 2 discusses the mixed methodology and its steps, including the building stock characterization to create an urban energy consumption mapping (current state energy map), which is later be used as a basis of saving scenarios analysis. Section 3 presents the pre -selection of relevant criteria supporting transition towards low carbon cities with aim at integrating them to urban energy map. Finally, conclusions are summarized in Section 4.

2. A Mixed Methodology for the Evaluation of Energy Saving Urban Scenarios

This section aims to offer a methodological framework able to support decision making in developing and evaluating Energy Saving Urban Scenarios. In particular, an iterative mixed methodology is proposed which joints GIS Urban Energy Consumption Mapping (UECM), with Multi-Criteria Decision Analyses (MCDA) (operations research approach) and Stakeholders Mapping (SM) (social research approach) is discussed. The meaning of integrating different tools and methods in this framework is due to their complementarity in fulfilling different tasks in the urban energy planning process [21]. In this study, a case study is proposed for better illustrating the methodology used. The case study refers to the middle-size city of "Settimo Torinese", located in the North-West part of Italy, in the continental climatic zone (2684 HDD at 20°C), including 3,608 residential buildings with 47,831 inhabitants.

2.1 An urban energy consumption mapping

A GIS-based analysis is used to assess decision making in spatial problems with environmental implications. Territorial constraints could be implemented into the GIS approach using different layers (i.e. urban land use, protection areas, community sites, infrastructures, zone with the major requalification requirement and etc.). This fact leads to reduce the study area by excluding those areas for which it is not needed the applying intervention [22].

Having an urban energy consumption and related emissions map, for both existing and new buildings and their environment are significant support to guide policy makers' decisions regarding the future energy saving scenarios and alternatives based on sustainable criteria. In such contest, a GIS-based analysis is extremely strong and useful to store, manage, and visualize a broad quantity of territorial data for planning purposes. By representing multiple layers it is possible to represent the development of the city where each item is located in a proper system of co-ordinates in order to associate with a geometric entity [23].

In this study, a GIS-based simulation model is proposed for testing how different scenarios and building typologies affect energy performance and carbon emissions of "Settimo Torinese" [24]. The main methodological phases development regards the building stock data collection, geo-referencing territorial data, and the building stocks characterization in order to evaluate the city buildings' energy performance and scenarios definition and assessment for saving energy consumption are shown in Fig. 1.

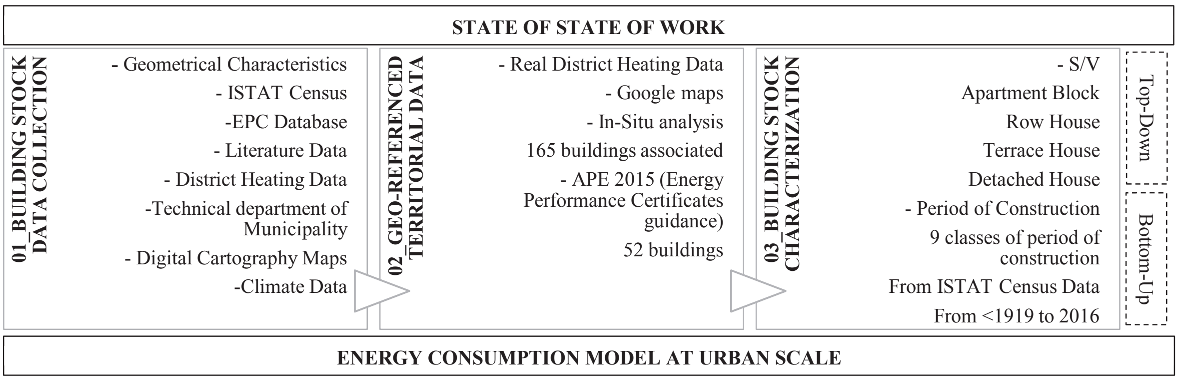

Fig. 1. Methodological Development for Urban Energy Consumption Mapping.

Regarding the building stock data collectiont phase, the buildings' digital cartography map, which is available at the technical departments of the municipality provides the information such as a number of floors, and buildings' type. The thermal energy consumption data for space heating have been derived by the energy-use registered by the district heating system (DH) for years 2011/2012_2012/2013_2013/2014_2014/2015. The annual space heating data have been normalized with respect to the standard Heating Degree-Days 2684 HDD (at 20°C).

The geometrical characteristics of building stock data have been defined from GIS map (ArcGIS 10.2), comparing the buildings' gross volume with the data provided by the DH distributor in order to be verified. A large building stock technical and performance characteristics information is available from the National Census database [25] .

The National Census 2011 database [25] provides information about population and buildings at census section scale (e.g. period of construction of building, demographic data and etc.). Regarding the new building construction data EPC database from 2009 to 2015 is used [26]. It is needed to implement such information by also taking into account the literature data [27].

However, the collected data is not suitable and organized to be straightly used for energy consumption modelling development. Indeed, they must to be analyzed and elaborated carefully in order to create a supporting dataset, taking into account both the geometrical data (area, perimeter and eaves height of the buildings) at the building scale and the census information level [25].

The second phase is dedicated to data geo-referencing the elaborated data collected, using google maps and in-situ analyses. Moreover, it was required to join the ISTAT census cartography with the buildings' map in order to have an effective tool which comprises all information related to the building stock [28]. Finally, it can characterize the building stock, taking into account the surface to volume ratio and the period of construction. In this regard, Table 1 illustrates the building stock characterization and the main characteristics of the archetype buildings in order to later implement the heating space consumption model to the whole city.

Table 1, Buildings characteristics from GIS data to real data (S/V is the surface to volume ratio)

	Typology of building	**Detached house**	**Terrace house**	**Row house**	**Tower**	**Total**
S/V(m^2/m^3)	S/V min	0.50	0.39	0.31	0.22	
	S/V max	1.60	0.49	0.39	0.31	
	S/V_{real} min	0.72	0.56	0.46	0.32	
	S/V_{real} max	2.30	0.71	0.56	0.45	
	Average factor for S/V_{real}	1.05	0.64	0.52	0.42	
Sum of Heated Volume (m^3)						
The buildings construction period classification as reported in the ISTAT National Census [25].	<1919	10,013	80,484	147,159	258,445	496,101
	1919_1945	28,629	60,761	98,088	308,650	496,128
	1946_1960	475,036	544,430	396,333	722,190	2,137,989
	1961_1970	739,743	811,001	353,899	636,046	2,540,690
	1971_1980	190,428	150,039	123,464	258,151	722,081
	1981_1990	287,148	103,006	126,800	206,691	723,645
	1991_2000	22,597	138,298	117,595	113,253	391,744
	2001_2005	-	49,239	93,043	65,575	207,857
	2005-2009	6,195	47,191	70,693	107,181	231,261
	2009_2015	320,984	118,898	62,692	104,343	606,917
	Total	2,080,774	2,103,347	1,589,767	2,780,524	8,554,412

Period of construction, the compactness and density of the buildings, as well as Heating Degree Days (HDD) can be considered as some effective indicators to model the energy consumption at urban scale [29,30,31]. The detailed methodological process and how to calculate whole city energy consumption for this specific case study can be found in [27,32]. With respect to the previous studies, in this paper the new buildings (built after 2009) are added in order to have a comprehensive urban energy map, including the high energy efficiency classes for whole city.

In Table 2 the simplified model used to represent the energy consumption for space heating at urban scale is represented, as a function of the construction period of building and the surface to volume ratio S/V.

Using consumption data of 160 existing buildings, linear correlations have been found to calculate space heating energy consumption as function of the period of construction and the surface to volume ratio for the case study. Then from the EPC database, 52 new buildings with consumption data were selected and a new correlation was deduced. Appling these simplified models to the whole city of Settimo Torinese the spatial distribution of energy consumptions can be represented. In Table 2 the space heating consumption are represented to evaluate the level of energy efficiency of buildings.

Table 2 , Yearly heating space consumption based on heating seasons 2011/2012, 2012/2013, 2013/2014 and 2014/2015 (climate corrected with 2684 HDD)

Heating Space Consumption ($kWh/m^2/y$) = Slope (kWh/m/y). S/V (m^2/m^3) + Constant ($kWh/m^2/y$)						
Number of Buildings	**Buildings' construction period**	**Torino (2462 at 20°C HDD)**		**Settimo Torinese (2684 HDD at 20°C)**		
		Slope (kWh/m/y)	Constant ($kWh/m^2/y$)	Slope (kWh/m/y)	Constant ($kWh/m^2/y$)	R^2
Literature [27]	<1919	130.82	140.75	114.89	123.89	0.99
Literature [27]	1919-1945	121.31	137.93	106.54	121.41	0.99

47	1946-1990	91.58	135.49	275.62	27.07	0.78
85	1961-1970	89.37	134.80	337.69	- 25.417	0.95
13	1971-1980	90.26	107.72	367.84	- 34.492	0.89
15	1981-1990	79.27	110.56	472	- 117.56	0.85
Literature [27]	1991-2005	69.95	97.61	61.432	85.912	0.99
Literature [27]	2005-2009	100.84	22.02	65.528	20.031	0.83
52	2009-2016	100.84	22.02	50.551	- 2.0092	0.84

Fig. 2(a) shows the final energy consumptions map for heating (kWh/m^{2}y) as well as an image representing the prevailing age of buildings for each census area and the buildings' typology and archetypes (see Fig. 3.(b)).

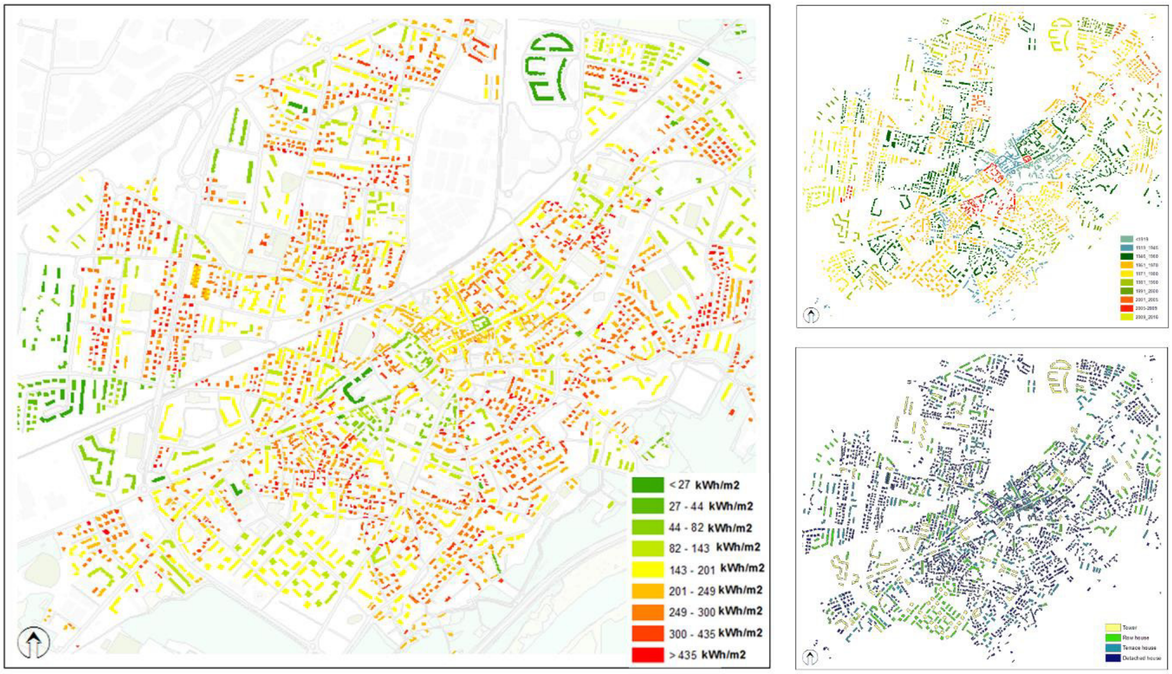

Fig. 2. (a) The final energy consumptions for heating (kWh/m2 y) (left); (b) An image representing the prevailing age for each census area (up right) and the Surface ratio to the volume (down right).

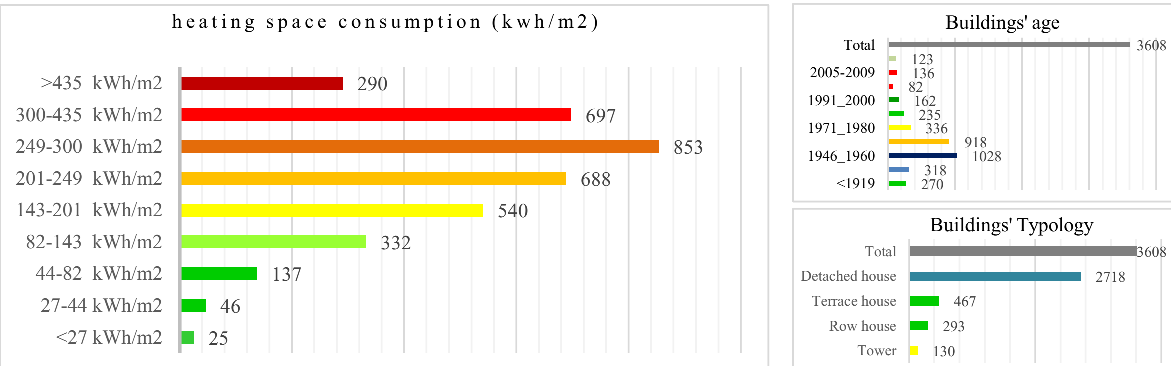

Figure 3, (a) Number of buildings belonging to different energy consumption range; (b) Number of buildings belonging to different archetype.

Higher energy consumption indicates old detached house and lower values indicate new compact buildings. As it is possible to note (see Fig. 3. (b)), in Settimo Torinese the 75 % of the buildings' stock are detached houses and more than 50% are built in 1946-1970 before the first Italian law on energy savings. It can be detected the average annual energy-use for space heating and hot water production equal to 256 kWh/m^2/y. As a result, (Fig. 3. (a)) More than about 50% of the residential buildings in the case study are in the low energy performance classes since they were built before the first energy saving law. Into this, it is significant to define different energy saving scenarios where is needed and shown in the map, integrating multi-criteria analysis in order to have an effective decision tool for urban planning.

2.2 Integrating Multi-Criteria Decision Analyses and Stakeholder Analyses with Urban Energy Maps

Notwithstanding the variety of MCDA approaches, all of them are characterized by common basic components (i.e. finite or infinite set of actions and alternatives, at least three assessment criteria, and, at least one decision-maker) [33]. According to the decision analysis methods in energy and environmental modeling field can be classified into three types: (1) Single Objective Decision Making (SODM): Decision Tree (DT); Influence Diagram (ID); (2) Decision support systems (DSS); (3) Multiple criteria decision making (MCDM): Multiple attribute decision making (MADM) (i.e. Multiple attribute utility theory (MAUT); Analytic hierarchy process (AHP); ELECTRE; PROMETHEE; OMADM.); Multiple objective decision making (MODM). [34] have pointed out that MAUT in combination with AHP and the outranking methods are very appropriate for most application in E&E areas. The Analytical Hierarchy Process (AHP) accounts for 20% of the identified studies, followed by ELimination Et Choix Traduisant REalité (ELECTRE) (15%), and Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE, 10%).

As aforementioned, sustainable development is a multidimensional issue characterized by high conflicting level concept, including ecological, socio-economic, technical and ethical indicators [35,14]. Therefore, the integration of GIS urban energy consumption mapping (see section 2.1), with Multi-Criteria Decision Analysis (MCDA) is useful in order to provide a decision support tool to select the best energy saving strategy to increase the sustainability of the district/city [36]. This tool can offer the cartographic and alphanumeric database, using the geo-referenced information which leads to investigate the suitability location. The proposed mixed methods approach development aims at supporting the transition towards low carbon cities is outlined in the flowchart (Fig. 3.), considering 3 macro-steps: intelligence (process model), design (planning model), choice (evaluation model) [37,38].

As shown in Fig. 4., the first method (see section 2.1 for modeling method) in the process refers to urban energy consumption mapping (current state), which will be used as the input and basis of the analysis.

The second method is the identification of the stakeholders who can affect or can be affected by the realization of objectives [39,40]. Stakeholders can be categorized into different actors such as political, bureaucratic, special/general interests and expert [39], considering different roles (e.g. experts, promoters, authorities, planners, energy suppliers, etc.). The final aim is to analyze of the relationships between the different stakeholders and the human point of view. In this regard, several number of stakeholders mapping techniques exist and the most widespread one is the power/interest matrix proposed by [41]. Indeed, in this initial part of process, the accurate and proper stakeholder grouping is needed to a better imagine of how relationships and communication between stakeholders can affect the project outcome and its final application [21]. Furthermore, stakeholder analysis is an ongoing and iterative procedure in whole decision process.

The third method proposed in Fig. 3 comprises the application of Multi-Criteria Analysis [37,38,42]. From methodological viewpoint, the process to build a model can be described as follows: 1. Process Model (intelligence phase) provides the decisional context analysis for structuring and identifying the decision problem to be evaluated. In this phase the relevant evaluation criteria should be established and identified (see section 3), assigning them later the proper weights of alternative options. 2. Planning Model (Design phase): Once the alternative options have been defined, it is necessary to structure the model and the evaluation matrix (criteria and alternatives matrix). This step consists the selection of the MCDA method. 3. Evaluation Model (Choice): after choosing the appropriate method, it can assess and evaluate the alternatives in order to rank/sort/choice/descript them [43]. Finally, a sensitivity analysis is suggested in order to examine the constancy of the obtained outcomes and the robustness of the model.

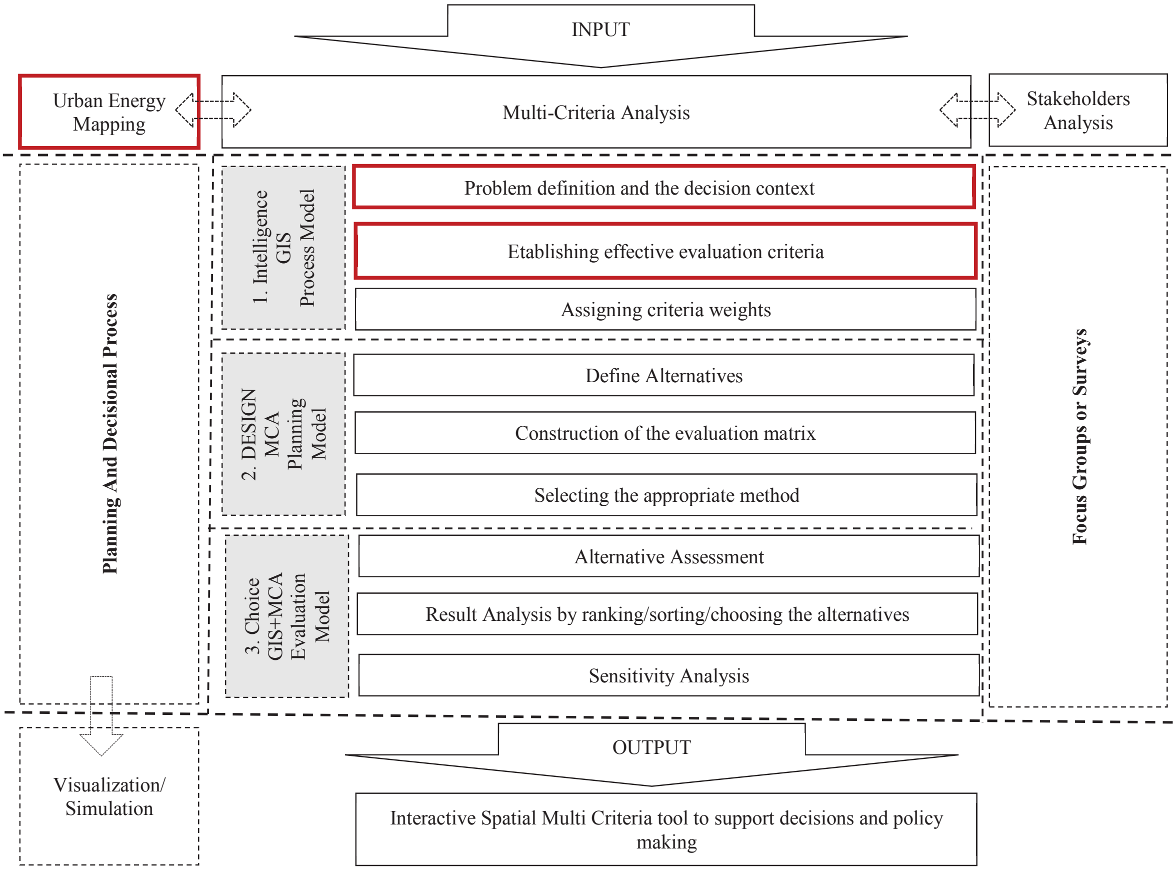

Fig.4. Mixed Methodology Approach Flowchart.

As a final output, an Interactive Spatial Multi Criteria visualize tool is expected to support decisions and policy making. The remainder of the paper will identify more in details the pre-selection of relevant criteria, which is assigned in step 1of MCDA process.

3. Identification of criteria as key performance indicators

Within this section, the set of evaluation criteria influencing the objective (urban energy saving scenarios) has been pre-selected and identified by considering the sustainable development in built environment [35] .

A first repository of indicators related to study is built up from existing methodologies and literature [44,45, 46, 47,48,49,50], and R&D projects [51,52,53,54,55]. Particularly, these projects have taken account to many International and European initiatives and harmonization and standardization activities (e.g. CEN TC 350, ISO TC59 SC17, Sustainable Building Alliance (SBA), UNEP SBCI and etc.) and National building evaluation tools (e.g. BREEAM, LEED, HQE and etc.) (See Table 3).

Table 3, Reviewed materials.

Issues targeted approach in terms of sustainable performances	Reviewed material	Number of considered evaluation criteria
composite performance index to measure and evaluate the industries	[44]	12
renewable energy technologies/sources	[45,49]	12;15
energy savings/energy efficiency/ energy retrofit	[46,48,51,47]	2; 9;13;9
future city energy	[55]	9
cities and forms	[50]	63
post-carbon cities	[52]	13
sustainability assessment of buildings	[54, 53]	11;52

The repository offers more than 100 numbers of indicators. The goal of the pre-selection process was to reduce them to be a practicable but still significant amount of criteria that are sufficient for conducting a concrete sustainability assessment of urban built environment energy saving projects [13]. The results of the first pre-selection phase are shown in Table 3. In the first step of the pre-selection process the number of indicators was reduced to 21 with the aim at selecting only the fundamental criteria for this study. The 21 identified sub-categories have been divided in 4 main sustainability sub-categories (i.e. Technological, Economic, Socio Economic, and Environmental). Table 4 presents the set of categories and sub-categories that has then been identified.

Table 4, Pre-Selected Categories and sub-categories..

Cat.	Sub-Categories	Description
Technological	Cost of saved primary energy [45]	economic assessment of the different actions
	Service life [47,48,54]	durability of the whole strategy in relation to the service life of each retrofit measure
	Reliability [49]	efficiency of the technology and the requalification result
Economic	Life cycle cost [53,54]	identify cost effectiveness of different design options and sensitivity of the cost resulting of the prices evolutions for products, services, energy and human operation
	Investment cost [48,55]	initial technologies capital cost
	Return on investment [44]	indicator of business risk and percentile savings
	Public funding support [48]	tax detraction
Socio -Economic	Socio-economic factors of inhabitants [46]	citizens' disposability and sensitivity to buildings' refurbishment
	Architectural impact [47]	aesthetic quality of a town or a city is
	Market maturity [45,54]	estimates the market availability and the status in the penetration process of a given technology, materials and services associated with the considered action
	Family investment [47]	average cost per household
	Labor impact [50,49,44,55]	potentiality of creating job and better regularity of the employee
Urban Form	Buildings and Land Use [52]	urban building density variation rate
	Volumetric compactness [50]	building compactness ratio
	Urban morphology [46]	distribution of building heights, the relative distance among buildings and the buildings' coverage ratio
Environmental	greenhouse pollutant emissions [56,55]	measure the equivalent emission of co2, which is avoided by the examined action
	Land requirement [49, 45]	land that is needed to install power
	Renewable energy[47,54]	energy produced by renewable sources

3. Final discussion and conclusive remarks

This paper has discussed a mixed methodologies iterative approach that integrates GIS urban energy mapping, stakeholders mapping, and multi-criteria decision analysis for the definition and evaluation of urban energy saving scenarios by means of the built environment.

With reference to the first method proposed in the process, the energy-use for each residential building of the whole city of case study was estimated, using geographic information systems (GIS) that can significantly help in the planning of actions. The methodology underlines the key role of the surface ratio to volume (m^2/m^3) and the building' age in order to categorize the building stock and estimate the whole city energy consumption. The analysis should be very precise in this step because the energy reduction with medium-long term objectives and several variables have to be considered and implemented. More than 50% of the residential buildings in the case study are in the low energy performance classes since they were built before the first energy saving law. As one can see from Figure 2, the average annual energy-use for space heating and hot water production equal to 256 (kWh/m2/y).

The high built environment energy consumption contributes a huge amount of CO2 emissions. This fact concerns on the public agenda, and consequently, the necessity for a both quantitative and qualitative evaluation criteria of related energy strategies and scenarios has emphasized.

Indeed, integrating the multi-criteria decision analysis with GIS allows choosing between different medium-long term energy saving alternatives. Through the stakeholders analysis, the participation of the experts in several focus groups acting at different level leads to better understand the problem, enhance the transparency of the decision process, and allow relevant concerns to be taken into account since the very beginning of the process.

In conclusion, the study highlighted the relevant evaluation criteria in terms of sustainable performances. From the point of view of the future work, it would be remarkable to identify and select the definitive indicators/alternatives (performance matrix) and expand the results of the application into the interactive visualization tool which plays a fundamental role in urban planning processes towards post-carbon city.

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