Bridging Urban Morphology and Energy Performance Analysis. A Case Study within the Alpine Region.

1. Introduction

The size, scale, shape and internal structure of cities are important factors determining their sustainability levels (Batty, 2008). This observation is even more important if we consider the energy issue (Droege 2007, 2008; Owens, 1986). The International Energy Agency (IEA, 2008) clearly recognizes the importance of energy use in cities and devotes an entire chapter to energy use in cities in its World Energy Outlook 2008 (IEA 2008). Some of the key points if this report are:

- Cities consume about two-thirds of the worlds energy and account for more than 70 percent of global greenhouse gases (GHG) emissions, but represent only half the population;
- By 2030, cities are expected to account for some 73 percent of global energy demand, while accounting for 80 percent of CO2 emissions especially from mobility and building (heating and cooling) sectors;

In this context urban planning and urban design have a wide responsibility in the optimization of cities energy systems. They can clearly contribute to solve a problem facing international sustainability targets.

According to EU (2005) and Vettorato (2011) the strategy to achieve "sustainable energy performances of urban settlements" can be subdivided in 3 complementary pillars (Figure 1):

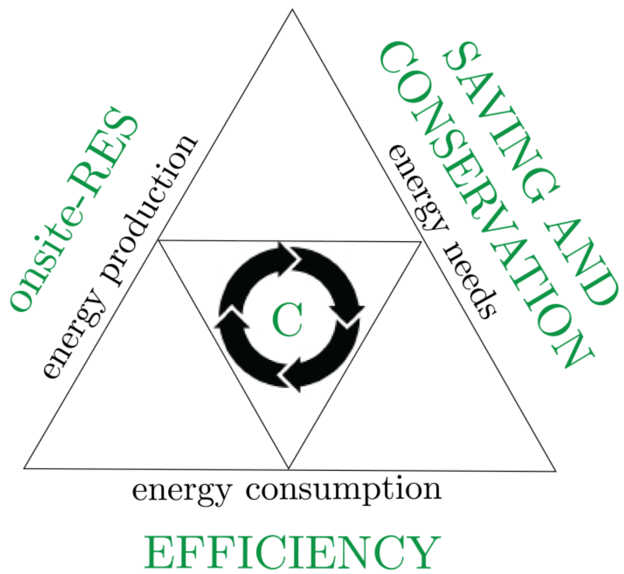

Figure 1: The three pillars of sustainable energy in cities (Vettorato, 2011)

- Energy saving and conservation: use less energy to achieve a lesser energy (urban) service, That means: reducing energy needs (reduce the amount of urban services that need energy).

- Energy efficiency: using less energy to provide the same amount of (urban) services. That means: reducing energy consumption.

- Renewable energy: exploiting local (on-site) and renewable sources of energy to match local energy demand.

According to Droege (2007, 2008), Owens (1986) and Vettorato (2011) these 3 strategies can be strictly connected with the form and the structure of urban settlements.
This finding is particularly relevant if we consider the challenge represented by existing settlements and buildings stocks. Most of them, in consolidated context like Europe, cannot be demolished and, instead, should be optimized to reach the most sustainable energy performance possible. The first research question of this work is:

Can urban morphology be considered a proxy for the assessment of energy performance of existing settlements?

The conceptual framework shown in Figure 2 presents the relationship between urban morphology and energy performances of urban settlements.
Urban morphologies through structures, design and forms induce modifications in the cities' energy systems like physical changes, induced energy consumptions and inefficiencies. These determines changes in the cities' energy demand/supply framework affecting:

- the stocks of needed urban services (mobility, heating and cooling, etc);
- the stock of energy needed to provide those services (suitable transport infrastructures and suitable heating and cooling technologies can be more or less energy efficient, etc.);
- the stock of energy that must be imported from outside systems (to match local energy demand).

Introducing the "sustainable energy development" concept described above it is possible suggests some targets that urban planning and design should reach:

- Energy conservation
    - Micro climate control: thermal comfort is one of the main energy consumer human activity in urban settlements (ASHRAE, 2004). The spatial classification of climate zones according to the regional climate conditions let to understand the relationship between energy needs for thermal comfort and land and urban morphologies.
    - Passive solar design: "*the harnessing of solar energy by appropriate design (passive solar energy) can lead to significant saving in conventional fuel at little or no economic or environmental costs*." (Owens 1986)
    - Proximity: the Soleri's and Register's (1987, 1993) concepts of "access by proximity" describe the benefits of locating urban activities closer together to save energy and resources.

- Energy efficiency
    - Low energy transport systems: decentralization of cities has been facilitated by the car. This led to a substantial growth in trip lengths and patterns. Efficient public transport systems need, instead, urban density. However bicycle remains the most energy efficient transportation mode and should be promoted (Zegras P C, 2005).
    - Building compactness: to minimize heat transfer thorough the building

envelope, the building shape should be as compact as possible, tending toward a cube (however other factors like temperature of the ground, winds speed and directions and solar irradiation influence heat transfer in buildings),(Energy and Resources, 2004).

- Renewable energy
  - Active renewable energy production (suitability): the production of energy from renewable sources in cities will reduce the energy dependence of urban settlements from imported and fossil fuels.(IEA/OECD 2009). The distribution of renewable sources of energy depends on physical environmental and morphological factors.

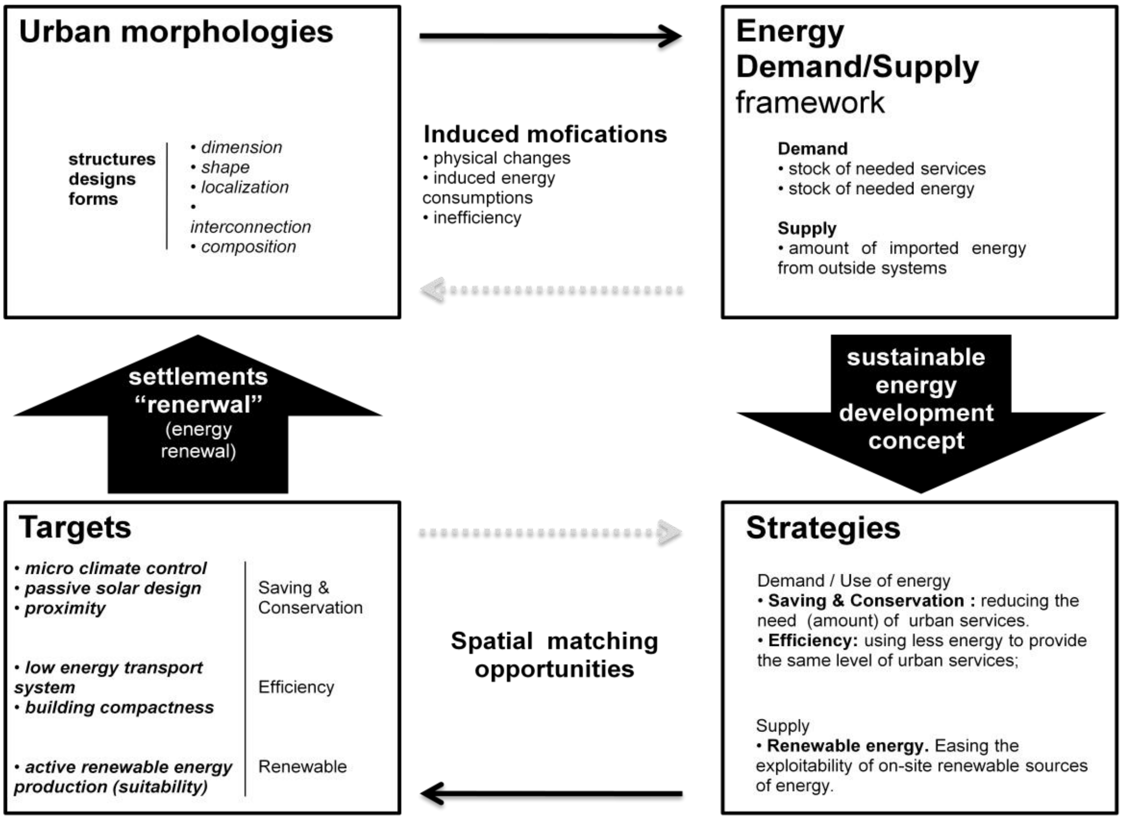

Figure 2: The conceptual framework on the relationship between urban morphology and energy performances of urban settlements.

Literature provides also many solutions and suggestions to design new settlements with sustainable energy criteria (Farr, 2008). Unfortunately for the urban renewal of existing settlements the analytical tools available in urban planning and design disciplines are not including the energy parameters, so far.

The second research question of this work is then:
"Which strategies and tools we have to renewal existing settlements from the energy point of view?".

To find an answer to this question first of all we should be able to assess the energy performances of existing urban settlements.
This paper presents a method to bridge urban morphology and energy performance of existing settlements.

The application of this method let to describe the state of the art of the energy performances of an existing settlement and to spatially indentify virtuous and bad areas from the energy performances point of view. It is also possible to suggest action for the energy renewal of different urban areas, here synthesized in the "urban renerwal" concept.

The method has been tested on a case study with complex morphology: Trento, a city located in an Alpine Valley.

2. The case study

The test area extends around Trento a city with 100,000 inhabitants located in an Alpine Valley: the Adige river valley (Figure 3). It is a narrow valley that is undergoing urban sprawl. The settlement system under examination is characterized by the existence, a part from the city, of many small centers, of varying sizes, which have developed over time both through endogenous development and a process of suburbanization originating in the city.
The complexity of the land morphology, due to the presence of the surrounding mountains and the Adige river, is very high.

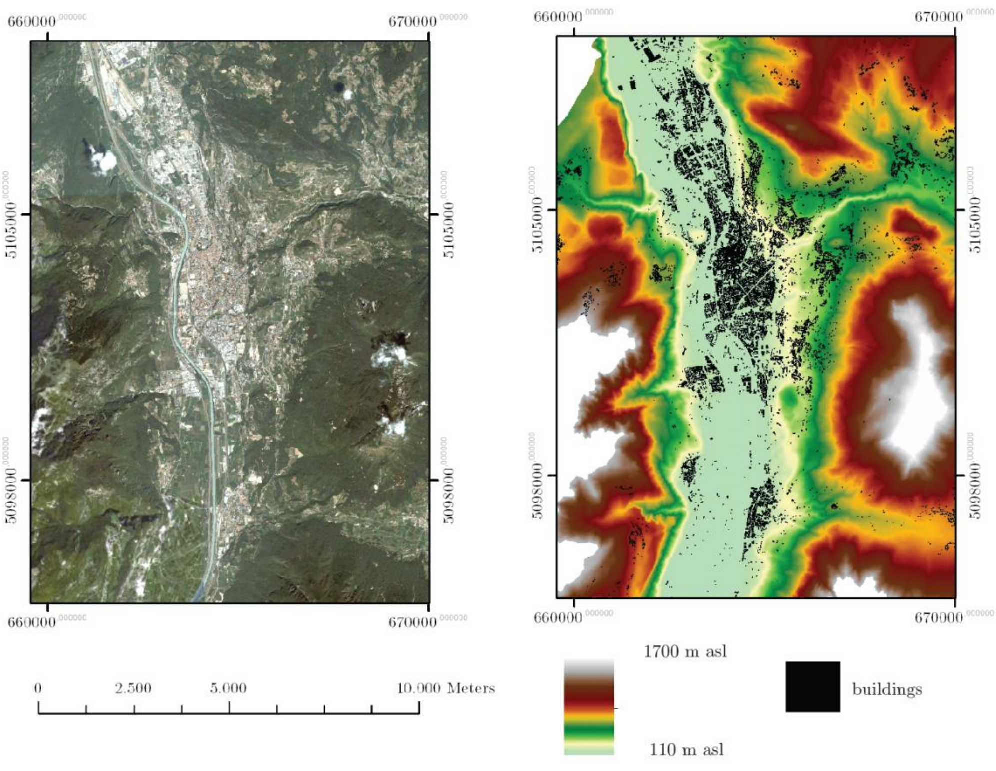

Figure 3: The case study area. The city of Trento, Italy.

3. Methodology

3.1 *Procedure*

The flowchart of the proposed procedure is presented in Figure 4.

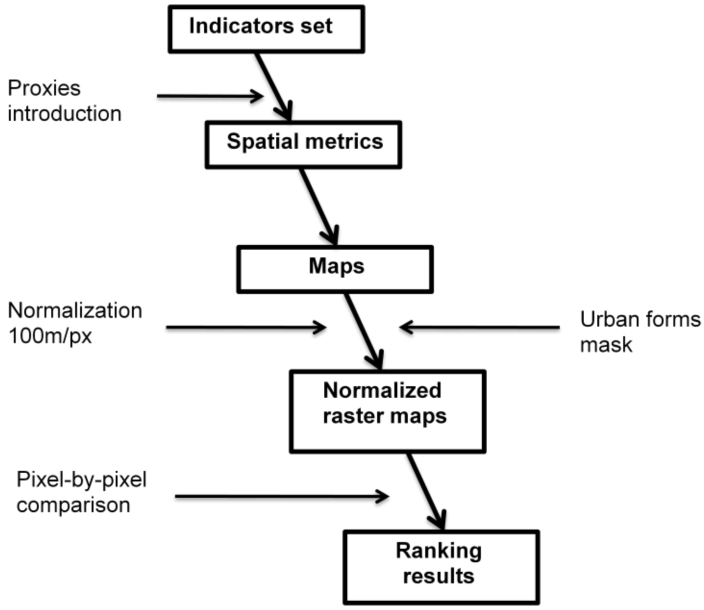

Figure 4: Procedure's flowchart

The construction of the indicators set based mainly on 3 elements:

- Its derivation from the conceptual framework presented above;
- A literature review on the sustainable energy in cities;
- The Pattern Oriented Modelling (POM) method (Grimm et al. 2005).

According to Alberti et al. (1999, 2008) a set of metrics (measurable indicators) suitable for this purpose must have these characteristics:

- Spatial: to consider spatial interactions;
- Quantitative or semi-quantitative: to let the comparison between the indicators;
- Customized on the case study: to fit local characteristics of the study area;
- Multiscale: to consider interactions between different spatial (and temporal) scales.

Basing on the previous assumptions it was possible to synthesize the complex interactions between urban morphology and energy performance through a list of patterns, in this case "spatial patterns".

Table 1 presents the set of spatial patterns used in the elaboration.

		Regional scale	**Urban Scale**	**Neighborhood scale**
Saving and Coservation	1	Local climate conditions		
	2		Housing and urban services proximity	
	3		Housing and job proximity	
	4			Natural illumination of buildings
	5	Natural sun exposition / lighting		
	6		Overheating aptitude	
	7			Building thermal conservation
	8		Green area factor	
Efficiency	9		District Heating and Cooling suitability	
	10	Regional transport		

		connections		
	11		Public transport accessibility	
	12			Walkability and bikeability
Renewable energy	13	Solarpower potential of land		
	14	Biomasspower potential of land		
	15		Ground Source Heat Pump (GSHP) potential	
	16			Photovoltaic and thermal potential energy of roofs and facades

Table 1: Spatial patterns set

3.2 *Dataset and proxies*

The dataset construction has been a critical step for the analysis elaboration. The energy performance analysis needs a wide range and amount of information in input. Available traditional urban databases did not always fulfill to this request as well lack of systematic records of urban-energy data. For the case study some spatial proxies has been used to obtain the requested spatial indicators.

The list of spatial patterns and the corresponding proxies is presented in Table 2.

Spatial metrics	**Proxies**
Regional climate conditions	Climate zones
Natural sun exposition / lighting	Hour of natural light on land
Regional transport connections	Main roads and rail network density
Solarpower potential of land	Watt/sq m / year on land (solar irradiation)
Biomasspower potential of land	Biomass availability
Overheating aptitude	Average Surface Temperature of land
Building thermal conservation	Building compactness (S/V)
Housing and urban services proximity	Urban basic services density (n/500sqm)
Housing and job proximity	Job density
Public transport accessibility	Public transport stops density
District Heating and Cooling suitability	Floor to Area Ratio (FAR)
Ground Source Heat Pump (GSHP) potential	GSHP potential
Natural illumination of buildings	Hours of natural light on buildings
Green area factor	Normalized Difference Vegetation Index
Walkability and bikeability	Average distance from a path

Table 2: Spatial patterns and corresponding proxies

A LiDAR survey provided information on the structure of urban areas. LiDAR is an optical remote sensor that measures properties of scattered light to find the range of a distant target, (the distance between the target object and the sensor, which position is known). When installed on an airborne platform, it can be used to generate a very high resolution 3D model of the terrain (Shan & Toth, 2009). In particular the high resolution 3D model obtained by this survey let to extract parameters like heights and volumes of buildings and to run physical models like sun irradiation (Vettorato & Geneletti, 2008) and micro climate models (Vettorato & Prosperi, 2011).

Regional climate zones have been derived by available literature (Los, 1990), while job density and service density have been derived by available statistics provided by the Local Authority (The Autonomous Province of Trento).
GSHP and Biomass power potentials assessment follows the method published in

Vettorato et al. (2011).
NDVI has been obtained by Landsat images freely available for the area (Landsat, 2005).
Roads, rails and cycle path have been obtained by available cartography provided by the Local Authority.

Each indicator has been elaborated in a map at a coherent reference scale, using the appropriate spatial dimension and information density. Then each map has been transformed in a raster map using a grid of 100m/px allowing the vertical overlay and a pixel-by-pixel comparison. An example of raster map format used in the elaboration is presented in Figure 5.

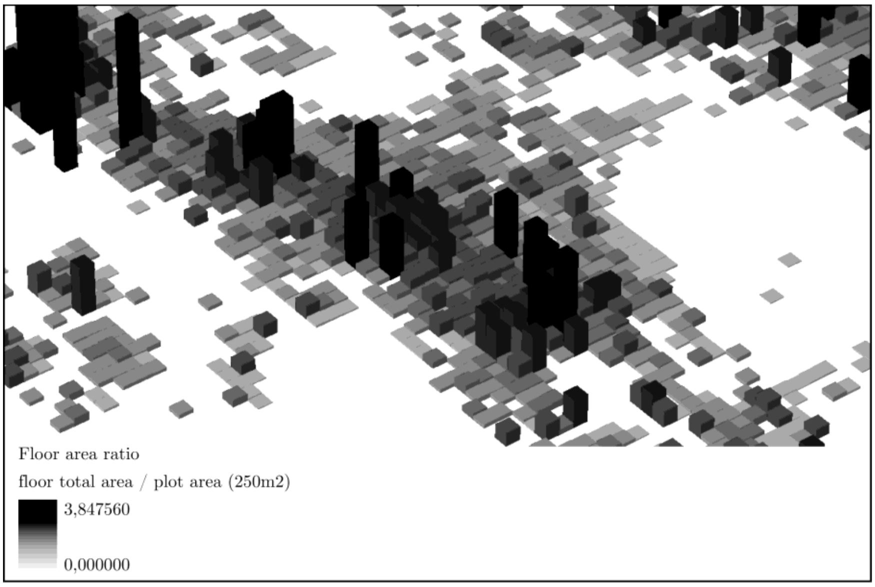

Figure 5. Raster map format. It represents the Floor to Area Ratio for the Trento city center.

3.3 AOI and Ranking analysis

Using a statistical approach, the cluster analysis, different urban forms have been mapped on the case study area. In particular 2 indicators, suggested by EEA (2006) have been considered: building density and population density.
The result, presented in Figure 6, shows an “island system” where black spaces represent the urban forms while white space represent the rural area.

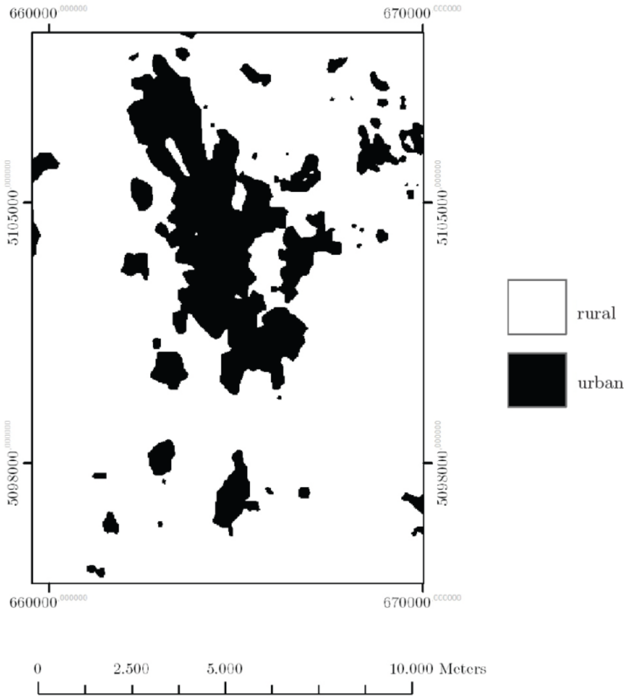

Figure 6: Urban Forms. The Area of Interest (AOI)

The urban forms have been used as a “mask” for the elaboration defining the “area of interest” (AOI).
On the AOI a ranking analysis has been performed, producing 3 maps of energy performance:

1- Performance on saving and conservation;
2- Performance on Efficiency;
3- Performance on Renewable energy exploitation.

Table 3 presents the scores and the thresholds used in the ranking analysis. They are mostly derived by local and international literature.

		Scores & theresholds		***Literature references for the theresholds***
	3 points	**2 points**	**1 point**	
Proxies (spatial metrics)				
Climate zones	Zone 1	Zone 2	Zone 3 and 4	*Los, 1990*
Hour of natural light on land	Over 8 h/day	between 5 and 8 h/day	under 5 h/day	*IEA/OECD, 2009; O'Cathian & Jessop, 1978; USBC, 2009*
Main roads and rail network density	between 500 and 1000 m	between 1000 m and 2000 m	under 500m and over 2000m	*Banister 1981, 2005; USBC 2009*
Watt/sq m / year on land (solar irradiation)	Over 4000 wh/m2/day	Between 2500 and 4000 wh/m2/day	Under 2500 wh/m2/day	*Vettorato & Geneletti, 2008*
Biomass availability	over 10 m3/ha/year	between 5 and 10 m3/ha/year	under 5 m3/ha/year	*Vettorato et al. 2011*
Average Surface Temperature of land	low and low-medium	medium	medium and medium-high	*Vettorato & Prosperi, 2011*
Building compactness (S/V)	over 100	between 50 and 100	under 50	*Energy and Resources, 2004*
Urban basic services density (n/500sqm)	over 15	between 10 and 15	under 10	*Farr, 2008*

Job density	over 35000 jobs/sqkm	between 20000 and 35000 jobs/sqkm	under 20000 jobs/sqkm	*Farr, 2008*
Public transport stops density	over 5 stops/500sqm	between 3 and 5 stops/500sqm	under 3 stops/500sqm	*Banister 1981, 2005; USBC 2009*
Floor to Area Ratio (FAR)	over 3	between 2 and 3	under 2	*USBC, 2009*
GSHP potential	over 3	between 2 and 3	under 2	*Vettorato et al. 2011*
Hours of natural light on buildings	Over 8 h/day	between 5 and 8 h/day	under 5 h/day	*Vettorato & Geneletti, 2008*
Normalized Difference Vegetation Index	over 0,4	between 0,1 and 0,4	under 0,1	*Landsat, 2005*
Average distance from a path	under 100m	between 100m and 250m	over 250m	*Banister 1981, 2005; USBC 2009*
Watt/sq m / year on building's roofs and facades	Over 4000 wh/m2/day	Between 2500 and 4000 wh/m2/day	Under 2500 wh/m2/day	*Vettorato & Geneletti, 2008*

Table 3: Scores and thresholds

4. Results

Figures 7, 8 and 9 present the resulting maps of the ranking analysis. These maps show very clearly that urban forms' energy performance are spatially very different and heterogeneous. With this method different urban areas are visually classified from the energy performance point of view.

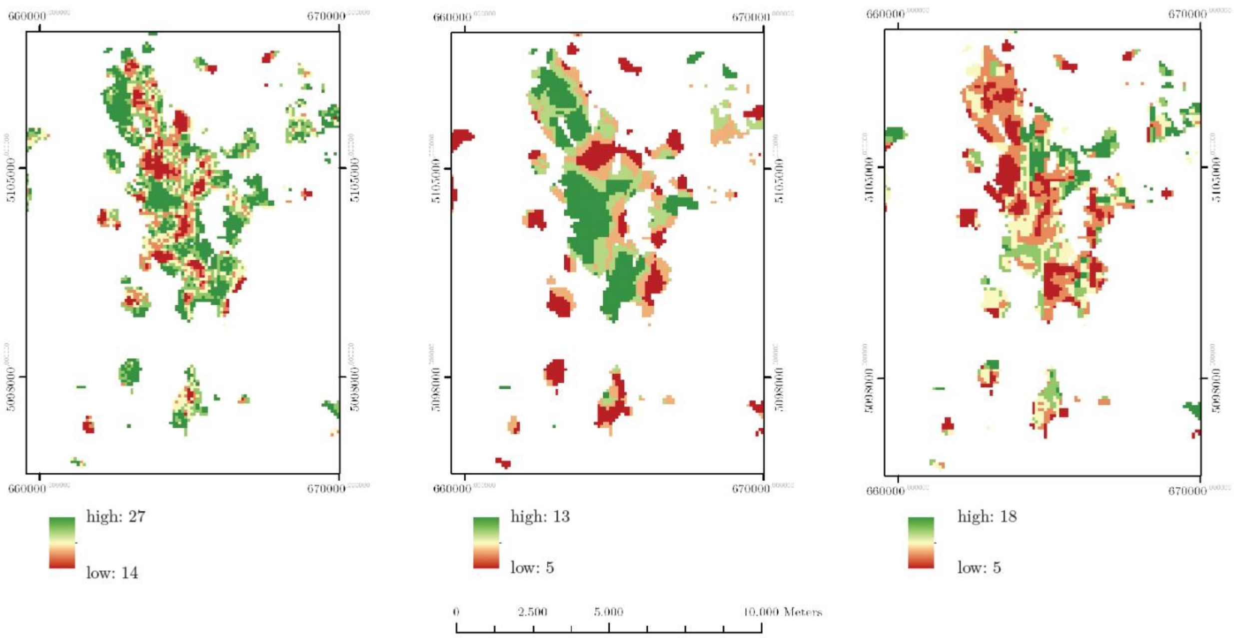

Figure 7: Energy performance map for Saving and conservation
Figure 8: Energy performance map for Efficiency
Figure 9: Energy performance map for Renewable Energy

Figure 7 presents the energy performance of the AOI from the Saving and conservation point of view. The spatial distribution of the performances is very heterogeneous. It is possible to observe, for example, that the city center presents both virtuous and bad

areas, like surrounding settlements.
Figure 8 presents the energy performance of the AOI form the Efficiency point of view. Here the spatial distribution of the performances is less fragmented. It is possible to recognize good performances in the city center while surrounding areas performed badly. In particular satellite settlements present the worst performances.
Figure 9 presents the energy performance of the AOI form the Renewable energy point of view: the potentials and the capacity of the areas to exploit renewable sources of energy. Here the city center performances are low while surrounding areas and satellite settlements perform better.

5. Discussion and conclusions. From the energy performance analysis to the energy renewal of settlements (the urban “renerwal”)

5.1 Strengths

This paper provided a contribution to the interdisciplinary debate on the relationship between urban sustainability and urban structure, with specific reference to energy. It provided a method to visualize spatial patterns for three key aspects of sustainable energy in cities: saving and conservation, efficiency and renewable energy exploitation.
The results showed that datasets and tools available so far can be used to provide an analysis of energy performance from a morphological point of view.
The presented method allows to spatially localize critical areas of intervention in order to bring them into line with sustainability criteria.

The produced knowledge base line, in fact, let to assess the state of the art of energy performances of a settlement.
This could be the starting point for the urban “renerwal” suggesting many strategies and actions to be performed to empower the weak areas.
On the case study area, for example, it was possible:

- to identify low energy performance areas;
- to explain why they are weak;
- to suggest actions to solve some of the identified energy performance problems;
- to identify virtuous areas and/or areas with high and unexploited potentialities.

A knowledge base on energy performance of urban areas must become one of the key factors to support the planning and design of urban settlements, jointly with traditionally-addressed factors, such as geological risk, nature conservation areas, and the protection of landscape. At the local level, low energy performances may increase energy costs, reducing the possibility to provide competitive and livable urban systems.

5.2 Weaknesses and further developments

The lack of data and the ad hoc methods used for the spatial analysis has forced to make some approximations. In particular some proxies have been introduced in the analytical steps to compensate the lack of data. Also, it was not possible to use a single energy unit of measurement for the spatial patterns of energy performance. This means that the results have been subject predominantly to visual comparisons. Likewise, it was not possible to compare performance data from the three different aspects of sustainable energy. Future developments should identify a unit of quantitative measurement of energy performance and the necessary conversion formulae to be used in the research works.
The sophistication of the proposed approach could be further improved by considering in particular the use of sensitivity analysis to assess to what extent the final results are affected by the use of different thresholds; in the present exercise arbitrary thresholds suggested by literature were used.
The cosiderations listed above show that the proposed approach is affected by

uncertainty factors. However, its main contribution resides in its sequence of analytical steps to support low-carbon urban design and urban "renerwal" for sustainable and liveble cities.

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