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Sustainable energy performances of urban morphologies

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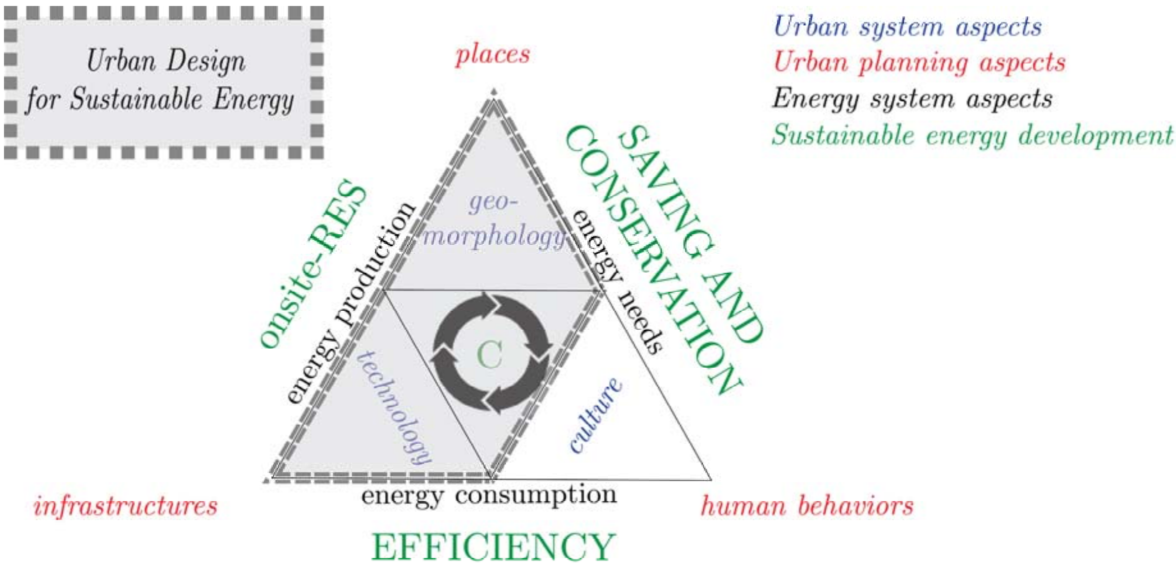

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Summary

This dissertation examines the concept of sustainable energy within a urban design context. In essence, the research aims to answer the question: "what role does the city's built environment morphology play, if any, in the sustainability of its energy system?". To answer this question, I first derive an operational definition of sustainable energy in the post carbon era: maintaining the capability to provide non-declining energy services in time. Providing non-declining energy services, in an urban design context, depends on urban morphologies ability to save and conserve energy, be efficient and produce energy from renewable sources without decrease the level of energy services. In other words we can think of a more sustainable energy urban built environment as one that saves energy, is efficient and produces energy from renewable resources per unit of throughput, with energy sustainability measured by urban morphologies energy performances and throughput measured by land unit. This is a normative framework. It can only indicate relative levels of sustainable energy of urban morphologies. Within a specific urban system this framework can allow us to measure which part of the city produce more sustainable energy urban patterns.

To employ this framework I utilize a Spatial Pattern Oriented Modelling approach. The energy performance of an urban morphology metric comes from its basis in the international debate on urban energy sustainability, its ability to account for a specific aspect of sustainable energy and the possibility for its derivation from the spatial pattern analysis. Drawing from the large research based on exploring the role of the urban morphology on urban energy system, I derived several spatial patterns indicators that assess the influence of urban morphology on energy performances of urban settlements. These spatial patterns metrics, combined, enable the exploration of sustainable energy within a given urban morphology configuration. I apply the framework to a case study area located in northern Italy between Alps, the transect Trento-Pergine-Valsugana, utilizing data from different sources and exploring the possibilities given by a high-resolution 3D spatial database, a LiDAR survey, and by a geolocalized human activities database, internet 2.0, for the urban morphology analysis with focus to energy. The Principal Component Analysis is used to estimate the correlation between different spatial patterns indicators while a ranking system, based on arbitrary thresholds and classes, is used to visually compare the scores of different sustainable energy performances of urban morphologies.

I conclude with the presentation of the results in the face of an international debate on sustainable energy and urban morphologies, with a discussion on the limits of the approach and on the approximation introduced to fill the gap of data scarcity and, finally, proposing further improvement to the methodology.

Chapter 1

1. Introduction

1.1 Research objectives, issues and questions.

The starting hypothesis, supported by this research, is that in urban settlements a strong relationship exists between “urban morphology” and “sustainable energy performances” of settlements. This dissertation aims to demonstrate this relationship exists and to propose a method to conceptualize and spatially visualize it. The used research method is the inductive reasoning based on empirical observations.

Humans can now officially be called an urban species [1.1]. More than half of the global population now live in cities and the United Nations [1.2] estimates that by 2030, 60 percent of us will live in them. Despite only representing 2 percent of the world's surface area, urban settlements are responsible for 75 percent of the world's energy consumption [1.3]. Almost 100 percent of this energy is imported in cities from outside [1.3]. According to U.N. Habitat [1.4], the world's cities emit 80 percent of global carbon dioxide as well as "significant amounts of other greenhouse gases".
The conclusion is easy: if you want to tackle the energy issue, tackle the cities.
According to IEA [1.5] cities planning influence, directly and indirectly, significant energy using areas. Improving the energy performances of cities can reduce energy consumption.
In the past, to improve energy efficiency in cities, the solutions have been focused on the micro scale and segmented interventions, mainly on the improvements of buildings' and vehicles' energy performances. Very rarely the researches were focused on the urban morphology at urban and territorial scales.
The “pioneer” Owens, in 1986, wrote “Energy, planning and urban form” [1.6]. This book, that could be defined a “milestone” in the research of sustainable urban morphologies from the energy point of view, suggested that cities spatial structure and built form affect the efficiency in the use of energy and the potential production of en-

ergy from renewable sources in cities. Unfortunately her great work was delivered in form of guidelines completely lacking of:

- tools to assess the state of energy performances of existing settlements;
- tools to produce the urban-energy datasets;
- conceptual models to be used in the definition of assessment methodologies.

On the wave of peak oil and climate change many other contributions have been published by scholars on these theme in the last 5 years, but very few tried to face these issues.

The questions that remain opened and that this work contributes to partially answer are:

- How can we assess the spatial interactions between urban morphologies and energy system?
- Can we assess them from a sustainable energy point of view?
- How can we collect and/or produce the datasets to describe these interactions?
- Which analytical instruments can we use to understand these interactions?
- How can we spatially represent and visualize energy performances of urban morphologies?

For these reasons the aim of this work is to propose, test and discuss a method to:

- analyze the energy state of urban settlements from an urban morphology point of view;
- assess the urban morphology from a "sustainable energy" point of view.

The research work faces the following issues:

- the actual controversial and debated definition of "sustainable energy";
- the complexity of the urban system;
- the poor knowledge, in literature, about the "interactions" between urban morphology and energy;
- the lack of urban-energy spatial dataset;
- the lack of methods and procedures, in literature, to collect, produce and analyze spatial energy databases;
- the high fragmentation, heterogeneity and segmentation of the available case studies.

1.2 Structure of the Dissertation

Following the definition of the research objectives and the basic research questions and research approach, Chapter 2 provides a background to the issue of sustainable development concept, tracing its origins and evolution, highlighting the relevant definitions, applying it to the urban settlements and energy contexts and outlining some of the efforts to measure the concept. First, a definition of "energy" and of "urban morphology" is given. Second, a background to the issue of sustainable development concept and the sustainable development options, strong and weak, is provided. Third, a definition of sustainable energy is given (saving and conservation, efficiency and production of energy from renewable sources) and it is applied to the urban morphology context. Fourth, the sustainable urban morphology concept is described in the dichotomy of Compact VS Sprawl. Fifth, an operational definition of sustainable energy development for urban morphologies is derived.

Chapter 3 describes the methodology. To understand the potential influence of the built environment morphology on energy performances and according to the literature and reviewing the relevant research, Chapter 3.1 proposes a theoretical model for the interaction between energy and urban morphologies and proposes a modeling approach to analyze these complex-system interactions. Chapter 3.2 proposes an operational framework to analyze multi-scale interactions between energy and urban morphologies based on an interaction matrix, a set of spatial pattern metrics (indicators of energy performances and urban compactness) and a set of tools to analyze spatial data (pixel-by-pixel analysis, multivariate statistical analysis and ranking system).

Chapter 4 focuses specifically on the different datasets available for measuring the built environment with focus to energy and on the opportunities given by new technologies.

Chapter 5 describes the test of the proposed method on the case study, introduces the empirical case, the transect Trento-Pergine-Valsugana describing its location, land morphology, urban compactness patterns and urban shapes. Afterwards the approximations introduced by the geo data collection and the adaptation of the interaction matrix to the context are described. Finally the results of the analysis are presented.

Chapter 6 discusses the analysis results and the research implications of the work.

Chapter 7 concludes the dissertation with general remarks and proposing further improvements to the methodology.

References for chapter 1

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Chapter 2

2. Background

“Energy will do anything that can be done in the world; and no talents, no circumstances, no opportunities will make a two-legged animal a man without it”.— Goethe, Johann Wolfgang Von (1749–1832)

“The global effort for sustainability will be won, or lost, in the world’s cities, where urban design may influence over 70 percent of people’s Ecological Footprint”. - Global footprint network, (2008)

"She was the mother of Chimera who breathed raging fire, a creature fearful, great, swift-footed and strong, who had three heads, one of a grim-eyed lion; in her hinderpart, a dragon; and in her middle, a goat, breathing forth a fearful blast of blazing fire. Her did Pegasus and noble Bellerophon slay" - Pseudo-Apollodorus, Bibliotheca 2.3.1

2.1 Energy and city

2.1.2 A short definition of “energy”

The word energy is a Greek compound. ἐνέργεια - *energeia* is translated in english as activity, operation, movement. Aristotle created the term in his Metaphysics [2.1] by joining ἐν (in) and ἔργον (work) and then he connected this concept with *entelechia*, “complete reality”. According to Aristotle, every object’s existence is maintained by *energeia* related to the object’s function [2.2]. The Merriam Webster Dictionary [2.3] give 6 different definition of energy: a) a dynamic quality, b) the capacity of acting or being active, c) a usually positive spiritual force, d) vigorous exertion of power, e) a fundamental entity of nature that is transferred between parts of a system in the production of physical change within the system and usually regarded as the capacity for doing work, f) usable power (as heat or electricity).

In physics, according to the accepted classification in GEM 1OR [2.4], *primary energy* is the *energy* extracted directly from the environment (i.e. it is a thermal equivalent of produced coal, crude oil, natural gas, collected biomass, *kinetic energy* of water or wind energy of solar radiation at the collector plane *thermal energy* of hot water or steam in the Earth's depth). *Secondary energy* is a conversion of *primary energy* in the form of *electrical energy* or *fuel*.
It is common in literature to use also the words *energy sector* to define a combination of processes of energy conversion and transportation from sources of *natural energy resources* to consumers of a vast range of *energy services* (mobility, lightning, heating, etc). Anyway *energy* in physics is a term which describes something that we cannot hold or see. We can only see the results of its application [2.5].
Due to the lack of a clear and universally recognized definition of *energy* this research, referring to the definitions given above, assume that: *energy* is the capacity of a (physical) system (to perform work and) to provide services.

2.1.2 A short definition of "urban morphology"

The Oxford Dictionary of Geography [2.6] defines Urban Morphology as "the form, function, and layout of the city, and the study of these features, including their development over time".
Karl Kropf compared the urban morphology to the internal structure of a material [2.7]. So if an understanding of internal structure is essential to successful 'manipulation' of a material, urban morphology is essential to urbanism and urban design. In this sense the primary concern of urban morphology is the structure of urban form.
The structure of urban form (or spatial configuration) is pervasive. There are different kinds of structure with different characteristics at different scales. Individual buildings, at one level of scale, do not have the same handling characteristics as a street, at another, or a town as a whole at yet another. The generic structure of urban form is a hierarchy of levels related part to whole [2.7].
Alberti reported that "*in an holistic context, cities can be defined as non-equilibrium systems. Random events produce system shifts, discontinuities and bifurcations. Patterns emerge from complex interactions that take place at the local scale, suggesting that urban development self-organizes. Emergent patterns are often scale-invariant and fractal, suggesting that urban morphology is derived from similar processes operating at the local scale*" [2.8].
As suggested by Alberti [2.8], from the urban ecology point of view, instead of asking

how emergent patterns of human settlements and activities affect energy processes, the question we should ask is how humans, interacting with their biophysical environment, generate emergent phenomena in urbanizing ecosystems. And how do these patterns selectively amplify or dampen human and ecological processes and functions. Cities are coupled human-natural systems in which people are the dominant agents. Urban Morphology, in this context, can be defined as the visual expression of the interactions between humans and their biophysical environment.
Urban morphology definition is also involved in the "compact VS sprawl" debate. Mature and irreversible processes are taking place in the world urban settlement configuration due to the increasing trend of urbanization of world population. According to EEA [2.9] sprawling cities, the opposite of compact cities, are "full of empty spaces" that indicate the inefficiencies in development and highlight the consequences of uncontrolled growth.

In this research urban morphology is used to describe the interactions that take place with hierarchy of scales between emergent spatial patterns in the complex system called city that undergoes to the pressure of uncontrolled urbanization growth.

2.1.3 The debate on energy and city

Cities are an important engine for economic growth and socioeconomic development. Rapid urbanization in recent decades has led to ever-expanding cities, creating massive requirements for energy to fuel growth and expand basic service infrastructure. This demand for energy has enormous implications for cities, particularly their operating budgets, competitiveness, service quality and cost, quality of life and local and global environmental impacts. The International Energy Agency [2.55] clearly recognizes the importance of energy use in cities and, in their latest World Energy Outlook 2008 report [2.55], devotes an entire chapter to energy use in cities. Some of their key findings include:

- Cities consume about two-thirds of the worlds energy use and account for more than 70 percent of global greenhouse gas (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 CO_2 emissions;
- Of this growth, 81 percent will come from non-OECD cities.

As suggested also in the recent report by IEA/OECD [2.56] the energy consumption and the use of fossil fules that produce CO_2 emissions can be strongly correlated with the GDP indicator. Cities, as reported also by Meine Pieter van Dijk 2007 [2.57] are the main contributors to nationals GDPs with an estimation of 70% of the total in 2011.

The escalating demand of energy use for basic urban services have resulted in serious pressures on service quality across all urban sectors – water/wastewater, power/heating, housing, city lighting, buildings and transport.

Figure 0a: Fuel shares in OECD electricity output – source: [2.56]

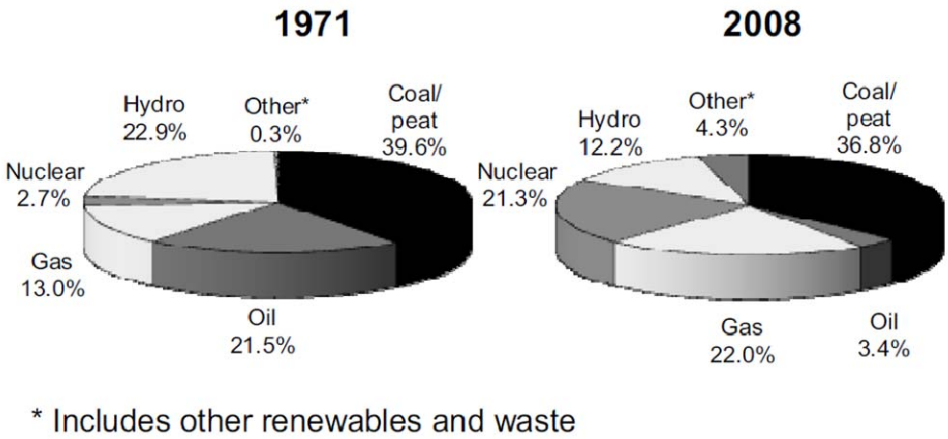
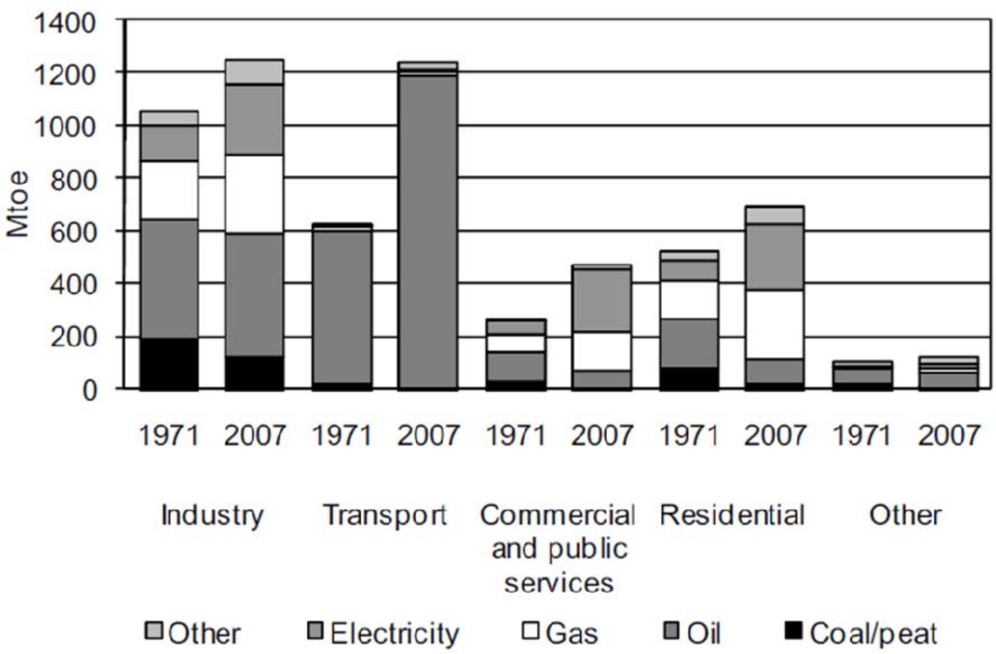


Figure 0b. TFC by fuel and by sector in the OECD – source: [2.56]



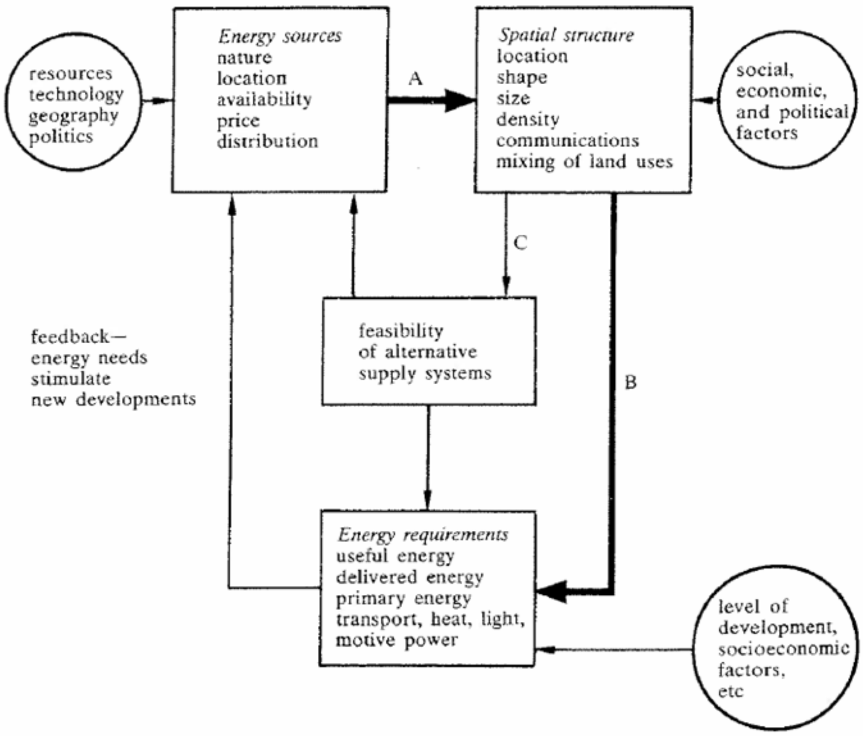
Energy is widely viewed as the lifeblood of cities, powering public services, hospitals and schools while moving people within the city and beyond. Without energy, water cannot flow to houses, offices cannot be heated and cooled, and commerce would come to a grinding halt.
At the beginning of the century, humanity is standing at the crossroads of cities. For the first time in history, the urban dwellers of the planet outnumber the rural ones. The global urban population exceeded the 50% mark in 2007 [2.54]. According to the last UN population estimate, 60% of the world population is expected to live in urban areas in 2030 and almost all of the growth is expected to occur in the urban less developed world. Beyond the demographic growth, urbanization is an ultimate cultural process and a key issue for sustainable development.

Cities occupy a very small percentage of the surface of the planet but consume an extraordinarily large share of its resources [2.58] 2% of land consumption VS 75% of energy consumption.
Population density is typically the defining characteristic of urban settlements and implies the geographical concentration of human, social, built and economic capital. The proximity of people and activities is a major source of advantages. Cities are the only places where people and resources congregate at a point beyond which synergetic effects become more important than simply accumulative ones.
The world has been urbanizing for centuries. Industrialized regions led urbanization and reached the "urban age" half a century ago. The gap in urbanization levels increased between 1950 and 1975 and has been narrowing since 1975. Urban dwellers represented already 50% of the total population in OECD regions in 1950 and 70% in 1975.
Cities evolved as a result of their assets. From the energy point of view the cities moved from the eotechnical phase, marked by a shift in the energy source from humans to animals and machines, to the paleotechnical phase, based on coal and iron, and from the neotechnical phase of assembly line production and oil to twenty-first century technologies and innovations transforming themselves into post-carbon settlements [2.58].

Historically, energy transitions—from the use of dispersed organic sources, through wind and water power, to large-scale exploitation of fossil fuels—can readily be linked with major shifts in settlement and transport patterns, culminating in the concentration of most of the population of developed countries into urban/industrial centres [2.54] Cheap energy for transport and agriculture, for example, certainly removed two of the most important constraints on the growth of towns—the requirement that they should be sustained by an agricultural surplus and the transport 'bottleneck' arising

from the need to be provisioned from ever more extensive surroundings.
If energy has been a permitting factor in the process of urbanization there can be little doubt that it has also exerted a profound influence on the location and direction of urban development during the twentieth century. Transport technologies and energy supply networks increased personal mobility, released industry from location constraints, helped "to turn city dwellers into suburbanites". And provided the fundamental permitting factors for urban growth to spread radially and at decreasing densities [2.54].
In short, there is ample evidence that energy supply, price, and distribution are among the important factors shaping urban and regional systems even if the relationship is indirect and complex [2.54].

Figure 0c. The energy — land use relationship is represented schematically in figure 1.1. source: [2.54]



In reality, in fact, it is far from being so clearly defined: cause and effects are often difficult to distinguish and many aspects remain unquantified. Few planners in Italy, for example would be able to find a documented "energy budget" showing sources, flows and end uses of energy in their county or local planning area. Statistics are usually available only at national level, even though energy budgets differ quite markedly on a smaller geographical scale and the potential for conservation and use of renewable sources is likely to show up more clearly in a "fine-grained localized analysis" [2.54]. There is surprisingly little work on this topic [2.54].

2.2 The concept of "sustainable energy development of urban morphologies" in the post carbon era

2.2.1 Strong or weak? Sustainability and sustainable development options

The concept of sustainability in the last years has become inflated. Its origin can be traced far back in the fields of economics and natural resources, relating to the capacity of natural stocks, the Malthuisian concept of resource exhaustion due to population growth [2.10] and fundamental economic principles on the relationship between consumption and wealth.
The prevailing modern usage of the word sustainability finds its recent roots in the environmental movement, for example, the 1972 UN Conference on the Human Environment and Meadows et al [2.11] *Limits to Growth*, which helped to push environmental concerns onto the global agenda. A follow-up to Limits to Growth, *Alternatives To Growth* [2.12] includes papers from a wide range of disciplines, presented a conference aiming to chart paths to potential "sustainable futures", which are associated with a "steady state" economy and a "just" society. Rees [2.13] credits the World Conservation Strategy of 1980 with the first explicit use of the term "sustainable development".
By the late 1980s the idea of (environmental) sustainability became formally integrated into mainstream development concerns with the release of the well-known Bruntland Report [2.14] which formalized the concept of sustainable development, recognizing the fundamental need to live within the earth's means and the implications for passing on the same, or grater, amount of total resources to future generations. By 1992, sustainable development hits centre stage when the United Nations convened the Conference on Environment and Development in Rio de Janeiro organized around the principal themes "environment and sustainable development" [2.59].
The idea of sustainable development then begins to take on a broader perspective than simply one of environmental concerns and by the 1990s the "three dimensions" of sustainability come to the so called three E's of sustainability: environmental, economic and social (equity) [2.59].
As Keiner et al. stated [2.15] the terms "sustainability" and "sustainable development", are arbitrary and user-defined, and have lost their clear meaning. In a rigorous interpretation, sustainability can be seen as a strictly scientific construct, related to, for example, carrying capacities, biological processes, ecosystem services and functioning. Can the system sustain itself in the time? How do we value future generations and what we leave to them? How do we value "non-economic" resources (i.e. ecosystem services and quality)?
How do we value the distribution of resources among current generations? Is sustainability really a new concept, or simply a new code to define balanced human-nature

interactions that have existed throughout time?
Sustainability regards, in fact, the interaction between human activities (economic and social) and nature (environment). Cities, according to UN [2.16], are the place of most of these interactions so urban settlements can be defined "the place of sustainability challenge". According to Wheeler and Beatley [2.17], in urban settlement context, the first one who studied the subject was probably Ebenezer Howard, and urban planner, in *To-Morrow* [2.18].
Regarding sustainable development, probably the most famous definition comes from the Bruntland Report: "to ensure that development meets the needs of the present without compromising the ability of future generations to meet their own needs". Rather than an operational definition of sustainability the Brundtland definition offers more a general statement of principles.
The economists' perspective offers another approach to arrive at this definition of sustainable development: "maintain the capacity to provide non-declining capital utility of infinity" [2.19, 2.59]. This definition introduced the concepts of strong (SS) and weak (WS) sustainability. The former requires that the quantity of natural resources should not decline over-time as this may reduce their total supply. It requires that natural resources should not be used at a rate which exceeds their rate of replenishment. The latter principle of sustainability requires that the quality of natural resources should not decline over-time as this may reduce their value [2.20].

According to Neumayer [2.21] the capacity to provide utility is conceptually embodied in four forms of capital: produced, natural, human and social. According to Pearce [2.20] WS assumes substitution possibilities between the component parts of capital. The WS paradigm was effectively founded in the 1970s (there was no such sustainability terminology at the time) by extending the neoclassical theory of economic growth to account for non-renewable natural resources as a factor of production. These highly aggregated growth models considered the optimal use of income generated from the extraction of a non-renewable resource and sought to establish rules on how much to consume now and how much to invest in produced capital to increase consumption later. The key question posed in these pioneering studies was whether optimal growth, as it is defined above, was sustainable in the sense of allowing non declining welfare in perpetuity? This was shown to be unlikely in a model including a non-renewable resource as a factor of production [2.59].
Much of the ecological literature denies this substitutability, at least across some classes of natural capital. Of particular interest are the "life support" functions of ecosystems, e.g. maintenance of carbon balance, hydrologic cycles, nutrient cycles etc. According to Pearce [2.20] economists have not so far achieved much success in capturing

all ecosystem functions, despite considerable progress in function valuation using the concept of total economic value (TEV) [2.21]. The suspicion remains that there is more to the total value of an ecosystem than the sum of the values of individual functions. If so, substitutability is open to question.
Proponents of SS argue that natural capital is to a greater or lesser extent non-substitutable. The SS approach is not only concerned about keeping the aggregate stocks of capital constant, but it also requires that the stocks of natural capital (ecological assets) should not decrease over-time [2.20]. This is mainly because natural capital performs four categories of functions. Firstly, it provides the raw materials for production and direct consumption such as food, timber and fossil fuels. Secondly, it assimilates the waste products of production and consumption. Thirdly, it provides amenity services, such as the visual amenity of a landscape. Fourthly, it provides the basic life-support functions on which human life, as well as the first three categories of natural capital functions, depends. There may be considerable substitution possibilities between the first category of natural capital functions — raw materials for production and direct consumption — and produced capital. Indeed, in the past the economy has consistently overcome production and consumption resource constraints [2.19, 2.22], although this is no guarantee of future performance and substitution is likely to become very difficult as resource efficiency becomes very high. If WS is apt, it is here though it should be bounded. It may also be possible to substitute some natural waste assimilative capacity and some natural amenity services. However, basic life support systems are almost certainly impossible to substitute [2.23]. Most importantly, this means the global environmental and ecological system that provides us with the basic functions of food, water, breathable air and a stable climate. They should hence be subject to an SS rule. We may wish to pursue SS for other reasons. Firstly, there remains considerable risk, uncertainty and ignorance attached to the way in which natural capital such as the global carbon and biogeochemical cycles works. It follows that we cannot be sure what effect damaging it will have. As Atkinson et al. point out, risk, uncertainty and ignorance are "always a reason for being cautious, unless society can be deemed to be indifferent to risk or positively to welcome it" [2.24]. Secondly, the loss of some natural capital may be irreversible. Thirdly, since there is evidence to suggest we are more averse to losses in utility than we are keen to gain it [2.25], this might imply that we are highly averse to losses in natural capital functions that directly provide us with utility.

From a sustainable energy perspective the problem can be explained by the means of "climate change". Fossil fuels provides the major part of energy for human activates, but they produce green-house gasses that change the global climate.

From an ecological perspective, the “strong“ sustainability rule requires that the total sum of greenhouse gas emissions should not exceed the assimilative capacity of the atmosphere and that, at least, irreversible and catastrophic effects on the global ecosystem should be avoided.
From a welfare theoretic perspective, a “weak“ sustainability approach is based on the principle that social welfare should be maximized and the total costs of climate change (abatement, adaptation and damage costs) should be minimized.
In a vision of a “post-carbon era” instead, the same use of fossil fuels should be minimized because is source of carbon emissions. In this sense the Strong Sustainability paradigm seems to fit much better the aims of finding better congruence modalities between human and nature interactions. For this reason the research is based on the strong sustainability approach.

2.2.2 Sustainable energy: the three heads of Chimera.

It is not difficult to find in literature references to sectoral sustainability, such as to sustainable housing, sustainable consumption, sustainable forestry, sustainable agriculture. Some of these sectors lend themselves naturally to the sustainability concept and, indeed, essentially formed the basis for modern ideas about sustainable development.
In the energy sector, the evolution of the sustainability concept followed a pattern similar to sustainability, more generally. Depending on who provides the definition, the definition is different. For example the World Nuclear Association defined the Nuclear power and waste as “sustainable” [2.26].
Anyway this is not the place for the debate on the many “interests” involved in the sustainable energy definitions and on the risks (environmental, geopolitical and social) related to nuclear power.
This research, as mentioned above, aims to be coherent with the chosen definition of strong sustainability: an ecological sound definition of sustainability.

Other definitions of “sustainable energy” very common in literature are:
"*Effectively, the provision of energy such that it meets the needs of the future without compromising the ability of future generations to meet their own needs. …Sustainable Energy has two key components: renewable energy and energy efficiency.*" [2.29]
"*Dynamic harmony between equitable availability of energy-intensive goods and services to all people and the preservation of the earth for future generations.*" And, "*the solution will lie in finding sustainable energy sources and more efficient means of converting and utilizing energy*" [2.30].
"*Any energy generation, efficiency & conservation source where: Resources are available to enable massive scaling to become a significant portion of energy generation, long*

term, preferably 100 years" – *Invest,* a green technology non-profit organization. [2.31].
"*Energy which is replenishable within a human lifetime and causes no long-term damage to the environment*" [2.32].

According to Peter Graham [2.27] the mechanism for ecologically sustainable energy and resource use, according to the fourth law of thermodynamics, is the keeping of energy quality in systems through the development of feedback loops.
Sustainable natural systems have evolved ways of turning the outputs of consumption into resources for production, thus reducing the need for the system's reliance on energy from outside sources [2.28].

In 1978 the StadOntwikkeling & Milieu and the TU Delft University developed a very interesting and operational definition of "Sustainable Energy" through the tool called "Trias Energica" [2.33].
The idea was re-introduced by Erik H. Lysen in 1996 under name "Trias Energetica" [2.34].
"Trias Energica" strategy consists of three steps where the next step should only be taken,
when possibilities for the former step are completely exhausted. These steps are:

1. Reduction of the energy use
2. Use of renewable energy sources
3. Efficient use of fossil energy

This research developed a definition of "Sustainable Energy" based on the contemporary definitions of "sustainable energy" and by the "Trias Energica" tool. The aim of this definition is to be integrated with the urban design and planning procedures.

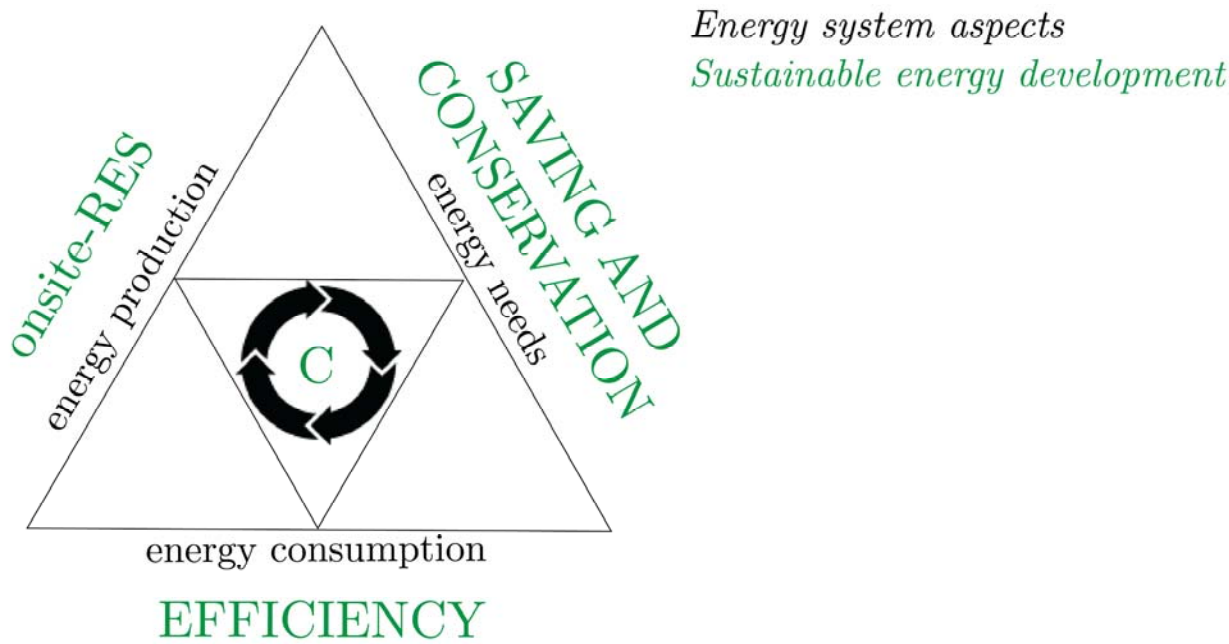
The definition is composed by three complementary sub-concepts, three heads of the same Chimera:

- Energy saving and conservation: use less energy to achieve a lesser energy service (reduce needs);
- Energy efficiency: use less energy to provide the same level of service (reduce consumption)
- Renewable energy sources exploitation: exploitation of on-site and renewable energy sources to match local energy demand (energy production)

The three components are joined, like with Chimera, by the same body: the feedback loop of close cycle (C) that turn waste from energy consumption into a source of en-

ergy keeping energy in the system for as long as possible.
The sustainable energy definition is presented in Figure 1.

Figure 1. Sustainable energy definition scheme



2.2.3 Urban morphologies with sustainable energy performances: an operational definition

A very important step of the research was the definition of the "research domain" and the elaboration of an operational definition of "sustainable energy urban morphologies". A vast literature [2.35, 2.36, 2.37. 2.38, 2.39, 2.40] agrees that urban systems and urban planning interact with the energy system (Figure 2) :

- determining the location of the settlements in the geo-morphological context
- determining the infrastructures according to the available and affordable technology
- and managing the human behaviors according with the local culture

These considerations leads to define the "domain" of urban morphologies design that regards structures, textures and forms partially excluding the aspects related to culture and human behaviors.
The relationships between sustainable energy development, energy system, urban systems and urban planning and, finally, the sustainable energy urban morphologies domain, are presented in Figure 3.

Figure 2. Urban system and urban planning aspects relevant for energy interaction.

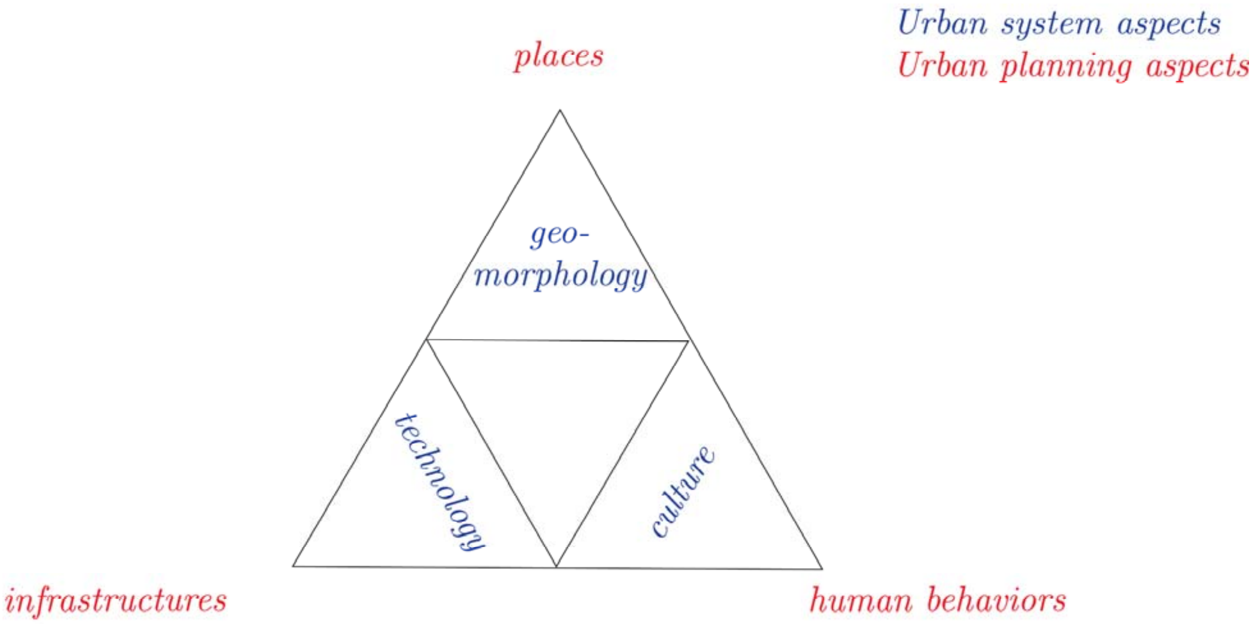
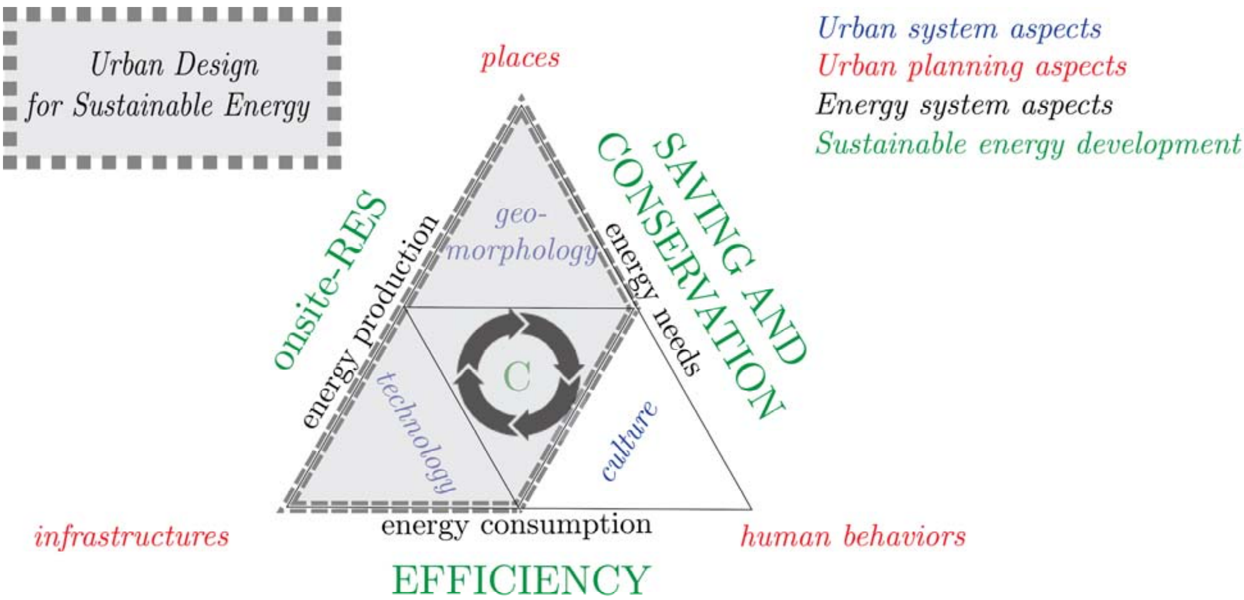


Figure 3. The domain of the research: Urban Design for Sustainable Energy. Relationship between Urban System, Urban Planning, Energy System and Sustainable Energy.



According to Alberti [2.36] "*The hypothesis that the spatial configuration of elements in an urban region influences ecosystem dynamics is based on the idea that the spatial patterns of the urban setting alter the biophysical structure and habitat and influence the flows of resources.* Only recently the relationship between urban patterns and energy efficiency, energy saving or renewable energy local exploitation is becoming increasingly important [2.37; 2.38]. Summarizing the state of the art of the debate it is possible to say that from an urban morphology prospective, urban development affects settlements' configurations (i.e. compact VS sprawl) influencing their dimension, shape, localization, interconnection and composition, determining, then, different morphologies of settlements (structures, textures, forms). Various configurations of the urban structure textures and forms imply alternative energy uses, and affect efficiency, conservation and energy production capabilities [2.39, 2.40, 2.41].
Some important implications of this relationship, as reported also by Alberti [2.37], are:

- that spatial structure and land use patterns directly influence urban energy flows for example by redistributing solar radiation;
- that the energy requirements of human activities are indirectly influenced by spatial configurations of settlements;
- that spatial structure is an important determinant of future energy supply, distribution systems, and exploitation of ambient energy sources.

Then, since different settlement configurations modify the urban energy flows through: physical changes, induced consumptions and feasibility of using alternative systems to supply resources and services, alternative urban morphologies (structure, patterns, forms) are expected to generate different "energy performances of settlements".

According to the previous assumptions it is possible to define the "energy performances of an urban settlement" as:

- the stock of services that it needs to operate (functions that require energy);
- the stock of energy that it needs to provide the required stock of functions;
- the amount of energy that it needs to import from outside systems.

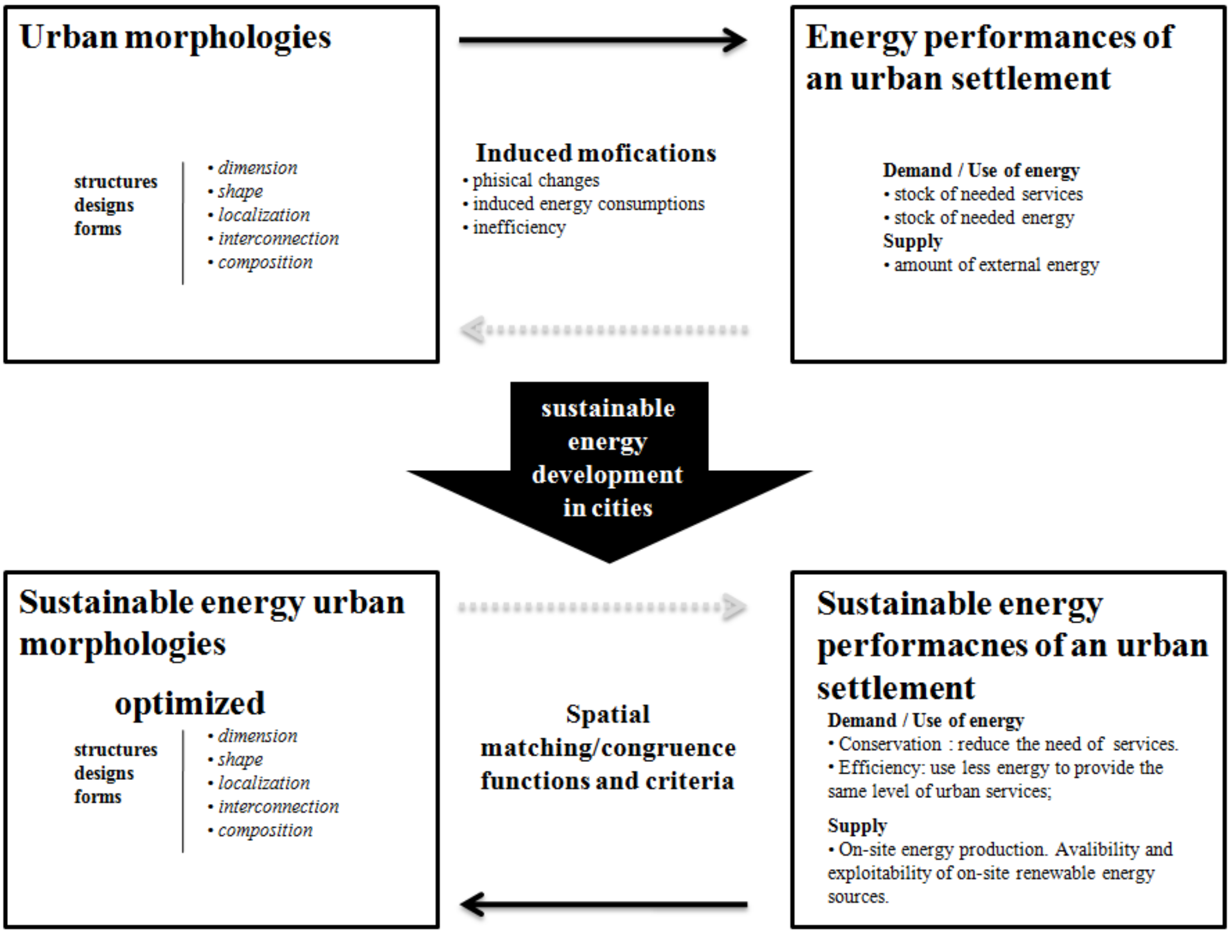
Assuming that urban settlements could be modeled as desired, as Lynch [2.42] stated, "*we must learn what is desirable so as to study what is possible*" it is possible to define the "urban morphologies with sustainable energy performances" those morphologies that are optimized to:

- Maximize the energy conservation: use less energy to achieve a lesser energy function (reduce needs);
- Maximize the energy efficiency: use less energy to provide the same level of function (quantitative and qualitative);

- Maximize the exploitation of on-site and renewable energy sources to match local energy demand.

Figure 4 presents the relationship between urban morphology and energy performances of urban settlements.

Figure 4. The relationship between urban morphology and energy performances of urban settlements.



2.2.4 Urbanization: Compact VS Sprawl. Sustainable energy and urban morphology

It is demonstrated that the trend of urbanization of world population is increasing and current projections indicate that approximately 70 percent of the world's population will be living in cities by 2050 [2.43].

Nevertheless it is necessary to consider that mature and irreversible processes are taking place in the world urban settlement configuration: compact VS sprawl is a very well -known dichotomy [2.44; 2.45]. According to The European Environment Agency [2.46], infact, "*urban sprawl can be described as the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding ag-*

ricultural areas. Urban sprawl is synonymous with unplanned incremental urban development, characterized by a low density mix of land uses on the urban fringe. Sprawling cities are the opposite of compact cities — full of empty spaces that indicate the inefficiencies in development and highlight the consequences of uncontrolled growth. Classically, urban sprawl was fuelled by the rapid growth of private car ownership and the preference for detached houses with gardens. In Europe, cities have traditionally been compact, developing a dense historical core shaped before the emergence of modern transport systems. However, European cities were more compact and less sprawled in the mid 1950s than they are today, and urban sprawl is now a common phenomenon throughout Europe. Moreover, there is no apparent slowing in these trends".

Human being is occupying and urbanizing every accessible place in the world. The last decade has been remarkable for the vast array of literature and intense debate about cities and their global impact. Problems of sustainability have worried governments and research organizations around the world. Cities have been seen as the cause of environmental degradation and resource depletion, casting an ecological footprint across the globe, far beyond their immediate regions [e.g. 2.47, 2.48, 2.49]. Today, it is globally stated that the search of best congruence modalities between environment and human settlements is necessary and urgent.

Despite this international debate a question is still open. Is the compact city more sustainable from an energy point of view?

The answer supported by the current international urban policies assumes that characteristics of an environment which is 'inherently' energy efficient, with low useful energy requirements have much in common with those which allow maximum opportunity for fuel conserving technologies.

So, according to these policies the most sustainable energy urban form it just the one that saves the most of the energy. But which is this urban form and which kind of energy should be saved?

Central to the debate has been the work of the Australian academics Newman and Kenworthy [2.50]. For a number of large cities around the world, they have related petroleum consumption per capita to population density. They found a consistent pattern with higher densities being associated with lower fuel consumption.

The conclusion from the exercise was that, if fuel consumption and emissions are to be reduced, there is a need for policies to promote urban compaction and public transport. A similar message emerged from the ECOTEC study for the UK Government [2.51]. This also produced evidence to suggest that higher densities are associated with less travel. Car travel accounts largely for the differences. People living at the lowest densities travel twice as far by car each week as those living at the highest densities.

This conclusion has been challenged, most notably by Gordon and Richardson, who, in addition to arguing against public intervention generally, criticized the study for underestimating the importance of non-work trips. Concentration in city centres is claimed to reduce journeys but the balance of empirical evidence suggests that it may not [2.51].

Again, Breheny [2.52, 2.53] in his retrospective analysis of population change over the past thirty years, suggests that "*energy savings from urban containment are likely to be disappointingly low*".

In "Energy Planning and Urban Form" Owens [2.54] explores the role of ambient energy sources and development footprints, which facilitate the use of both active and passive solar energy. She concluded that the orientation, density, or spatial needs of these measures imply 'that total reliance on renewable energy sources is not compatible with highly urbanized spatial structures' [2.54]. Some forms of renewable energy future seem at first to be precluded by the kind of compact spatial structures which have many other energy advantages. She advocates "*energy-flexible land use patterns*" which can take advantage of combined heating and power systems, as well as low technology options.

As a conclusion it is possible to state that probably low densities can be sustainable from an energy point of view (or at least no more unsustainable than compact urban forms). Compact, dispersed and multinucleated urban forms are the three choices. Each of them can found pros and cons from an energy point of view.

In achieving energy sustainability the arguments both for and against these positions do not appear to provide conclusive evidence other than marginal gains resulting from changes in urban form alone, unless it is associated with geo-morphological, technological and cultural considerations.

Unfortunately the debate on urban form and energy needs was stopped by the political agenda [2.51]. Given the high political priority afforded to questions of global warming in the sustainability debate, and the knowledge that transport is the fastest growing contributor to CO2 emissions, the Newman and Kenworthy and ECOTEC message has been accepted readily. Newman and Kenworthy made the point that land use planning and hence a focus on densities is likely to remain a major tool for reducing urban energy consumption because of governmental fear of economic measures, and particularly prices [2.51].

This logic, recently adopted by the international community [2.46] , clearly supports a policy of urban compaction, because this would tend to halt or slow down urban decentralization [2.51].

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Chapter 3

3. Methodology

A 'sustainable city' enables all its citizens to meet their own needs and to enhance their well-being without damaging the natural world or endangering the living conditions of other people, now or in the future.' - Girardet (2000)

3.1 City as a system: A complex system approach to human-nature interactions

3.1.1 A Pressure State Response conceptual model for urban-energy systems with focus on urban morphologies

The development of a model to estimate the energy performances of urban morphologies is required by emerging environmental and economical problems (i.e. climate change, oil peak, etc.).

Although present in the environmental debate since the early times, the interest for natural resources in the broad sense came to the forefront of the global scene in the Rio Conference of 1992 and the adoption of Agenda 21. This has boosted the development of economic-environmental accounting.

In OECD countries the prevalent framework for reporting on the state of the environment are the linear Pressure-State-Responses [3.1] and the more detailed variant Driver -Pressure-State-Impacts-Responses introduced by OECD in 1993 [3.4].

As reported also by [3.3, 3.4] our understanding of the world has changed since that time, partly because the achievements of the period (recognition of environmental statistics, production of indicators and regular publication of state of environment reports) have highlighted what has still to be done and the limits of the used environmental accounting approach to solve, for example, the energy and climate change issues.

Rapport and Singh [3.3] reported that the in PSR approach:

- the focus on isolating ''pressures'', ''states'', and ''responses'' tends to provide a static representation of the environment, ignoring the significant dynamic processes that comprise the interactions between these components;
- lacks a 'bottom line' that would provide the policy community and the public with an overall assessment of environmental trends.

They concluded that these limitations can be overcome by adopting an *ecosystem health approach*, which allows for a determination of the overall viability of environments and for the identification of the collective pressures from human activity that threaten that viability. An ecosystem health approach also allows for a more explicit connection between the state of the environment and human well-being.

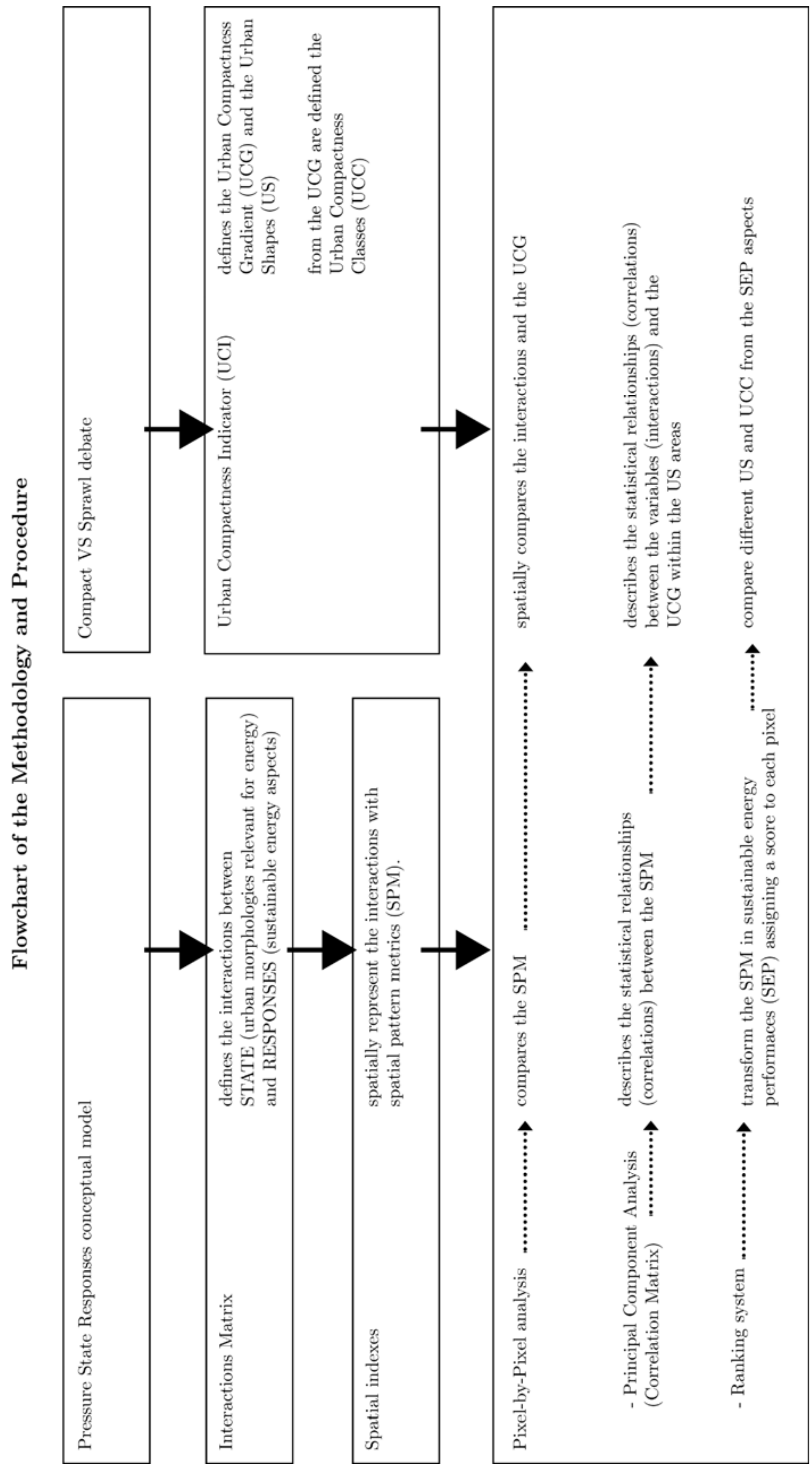
Starting from these considerations Weber [3.4] recently proposed to revise the DPSIR framework focusing on the STATE taken in the broader sense of "socio-ecological system" or "socio-ecological production landscape". Addressing pressure one by one, in fact, is not possible due to the complexity of the environmental system and, moreover, is not enough because positive and negative synergies have to be considered. From an urban energy point of view, for example, the indicators set proposed by the traditional DPSIR, based on the "pressure", is not suitable to measure the energy performances of an urban configuration. To assess all possible pressures it is costly; it is very difficult to add them up to a composite index or a general aggregate.

On the other hand it is necessary to approach the energy performances of urban settlements by the direct observation of the urban system resulting as a consequence of these pressures. Concluding, according to the previous assumptions, the "pressure" approach is not viable to address the energy issues in socio-ecological systems. An approach focused on the State should be used instead.

From an Urban Ecology point of view [3.5] urban settlements can be defined as the places of human-nature interactions: the "socio-eco-logical system". "*As humans transform natural landscapes into highly human-dominated environments, they create a new set of ecological conditions by changing ecosystem processes and dynamics.*" [3.5]

To effectively plan urban settlements that will be ecologically resilient recent advances in Urban Ecology theories propose to start from the idea that humans are an integral part of ecosystems and that cities cannot be fully understood outside of their ecological context.

Figure 5. Methodology flowchart



As reported by Alberti [3.5] "*the evolution of cities as part of nature is hardly new. It dates back at least to Geddes if not much earlier. Anne Spirn noted that an understand-*

ing of the interdependence between cities and nature was already present in the writings of Hippocrates (ca. 5th century BCE), Vitruvius (ca. 1st century BCE) and Leon Battista Alberti (1485)".

Despite this ancient knowledge about human-nature interactions only recently we understood that in studying the ways the humans and ecological processes interact, we must consider that many factors work simultaneously at various levels. Ecologists have primarily studied the dynamics of species populations, communities, and ecosystems in non-urban environments. They have intentionally avoided or vastly simplified human processes and institutions. Social scientists have only primitive ways to represent ecological processes. Neoclassical economics completely disregard the dynamic interactions between land development and environmental change for example using the theory of land rent to explain the behaviors of households, businesses, and governments that lead to patterns of urban development.

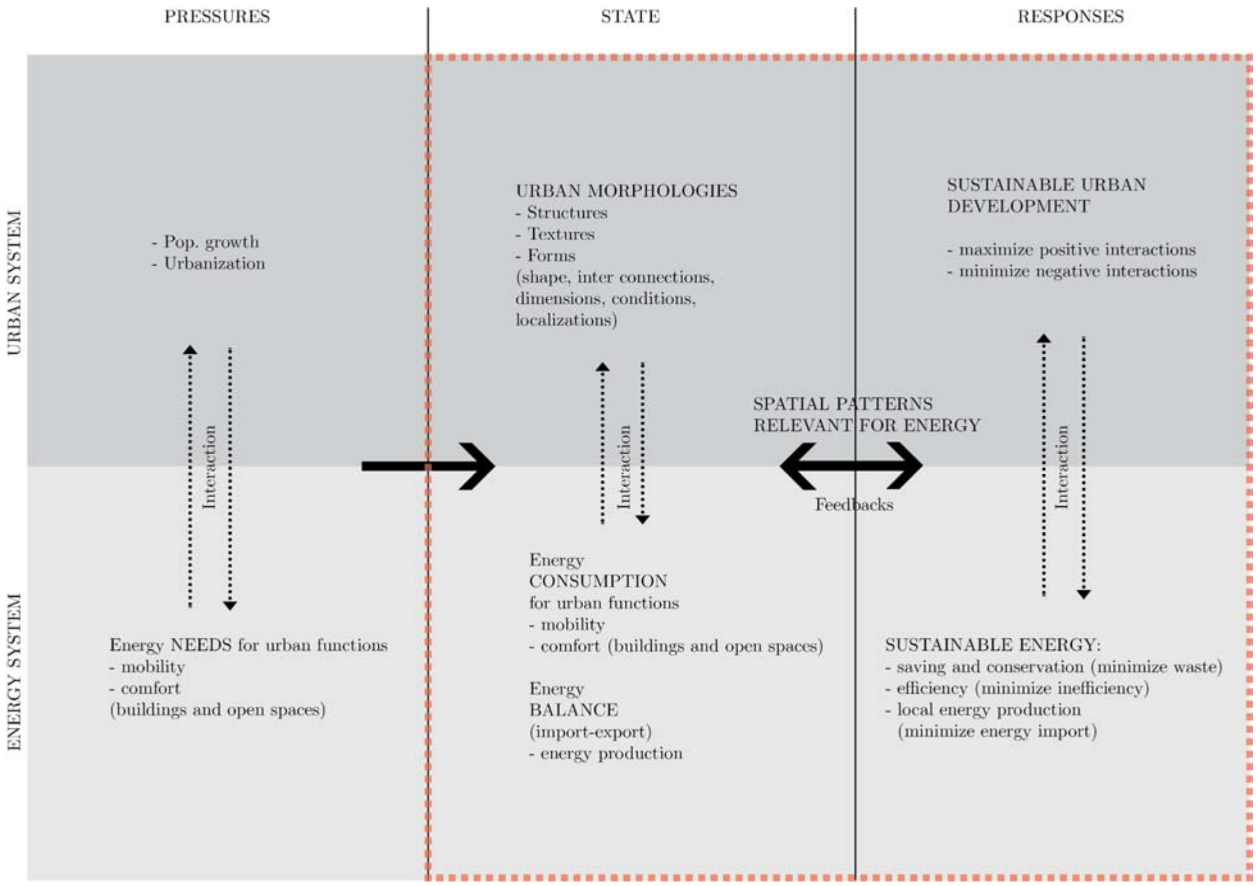
If we simply link traditional disciplinary models of human and ecological systems, we may misrepresent system dynamics because system interactions may occur at levels that our models fail to consider. This is particularly true in urban ecosystems, since urban development controls ecosystem structure and function in complex ways. Furthermore, these interactions are spatially determined. The dynamics of land development and resource uses and their ecological impacts depend on the spatial patterns of human activities and their interactions with biophysical processes at various scales. Humans generate spatial heterogeneity as they transform land, extract resources, introduce exotic species, and modify natural agents of disturbance. In turn, spatial heterogeneity, both natural and human-induced, affects resource fluxes and ecological processes in urbanizing ecosystems [3.5]. Landscape ecology is, perhaps, the first consistent effort to study how human action (i.e., changing spatial patterns) influences ecological processes (e.g., fluxes of organisms and materials) in urbanizing environments.

In this framework it is possible to consider the energy system in cities as an ecological process [3.5] or an ecosystem service, an ecological function that have value to individual or society [3.6] that like other ecological processes is sensitive to spatial configurations. Spatial configurations affects the fluxes of energy resources that ultimately control the underlying urban energy patterns and performances. Vice versa in this context it is possible to hypothesize that, in cities, changes in spatial configurations of urban morphology can modify the fluxes of energy resources and then control urban energy patterns and performances.

But as Lynch [3.7] suggested in *A Theory of Good City Form* "we must learn what is desirable so as to study what is possible". A gap exists between the "optimum" urban morphology that provides the best energy patterns and performances and the existing urban morphologies. This gap is the measure of the distance between what is possible

to obtain from urban re-design, renewal, reconversion of an existing urban settlement and the existing conditions.
Linking all the consideration explained above the research proposes a Pressure State Response conceptual model for Urban-Energy systems with focus on urban morphologies.
The hypothesis is that focusing on the State, considered as the state of the interaction between energy system and urban morphology (quantity, quality, structure and functioning of the physical part of a urban settlement) it is possible to synthesize all the pressures and changes in spatial patterns that determine energy conditions in urban settlements. Afterward linking this resulting patters to expected "sustainable energy performances" it is possible to assess the state of "urban morphologies energy performances" from a sustainable energy point of view.
The Pressure State Response conceptual model for Urban-Energy systems is presented in Figure 6.

Figure 6. Pressure-State-Responses for urban-energy system with focus on urban morphologies.



The PRESSURES are determined by the interaction between, on the one hand Popula-

tion growth and urbanization process, and on the other hand by the energy needs for urban functions, mainly for mobility and built environment (buildings and open spaces comfort).
The STATE is explained on the one hand by the interactions between the resulting urban morphologies (structures, textures, forms) and on the other hand by the energy consumption for urban functions that determine the energy balance.
The RESPONSES are, from the energy point of view, the “sustainable energy targets” that determine actions for energy saving and conservation, efficiency and production from renewable energy, and from the urban morphology point of view the design of morphologies that can maximize the positive interactions and minimize the negative interactions with sustainable energy targets.
Assuming that the pressures cannot be diminished because this should limit the (population) growth the iterations between state and responses will determine, in the urban design context, sustainable energy performances of urban morphologies.

3.1.2 Modelling: Urban metabolism VS Pattern Oriented (POM)

Cities are complex, self-organizing systems that evolve through a multitude of mainly bottom-up decisions and actions. However, the spatial organization that emerges profoundly affects how efficiently the system as a whole uses energy and processes materials. Complex systems typically keep the modelers from building models that are too simple in structure and mechanism, or too complex and uncertain. Exciting progress has been made in modeling urban metabolism, including energy dynamics, and developing an integrated theory of how cities evolve. These approaches, that aims to model the urban dynamics thought a very detailed representation of the “real word”, similar to a “virtual reality” approach [3.8], uses very complex mathematical models that need a lot of information as input and are very difficult to be managed. They aims, for example, to model the city object by object, building by building, road by road, tree by tree, person by person. These models are very comprehensive but also very expensive in terms of data needs and computational resources.
Recently a new theory to address the complex-systems analysis applied to ecosystems' modeling. This is called Pattern Oriented Modeling (POM) strategy and it has been presented to the scientific community and published in the Science Magazine [3.10].
The POM is presented as a way to focus on the most essential information about a complex system's internal organization.
POM follows the basic research program of science: the explanation of observed patterns [3.9].
Patterns, in the POM model, are intended as observations of any kind showing nonrandom structure and therefore containing information on the mechanisms from which

they emerge. Complex systems contain patterns at different hierarchical levels and scales.

In the words of Grimm et al [3.9]. "*Ecosystems, for example, contain patterns in primary production, species diversity, spatial structure, dynamics of component species populations, behavior of individual organisms, resource dynamics, and response of all these to disturbance events and stress. Useful patterns need not be striking; qualitative or "weak" patterns can be powerful in combination. For example, we can easily identify a person in a crowd even without a strong pattern (e.g., a photograph) by using a set of weak patterns: sex, approximate age, hair color, size, etc. Each of these characteristic patterns excludes many individual*".

Patterns are defining characteristics of a system and often, therefore, indicators of essential underlying processes and structures. Patterns contain information on the internal organization of a system, but in a "coded" form. The purpose of POM is to "decode" this information.

The motivation for POM is that, for complex systems, a single pattern observed at a specific scale and hierarchical level is not sufficient to reduce uncertainty in model structure and parameters.

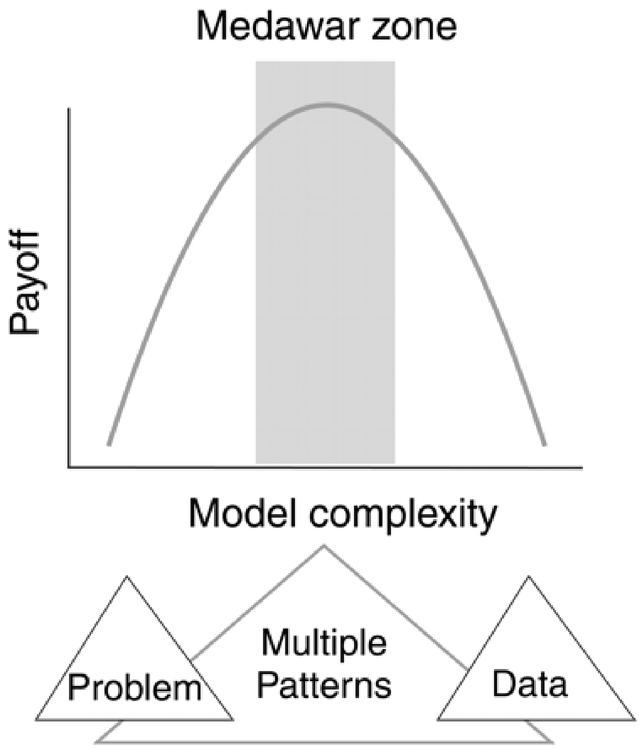
Thus, in POM, multiple patterns observed in real systems at different hierarchical levels and scales are used systematically to optimize model complexity and to reduce uncertainty.

Finding the optimal level of resolution in a bottom-up model's structure is a fundamental problem. If a model is too simple, it neglects essential mechanisms of the real system, limiting its potential to provide understanding and testable predictions regarding the problem it addresses. If a model is too complex, its analysis will be cumbersome and likely to get bogged down in detail.

The way to find an optimal zone of model complexity is defined in the POM theory as the "Medawar zone" (figure 7).

"Payoff of bottom-up models versus their complexity. A model's payoff is determined not only by how useful it is for the problem it was developed for, but also by its structural realism; i.e., its ability to produce independent predictions that match observations. If model design is guided only by the problem to be addressed (which often is the explanation of a single pattern), the model will be too simple. If model design is driven by all the data available, the model will be too complex. But there is a zone of intermediate complexity where the payoff is high. We call this the "Medawar zone" because Medawar described a similar relation between the difficulty of a scientific problem and its playoff. If the very process of model development is guided by multiple patterns observed at different scales and hierarchical levels, the model is likely to end up in the Medawar zone." [3.9]

Figure 7. The Medawar zone [3.9]



Modeling has to start with specific questions. From these questions, it is possible to formulate a conceptual model that helps us decide which elements and processes of the real system to include or ignore. With complex systems, however, the question addressed by the model is not sufficient to locate the Medawar zone because they include too many degrees of freedom. Moreover, the conceptual model may too much reflect our perspective as external observers, with our specific interests, beliefs, and scales of perception.

A key idea of POM is to use multiple patterns observed in real systems to guide design of model structure. Using observed patterns for model design directly ties the model's structure to the internal organization of the real system.

To develop a Pattern Oriented model the question to be answered is: "What observed patterns seem to characterize the system and its dynamics, and what variables and processes must be in the model so that these patterns could, in principle, emerge?"

This use of patterns might force us to include state variables and processes that are only indirectly linked to the ultimate purpose of the model and are not part of our initial conceptual model. Ideally, the patterns used to design a model occur at different spatial and temporal scales and different hierarchical levels, because the key to understanding complex systems often lies in understanding how processes on different scales and hierarchical levels are bound to each other.

Again, according to Grimm et al. [3.9] when designed to reproduce multiple patterns,

models are more likely to be "structurally realistic". In particular, model components correspond directly to observed objects and variables, and processes correspond to the internal organization of the real system, so that the model "not only reproduces the observed real system behavior, but truly reflects the way in which the real system operates to produce this behavior" [3.11].
The method proposed in this research apply the POM to the complex system "urban morphology – energy performances" assuming the model components as the urban morphology spatial patterns and the processes as their sustainable energy performances.

3.1.3 A Urban Compactness gradient

According to [3.5] and [3.12] urban compactness gradients can effectively measure urban compactness spatial patterns (compact VS sprawl). Gradients have been applied to study the human impact on ecosystems. Alberti [3.5] hypothesized that predictable landscape patterns can be observed along a gradient of human-induced changes—from urban to suburban, cultivated and managed to natural. The gradient paradigm has also been proposed as an effective approach to studying the urbanizing landscape. Again Alberti [3.5] suggests that ecological conditions in urbanizing regions can be systematically analyzed by quantifying changes in ecosystem structure and function in relationship to varying levels of urbanization. According to [3.5] formal hypotheses about the relationships between urban gradients and ecosystem functions have been developed, and a number of studies have been conducted or are underway to empirically test them in diverse urban regions.
Traditional approaches to urban-to-rural researchers have tended to simplify the actual urban spatial pattern to a few aggregated variables such as population density or built-up density, both of which are expected to change predictably with distance from the urban core. Settlements, with this instrument, are visually described in relation to their changes in internal density: as agglomerations with concentric rings of development surrounding a dense core, as polycentric "archipelago" settlements, as dispersed dots in a rural area.

Integrating urban compactness gradient analyses with spatial pattern metrics (SPM) of energy performances can be a good strategy to more effectively link urban development patterns to their energy performances.
Such density metrics in fact add important elements to test hypotheses about the relationships between urban morphologies and energy. Of course, it is also crucial to consider the scale at which the density is studied. Different density patterns can be observed if we measure these parameters at the scale of the neighborhood, city, or metropolitan area.

The European Environment Agency [3.13] in the MOLAND project suggests three aspects to be included in the urban density analysis that are: Built-up volume, and Population.
The research assumed these variables to develop a urban density gradient applied to the case study. The urban density gradient was then compared with the spatial pattern metrics of energy performances.

3.2 Sustainable energy and urban morphologies: an integrated PSR-POM approach for urban - energy systems

3.2.1 Description of the interactions between urban morphologies and sustainable energy concept

In the following paragraphs I included different aspects of sustainable energy that, according to the literature, become important in the design of urban morphologies with sustainable energy performances.

Energy Saving and Conservation

Micro climate design of urban morphologies

Human thermal comfort is defined by ASHRAE as the state of mind that expresses satisfaction with the surrounding environment [3.13]. Maintaining thermal comfort for occupants of buildings or other enclosures is one of the main energy consumer human activity in urban settlement especially in mild to harsh climate zones (warming) and in hot humid climate zones (cooling).
In general the difference between the external climate (mainly defined by temperature and humidity and the desire climate is used to measure the energy needs to reach the thermal comfort [3.14]. Different latitudes of the world determine thermal comfort needs variations based on climate [3.15]. At the same latitude what can differentiate climate conditions in the same rigion is the altitude. Expecially in mountain regions thermal comfort needs may vary based on climate zones. A spatial classification of climate zones according with the regional climate conditions (e.g. altitude, temperature, precipitation and wind velocity) can help to better understand the relationship between energy needs for the thermal comfort of an urban settlement and its morphology and localization [3.16].
Particularly in the temperature zones on the planet the costs are associated with increases in energy demand for cooling in the summer and heating in the winter [3.17].

Smart location of urban settlements can reduce the energy needs for the climate comfort in urban environments. A 1 degree C° increase in average temperature decreases residential space heating needs by 6 to 10 percent and increases space cooling needs 5 to 20 percent [3.18].
In meteorology and climatology, geographical data plays a key role. This requires not only synoptic data about weather elements from many years, but also data about the geographical environment. This data significantly influences spatial distribution of meteorological elements that are shaped and influenced by geographical factors. Mainly, but not solely, the applied data pertains to the topographic profile. For instance, air temperature is clearly correlated with the height above sea level, distance from water reservoirs, slope, longitude and latitude [3.19].
Cities, however, create their own climate. The most important factors are the change of the natural surface characteristics into artificial structures with artificial materials. This results in changes of the biosphere with less green covered surfaces with a pronounced effect on the physical environmental conditions of radiation, wind, temperature and Humidity [3.19, 3.20, 3.22].
Air temperature in densely built areas is higher than in the rural surrounding country [3.24, 3.21]. The prime factors are the increased absorption of heat caused by the changed land cover and the ability of these structures to store heat very effectively. Heating and other increased energy use contribute to increased outdoor temperature during winter at high latitudes. At lower latitudes, air conditioning increases outdoor temperatures. The forced drainage of rainwater is changing the water balance and less vegetation gives less evaporative cooling which also contributes to the urban heat island effect [3.25].
In cold climates the urban heat island can be beneficial in reducing the heat demand, but in warm climates the urban heat island effect can significantly worsen the outdoor comfort and the energy demand for buildings. The intensity of the urban heat island can be up to 12 °C depending on the size of the city. The bigger the city the more intense is the effect [3.19, 3.20, 3.22].
Urban morphology has an important role in shaping of urban heat island phenomena. Intelligent city planning can neutralize, for instance, the intensified heat island effects brought about by unlimited growth of cities, raising densities, and climate change effects. Intelligent use of cladding materials and surfaces can decrease temperatures in zones where it is required, e.g., on roof tops in summer and above pavements [3.26]. For this reason the urban design and planning should be involved in the research and/ or the solutions to this problem.
Several authors [3.19, 3.20, 3.21, 3.22, 3.23, 3.24] reported in fact the relationship between structural and morphological aspects of urban settlements. These relationships

include:

- The air temperatures are driven by the heating of urban surfaces, since many man-made surfaces absorb more of the sun's heat than natural vegetation does;
- The urban building materials are impermeable and watertight, so moisture is not readily available to dissipate the sun's heat;
- The areas with the least vegetation and greatest development tend to be hottest;
- Temperature of dark, dry surfaces in direct sun can reach very high temperature during the day;
- Vegetated surfaces with most soil under the same conditions reach only lower temperature;
- Dark materials in concert with canyon like configurations of buildings and pavement collect and trap more of the sun's energy;
- Heat islands tend to become more intense as cities grow larger.

From an urban morphology point of view, these characteristics can be sorted into the four main causes of heat island formation: (1) reduce evaporation; (2) increased heat storage; (3) increase net radiation; and (4) reduced convention. These can, according to [14] be shown as in Table 1 below.

Table 1. Characteristics of Urban Heat Island formation form an urban morphology point of view.

MORPHOLOGICAL ATTRIBUTE	ENERGY IMPACT
Lack of vegetation	Reduces evaporation
Widespread use of impermeable surfaces	Reduces evaporation
Increased thermal diffusivity of urban materials	Increases heat storage
Low solar reflectance of urban materials	Increases net radiation
Urban geometries that trap heat	Increases net radiation
Increased levels of air pollution	Increases net radiation
Urban geometries that slow wind speeds	Reduces convection
Increased energy use	Increases anthropogenic heat

Cool surfaces (cool roofs and cool pavements) and urban greening can have a substantial effect on urban air temperature and hence can reduce cooling-energy use. On a small scale the shading and shadowing effects of trees will reduce the energy used to cool down buildings [3.27]. At a large scale, the evapotranspiration from vegetation and decreased reflection of incoming solar radiation by green surfaces and increasing refection by high reflective surfaces will cool a urban settlement a few degrees in the summer [3.28]. The urban green morphology is a proxy for the microclimate prediction of a settlement [3.29].

Passive solar design of urban morphologies

Originally passive solar design refers to a number of intelligent building design techniques that reduce or eliminate the use of fossil fuels and electricity for heating, cooling and lighting buildings (during the day). The modern version of this traditional approach to building design was developed beginning in the 1970s. The idea behind passive solar design was to incorporate sunlight and natural ventilation into the basic design of the building, minimizing the need for mechanical systems. In many of the hot, arid climate zones, this is an excellent design strategy. In hot, humid zones, more focus needs to be given to ventilation and less to heating.
But a city is more than the sum of its buildings. Extending this concept to urban morphology it is possible to make some considerations.
In the words of Owens and Cope [3.30] "*the harnessing of solar energy by appropriate design (passive solar energy) can lead to significant savings in conventional fuel at little or no economic or environmental cost. There are two separate but related elements to consider. First, houses can be designed to take advantage of solar gain, for example by including wide frontages, large glazing areas on the south elevation and conservatories. Such buildings are often referred to as 'passive solar houses'. The other element relates to the siting, orientation and layout of buildings to maximise solar gain and avoid overshadowing. Even conventional houses can take advantage of these factors to make small energy savings (of the order of one per cent), but they become more critical for houses designed with passive solar energy in mind. Empirical evidence demonstrates that in the optimal situation (passive solar houses on an ideal site) energy demand for space heating might be reduced by 11—12 per cent. Research suggests that* with attention to layout and orientation, 80 per cent of these maximum possible savings can be achieved in passive solar houses on real sites with densities up to 40 dwellings per hectare. At higher densities it becomes difficult to avoid some houses being seriously obstructed or having poor orientation. The most significant constraints are likley to occur on urban sites which tend to be small (typicaly 0.5 hectares), developed to a high density (40—80 dph) and overshaded by existing buildings.
Built form exerts a systematic influence on energy requirements for space heating. Other things being equal, detached houses require as much as three times the energy input of intermediate flats. Though in practice a large number of variables determine heating requirements' a trend towards built forms like terraced housing or low rise flats could result in significant reductions in energy demand ".

Another aspect of energy saving and conservation of urban morphologies is the Natural lighting. Indoor and Outdoor Lighting is needed by urban settlements to provide the ambient comfort. Artificial lighting of spaces consume energy. Natural lighting of buildings interiors and of outdoor spaces from daylight, instead, save energy and improve the climate comfort [3.31, 3.32, 3.33]. At a regional scale Natural Lighting is affected by land morphology, especially in mountainous regions (for an example see the case of Rattemberg town [3.52]. At the Urban scale it is affected by the interactions between urban objects (buildings, trees, etc) and the sun's path [3.31]. A Smart localization and a optimized design of urban settlements can improve the natural illumination of indoor and outdoor urban spaces, saving energy [3.34].

Proximity design of urban morphologies

The concept "access by proximity" [3.35, 3.36, 3.37, 2.59] can be attributed to Register descriptions of the benefits of locating urban activities close together to save energy and resources [3.37]. Register was inspired by Soleri's arcological imaginings and his concept of super-dense, car-free, cities that exploited three-dimensional form in order to maximise the proximity of people and activity, reducing energy and resource requirements [18]. Register maintains that "*the primary principle at the base of both evolutionary change and city functioning has to do with access by proximity, that is, the occurrence of many things and functions close together*" [3.35, 3.36]. Reflecting Soleri and de Chardin's views, he relates this to the evolutionary imperative by observing that evolution "*seems to move toward ever more functions at ever smaller physical distances*" [3.37, 3.36, 2.59].
With a similar concern for reducing unnecessary traffic and increasing social interchange, Engwicht concluded that the very purpose of cities was to maximise exchange whilst simultaneously minimising travel [3.35, 3.36].
Having people live where they work is a key element in obtaining effective and meaningful levels of local control, reduction of commuting is important in obtaining better energy efficiencies and both measures lead logically to concepts of 'proximity planning and design' (putting workplaces and services near to habitations). Mixed-use urban environments improve proximity (of workplace, shopping,daycare, and other basic services to habitations).
Proximity planning favours pedestrian and bicycle access over all others with wheeled transport and other mechanical means of moving people or goods used as a last resort.
Bikeability and walkability are two terms to define the attitude of a place to be cycled or walked. Landslope affect bikeability and walkability [3.38]. Especially in mountains regions the location of an urban settlement can, a priori, determine the attitude of its inhabitants to use "sustainable energy transport" modalities for local mobility [2.59].

Density design of urban morphologies

District Heating and Cooling suitability (DHC)
DHC is an integrative technology that can make significant contributions to energy saving.
The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating and cooling.
The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. [3.39] In many countries with long district heating tradition, such as is the case in Scandinavia, district heating is well developed and the market development has been slowed by increased use of energy efficiency measures in buildings. When available at all, district heating reaches often about 80 -90 % of the central city area, for example in Helsinki.
The problem with this technology is the urban building density that determine the heat density demand. Systems with low heat density are struggling with relatively high investment costs and high heat losses. [3.39] Building density patterns can be used as a proxy to estimate the suitability of DHC technologies in urban areas.

Energy efficiency

Transport modalities and urban morphologies

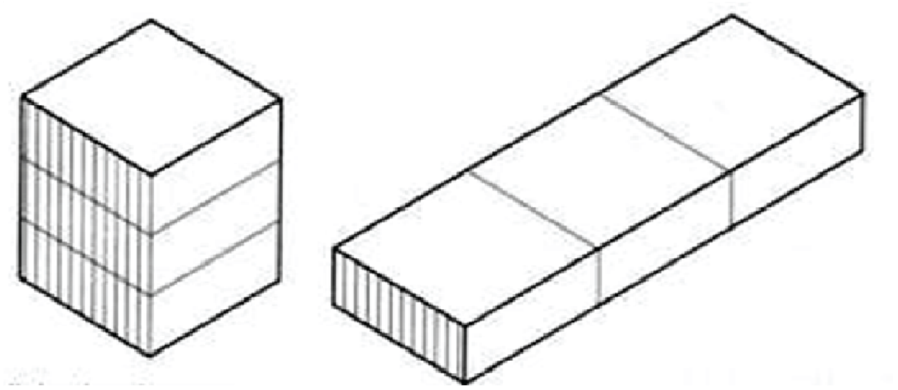
Bicycle is the most energy efficient transportation mode. It is 3 times more efficient than walking, 5 times more efficient than using the train and 15 to 20 times more efficient than driving a car [3.40].
According to [3.46] use of space by motorized traffic facilitates the movement of the motorist, but reduces the accessibility of others as transport routes become barriers, as parked vehicles form obstacles for pedestrians and cyclists. Car dependency results in traffic domination in urban areas, sometimes splitting communities. From the urban morphology point of view the roads that mostly affect the “energy efficient transport” with space fragmentation and road un-safety are the second level roads : arterial and collectors.
Arterials are major through roads that are expected to carry large volumes of traffic. Arterials are often divided into major and minor arterials, and rural and urban arterials. Collectors collect traffic from local roads, and distribute it to arterials. The pri-

mary roads are the roads that provide largely uninterrupted travel for motorized traffic connecting remote distances. Local roads (third level) have the lowest speed limit, and carry low volumes of motorized traffic and are then compatible with bikeability and walkability.

An energy efficient transport system should use public transport and primary roads to provide regional connections, reduce the secondary road network in urban areas in favor of public transport and third level road network.

Building compactness

Figure 8. Building compactness



Theoretically, to minimize heat transfer through the building envelope the building shape should be as compact as possible, tending toward a cube. However, other factors influence heat transfer through the building envelope:

- Temperature of ground, air or snow with which the building envelope is in contact;
- The direction and speed of winds blowing at the building;
- Solar radiation incident on the building.

Building compactness is given by the ratio S/V. According to [3.41] in hot dry climates the S/V ratio should be as low as possible to minimize heat gain. In cold-dry climates S/V ratio should also be as low as possible to minimize heat losses. In warm humid climates, the primary concern is to create airy spaces; this might not, however, necessary minimize the S/V ratio.

From an energy efficient urban morphology point of view building compactness is preferable.

Public Transport

Decentralization of cities has been facilitated by the car, in combination with efficient

public transport. This has resulted in a substantial growth in trip lengths and patterns that are dispersed rather than concentrated
on the city centre. This in turn increases car dependence and reduces the possibilities of promoting efficient public transport [3.39].
From the urban morphology point of view the density of public transport infrastructure weighted by the public transport frequency is a proxy for the public transport accessibility of an urban settlement.

Renewable Energy source exploitation

A recent report by IEA/OECD [3.44] stressed the opportunity and the feasibility to integrate Renewable Sources of Energy (RES) in city design to obtain more sustainable urban areas. This will reduce cities dependence from fossil energy, and lower their carbon footprint. According to this report, capturing and converting renewable energy within cities can be promoted by a suitable design of the built environment and of land uses at local scale.
Unfortunately, last century's settlements were rarely designed to optimize the use of renewable energy. In the words of [3.43] "Usually, when urban planners start the design of a new settlement, they look for pre-existing landmarks, such as roads, railways, rivers, etc. and align the new buildings and streets accordingly. Very rarely do they look for the most ancient pre-existing landmarks: the path of the sun and prevailing winds".
Attempts to increase renewable energy use in cities have focused mainly on the improvement of the energy performances of buildings [3.43, 3.42]. In this context, construction schemes, such as Passive and/or Active Houses Design, have been developed and applied, enabling the integration of technologies into the roof and façade of buildings to capture the renewable energy directly for internal use, as well as for the export of surplus. However, the unsuitable location of buildings can reduce the benefits of these technologies. Knowledge of the availability of RES in a given region is fundamental to assess the potential supply to future urban developments. Hence, the location, the spatial distribution and the intensity of RES are key factors to support the design of "renewable settlements" [3.42].
The distribution of RES depends on physical and environmental factors. For example, solar energy depends on latitude, climatic variables (in particular cloud coverage and atmospheric turbidity) and terrain morphology (slope and aspect); ground source heat pump potential (GSHP) depends on geological characteristics and the presence of groundwater; wood biomass potential depends on forest cover. By analyzing such characteristics it is possible to estimate the spatial distribution of the potential energy supply from RES of a given region. Some RES (i.e. solar and geothermal heat), cannot be simply moved from a location to another, hence the design of renewable settlements

requires to spatially match energy supply and demand. This can be performed only if reliable knowledge, with a suitable spatial resolution, is available on the distribution of RES [3.45]

From the urban morphology point of view the patterns of RES potential determine the suitability in the use of these energy sources in urban settelements but the same structural and spatial configuration of urban morphologies determines RES potentials [3.45].

3.2.2 Scales

According to the sustainable development debate the tree components of sustainability in the city are Economic, Social, Environmental and have to be considered together.

The challenge of finding a sustainable urban morphology has induced to propose new frameworks for the redesigning and restructuring of urban places to achieve a higher level of sustainability [3.47].

These approaches have been addressed on different spatial scales:

- *the regional and metropolitan scale*;
- *the city/urban scale*;
- *the neighborhood/community scale;*
- *the building scale.*

A critical review of these approaches demonstrates a lack of agreement about the most effective analytical scale in the context of sustainability [3.47].

From the sustainable energy point of view some critical analysis can lead to the same considerations.

According to [3.48] different aspects of spatial structures of settlements become important, if related to energy, as we move across various scales (Figure 8).

Figure 8. Significant (urban) structural variables at different scales (relevant for energy) [source: 3.48].

Structural variable	Scale
Settlement pattern (for example, size and spacing of settlements, etc)	regional
Communication network between settlements	subregional
Size of settlement (area)	
Shape of settlement (circular, linear, etc)	
Communications network within settlement (radial, grid, etc)	individual settlement
Density	
Interspersion of land uses	
Degree of centralisation of facilities	
Layout (estates, etc)	neighbourhood
Orientation (of buildings or groups of buildings)	
Siting (in relation to microclimate)	building
Design	

In geography anyway, the notion of scale can be a source of ambiguity. It is always used in the sense of spatial resolution, but it can just as well refer to cartographic representation or *levels* of observation and analysis.
Today, we no longer have to demonstrate that the analysis of a spatial event is directly linked to the geographical level of observation representing granularity, i.e. the *order* of magnitude chosen for the analysis. This leads to the consideration of space in relation to different orders of magnitude, each defining distinct perception levels. Moreover as the notion of scale is connected to the notion of measure of space or time going from one scale to another means changing units of measure.
The method proposes the following scales, or order of magnitudes, for the spatial analysis:

Table 2. Analytical scales

Spatial Scale	Topographic scale	Raster resolution
Regional and metropolitan scale	1:100.000 – 1:25.000	Da 500 m a 250 m /px
Urban scale	1:25.000 – 1:10.000	Da 250 m a 100m /px
Neighborhood scale	1:10.000 – 1: 2.000	Da 100m a 25m /px

With the development of geographic information systems (GIS), the acquisition of knowledge at different scales and the transition from one level to another are becoming technically easier. However, this creates new conceptual and methodological problems. Processing and management of data at different geographical scales will now become multidisciplinary. In the case of energy performances of urban morphologies the disciplines involved are at least: urban planning and design, spatial analysis, statistic, engineering, technical physics, ecology.

3.2.3 The Interaction matrix

Driving from the considerations presented in the precedent paragraphs about analytical scales and interactions between sustainable energy and urban morphologies, an interaction matrix that systematize these relationships is presented.
The aim of this tool is to prepare the analytical framework for the analysis of the spatial relationships between urban morphologies and sustainable energy performances.
The matrix is based on the PRESSURE-STATE-RESPONSE conceptual model presented in Chapter 3.
In the X axes we find the STATE represented by different urban morphologies ordered by scale (regional, urban and neighborhood) and by urban function (urban comfort,

mobility, energy production).

In the Y axes we find the RESPONSES, represented by three aspects of sustainable energy (saving and conservation, efficiency and renewable energy).

The output of the matrix is then used to define the set of spatial indicators to describe the spatial patterns of energy performances of urban morphology.

The structure of the interaction matrix is presented in Figure 9, while the complete interaction matrix is presented in Figure 10.

Figure 10. Multiscale structure of the interaction matrix

	RESPONSES				
STATE			Energy saving and conservation	Energy Efficiency	Renewable energy production
	Regional scale		INTERACTIONS		
		Comfort			
		Mobility			
		Production of energy			
	Urban scale				
		Comfort			
		Mobility			
		Production of energy			
	Neighborhood Scale				
		Comfort			
		Mobility			
		Production of energy			

Figure 11. The interaction matrix. C=Comfort; M=Mobility; P= energy Production

			RESPONSES		
			Saving and Conservation	**Efficiency**	**Renewable Energy Sources**
		Regional scale morphologies			
STATE	C		Local climate conditions		
	C		Natural sun exposition / lighting		
	M		Road network slope		
	M			Intermodal connections of main transport networks	
	M			Main road network density	
	P				Solarpower potential of land
	P				Hydropower potential of land
	P				Biomasspower potential of land
	P				Windpower potential of land
					Geothermalpower potential of land (high temperature)
		Urban scale morphologies			
	C		Urban Heat Island aptitude		
	C			Building thermal conservation	
	M		Housing and urban services proximity		
	M		Housing and job proximity		
	M			Secondary road network density	
	M			Public transport accessibility	
	P		District Heating and Cooling suitability		
	P				Hydropower potential from drinkable water plant
					Ground source heat pump (GSHP) potential
		Neighborhood scale morphologies			
	C		Natural illumination of buildings		
	C		Green area factor		
	M			Walkability and bikeability	
	P				Photovoltaic and thermal potential energy of roofs and facades
	P				Windpower potential on buidings roofs

3.2.4 Tools

3.2.4.1 The Indicators set: energy performances of urban morphologies

From the interactions matrix a set of spatial indicators is derived. These indicators are given in form of spatial patterns metrics. Every spatial pattern metric can finds in literature several ways to be calculated. For ease of presentation the procedures to obtain the indicators are not described in this section. Table 3 contain the list of the spatial patterns metrics and the corresponding references in literature. In the case study section, instead, the procedure followed to obtain each single metric is described.

Table 3: The indicators set: spatial patterns metrics and the corresponding references in literature

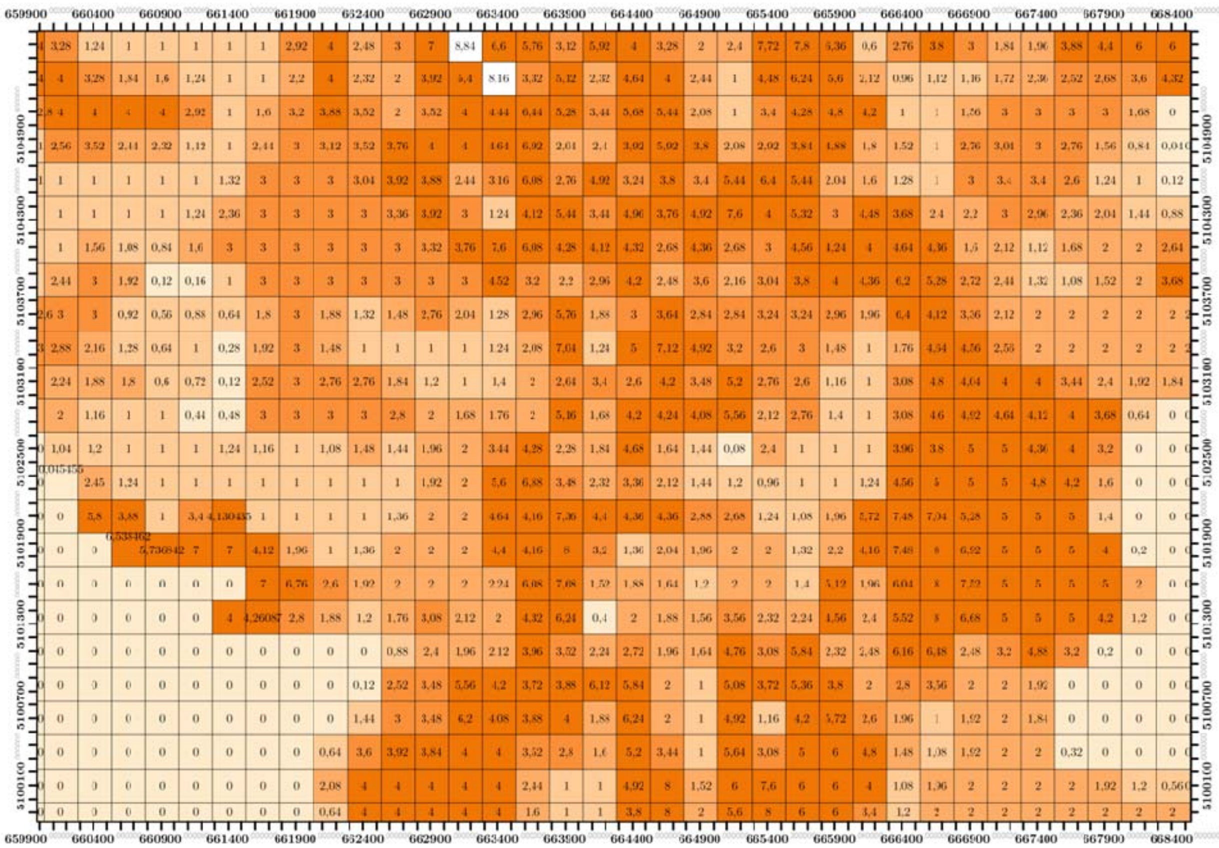
Interaction	**spatial index**	**References**
Local climate conditions	Climate zones	[5.1]
Natural sun exposition / lighting	Available hours of light / m2 /day	[5.19, 5.21, 5.34]
Road network slope	Land slope	[5.24], [5.35]
Intermodal connections of main transport networks	Spatial density of interconnections between different transport networks	[5.24], [5.34]
Main road network density	Spatial density of main road network	[5.19, 5.21, 5.34]
Solarpower potential of land	Incident sun beam irradiation in W/m2/day	[5.19], [5.28]
Hydropower potential of land	Gwh/year/km2	
Biomasspower potential of land	Potential m3/ha/year	[5.29, 5.30, 5.31, 5.32, 5.33]
Windpower potential of land	Potential Mwh/year/km2	[5.12]
Geothermalpower potential of land (high temperature)	Potential Mwh/year/km2	[5.12]
Urban Heat Island aptitude	Overheating aptitude of surfaces	[5.27, 5.34]
Building thermal conservation	Building compactness	[5.27, 5.34]
Housing and urban services proximity	Spatial density of urban services	[5.27, 5.34]
Housing and job proximity	Job density	[5.24], [5.35]
Secondary road network density	Spatial density of secondary road network	[5.24], [5.35], [5.24], [5.35]
Public transport accessibility	Public transport stops density/ frequency of public transport	[5.24], [5.35]
District Heating and Cooling suitability	Building density	[5.27], 5.19]
Hydropower potential from drinkable water plant	Potential Kwh/year/drinkable water plant	[5.12]
Geothermal potential of district (low temperature)	GSHP suitability	[5.19], [5.28]
Natural illumination of buildings	Avaliable h/light/m2 on building surface	[5.12]
Green area factor	Normalized Difference Vegetation Index (NDVI)	[5.28]
Walkability and bikeability	Spatial density of tertiary road network	[5.35]
Photovoltaic and thermal potential energy of roofs and facades	Incident sun beam irradiation on buildings surfaces (roofs and facades) in w/m2/day	[5.19]
Windpower potential on buidings roofs	Potential Kwh/day/building unit	[5.19], [5.28]

3.2.4.2 Pixel by pixel analysis

Spatial indexes are rendered in raster images of a standard resolution to permit the use of the pixel-by-pixel comparison approach [1]. Each pixel refer to a land unit, according to the spatial resolution of the grid, and represent the value of the spatial index. The pixel composition renders the spatial patterns of the indexs. Traditional pixel-by-pixel comparisons involve overlaying mappings to evaluate the similarity between two or more maps.

Figure 12 give an example of the resulting maps.

Figure 12. Render of a spatial pattern metric in a grid form (urban services density, City of Trento).



3.2.4.3 Multivariate statistical analysis

Once the locations have been characterized, the intensity and the types of spatial differentiations have been determined, and the similarities and contrasts have been brought to light, the next task consists of finding the relationship between these features of spatial organization and to determine the exchanges these locations maintain among each other, as well as the mutual influences they have on each other: the interactions driven by spatial organization [3.50].

Multivariate Statistical Analysis applied to raster images (MSARI) is selected to examine relationships among the spatial patterns metrics that are treated as variables. The MSARI technique allows exploration of relationships between many different data layers or types of attributes [3.51]. The Multivariate statistics is a form of statistics encompassing the simultaneous observation and analysis of more than one statistical variable. In particular the Principal Component Analysis (PCA) involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. It is mathematically defined as an orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection of the data comes to lie on the first coordinate (called the first principal component), the second greatest variance on the second coordinate, and so on [3.51]. In particular the correlations matrix is used to verify the relationships between the variables and to identify positive and negative correlations between them.

3.2.4.4 A ranking system

Finally a ranking system is used to assign scores to each aspect of "sustainable energy performances". In particular, arbitrary thresholds derived by literature are used to assign a score to each pixel for each spatial index. The scores are then summed for each pixel and for each spatial index belonging to a sustainable energy performance aspect (Saving and Conservation, Efficiency and Renewable energy production). The resulting maps are used to visually appreciate the differences in sustainable energy performances for the urban settlements areas.

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Chapter 4

4. Remote sensed datasets: new frontiers for the construction of a dataset for urban-energy planning and design

Remote Sensing is a powerful tool to assess environmental phenomena. The process of collecting geographic data to describe environmental phenomena over the past thirty years has seen the mapping industry moves from brute force approaches (e.g., field surveying) to passive sensing approaches (e.g., photogrammetry and passive remote sensing) [4.1]. Today the integration of Aerial Photography, Multispectral Images and low resolution Digital Elevation Models (DEMs) represent the core of most environmental process modeling [4.2]. This technique proved to work very well at the regional scale but local environmental phenomena exists that call for a deeper scale analysis. Urban Environments' phenomena are between them. In Urban Environments it is very difficult to automatically distinguish the objects by using traditional classification methods because of the high complexity of the urban pattern. A Three-dimensional urban model is necessary as a base for many urban energy analysis such as urban morphology energy efficiency, solar energy source potential estimation and urban heat island assessment [4.11, 4.12].
Recently, the panorama of mapping industry for geographic data collection moved to active sensing approaches: e.g., LiDAR and Radar [4.1].

4.1 The opportunities given by the Airborne LiDAR sensor for 3D representation of urban morphology spatial patterns relevant for energy

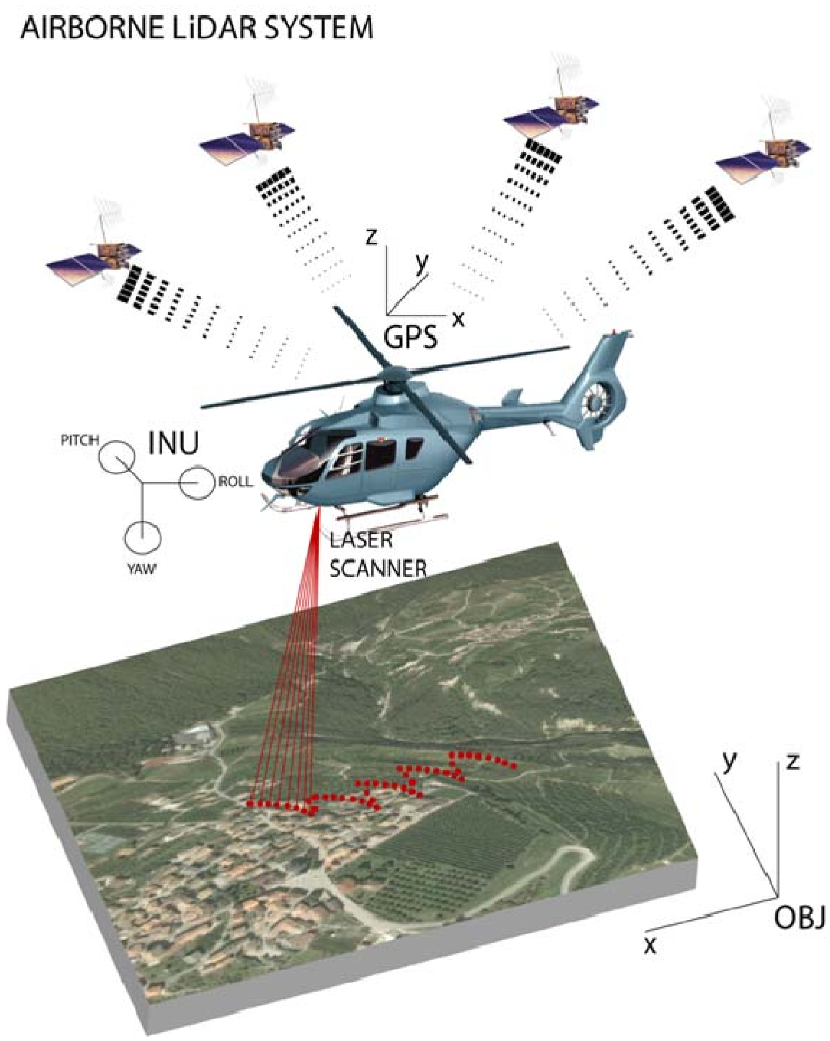
The LiDAR Technology
The LiDAR (Light Detection and Ranging technology) is an optical remote active sensor that measures properties of scattered light to find range and/or other information of a distant target. The method to determine distance to an object or surface is to use laser pulses. Using accurate timing, the distance to the feature can be measured. By knowing the speed of light and the time the signal takes to travel from the sensor to

the object and to come back to the sensor, the distance can be computed using the basic relationship:

$$D = vt/2$$

where D is the distance from the aircraft to the object (this is one-half the total distance that the laser signal actually traveled), v is the velocity or speed of light, and t is the time between emitting and receiving a particular signal [4.3].

Figure 13. Airborne LiDAR system



The LiDAR technology has been in existance for 30 years but became commercially available only recently [4.4].

Airborne LiDAR is relatively new technology complementary to traditional field surveying, multispectral and photogrammetric approaches. This system collects data from the first surface hit by laser beams. The resulting DEMs are representative of the ele-

vation of that surface composed of both the “bare earth” surface and above ground features. Used in combination with an aircraft (Figure13) the LiDAR provide laser-based measurements of the distance between an aircraft carrying the sensor and the ground [4.4].
On a functional level, airborne LIDAR is typically defined as the integration of three technologies into a single system capable of acquiring data to produce accurate ad high resolution DEMs in physical applications. These technologies are: Lasers, Global Positioning System (GPS), and Inertial Navigation Systems (INS). Combined, they allow the positioning of the footprint of a laser beam as it hits an object, to a high degree of accuracy.
The integration of LiDAR with airborne GPS facilitates the wider use of high resolution DEMs in physical applications [4.5]. Advancement in LiDAR technology have allowed 3D information of environment to be remotely obtained over large areas. LiDAR produces fine scale 3D data from which environmental structural attributes can be derived. It can operates during the day and the night and it is not affected by shadows, dark soils, and different light conditions, unlike conventional aerial photography or multispectral images [4.6]. The resulting measurements can be post-processed to provide a DEM with a precision up to 15cm [4.7, 4.4].
The method of survey with an airborne LiDAR is rapid, relatively economic, allows survey over difficult terrain, and large areas [4.5] providing information simultaneously of both surface and topography. It was estimated that LiDAR allows a quick collection of topographic data for large areas, up to 90 km^2 per hours [4.5] and while first-pulse LiDAR measures the range to the first object encountered, such as the vegetated surface the last-pulse LiDAR measures the range to the last object represented, for example, by unvegetated surface. By acquiring such first and last pulse data simultaneously, both object heights and the topography of the ground beneath can be addressed in a single pass [4.8]. The 3D point cloud could be then filtered and classified as ground, vegetation, structures etc., in order to obtain Digital Terrain Model (DTM) (Figure 14) depicting only the ground and Digital Surface Model (DSM) (figure 15), which also includes all other objects like for example buildings and trees [4.9]. The difference between DSM and DTM produces the Normalized DSM, nDSM, (figure 16).

Figure 14. Digital Terrain Model (DEM derived from Last-pulse LiDAR) 1m resolution, depicting only the ground, the “bare earth”. Levico lake area – Province of Trento, Italy: shaded relief map (left), surface render (right).

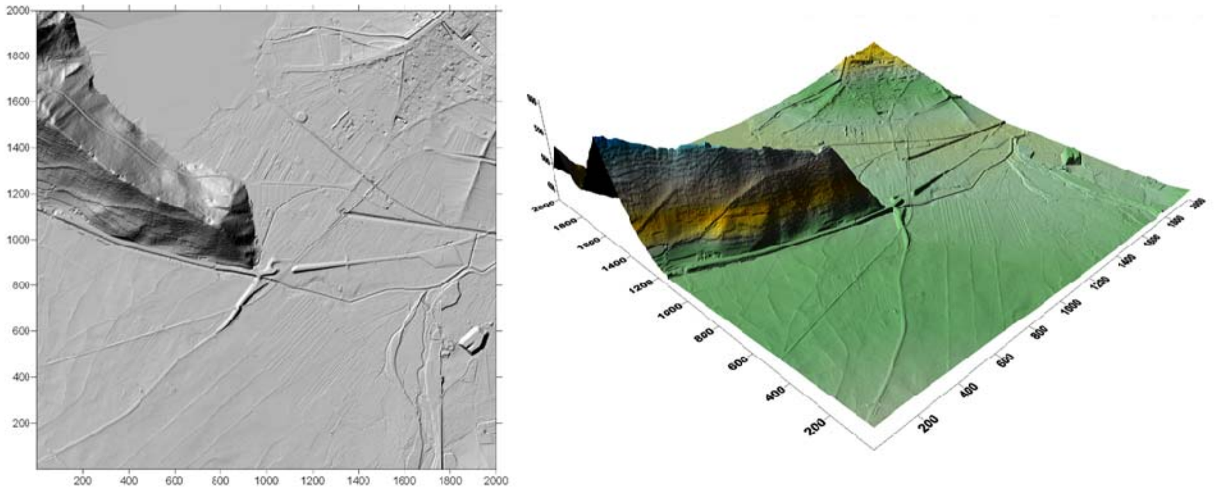


Figure 15. Digital Surface Model (DEM derived from first-pulse LiDAR), 1m resolution , includes buildings and trees. Levico lake area – Province of Trento, Italy: shaded relief map (left), surface render (right).

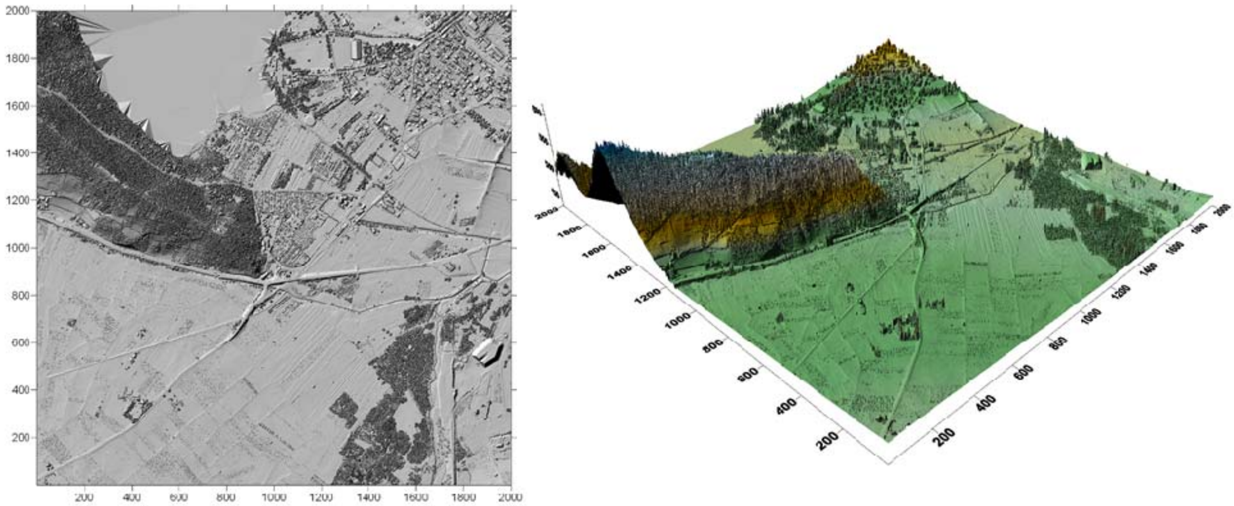
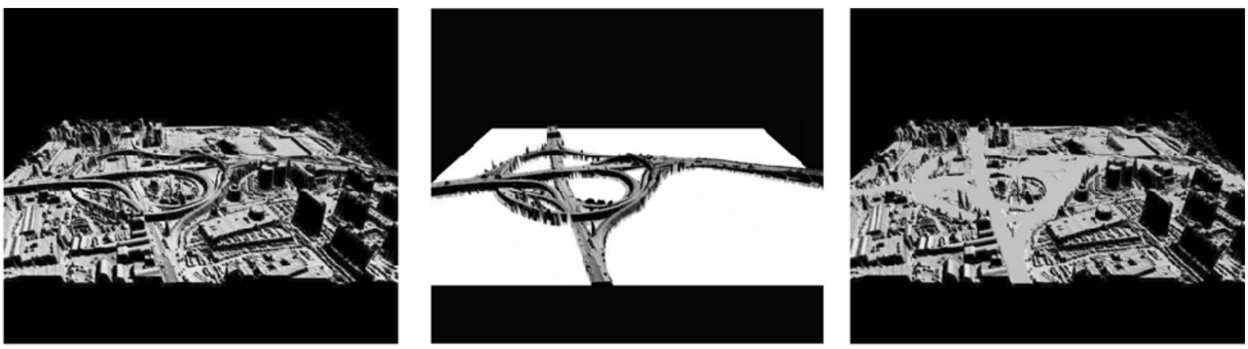


Figure 16. DSM, DTM and nDSM. Trento northern area.



Accurate 3D digital models of urban environments are required for a variety of applications. Using the proper operational parameters, airborne LiDAR offers the ability to accurately map urban environments without shadowing. Detailed DSM can be extracted from the LiDAR data, and enhanced for applied analysis using specialized 3D rendering software. By adapting a set of appropriate geometric primitives and fitting strategies, the system can model a range of complex buildings with irregular shapes [4.10]. The amount of information contained in such high-density 3D point clouds is enormous. A number of natural and manmade features, such as bare topsoil, trees, roads, buildings, waterways, power line, bridges and ramps are all easily discernable to the human eye in cross sections and range and intensity images [4.1].
The panorama of application that LiDAR data can support in urban environment modelling is very wide. The first uses of airborne LiDAR in urban modelling includes telecommunications, law enforcement and disaster planning, but there are still many application to be explored. Vettorato and Geneletti [4.11] for example demonstrate the effectiveness of LiDAR data in the estimation of potential solar energy applied to building roofs to produce energy by thermal or photovoltaic solar panels.

Figure 17. Solar Irradiation Model applied to LiDAR data in a urban context. Roncegno Terme – Trentino, Italy.

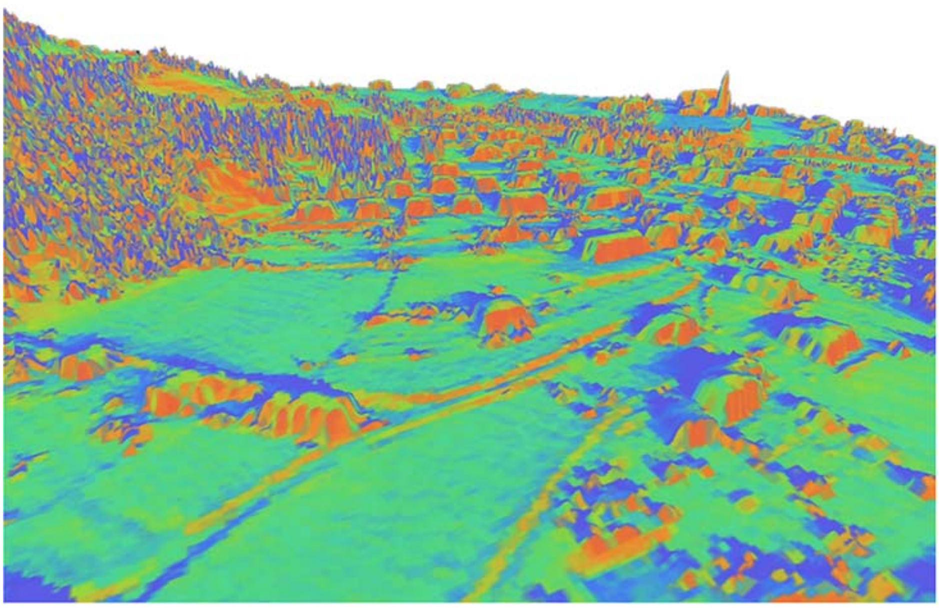


Figure 18. Trento area: 3D render of LiDAR survey and Orthophoto.

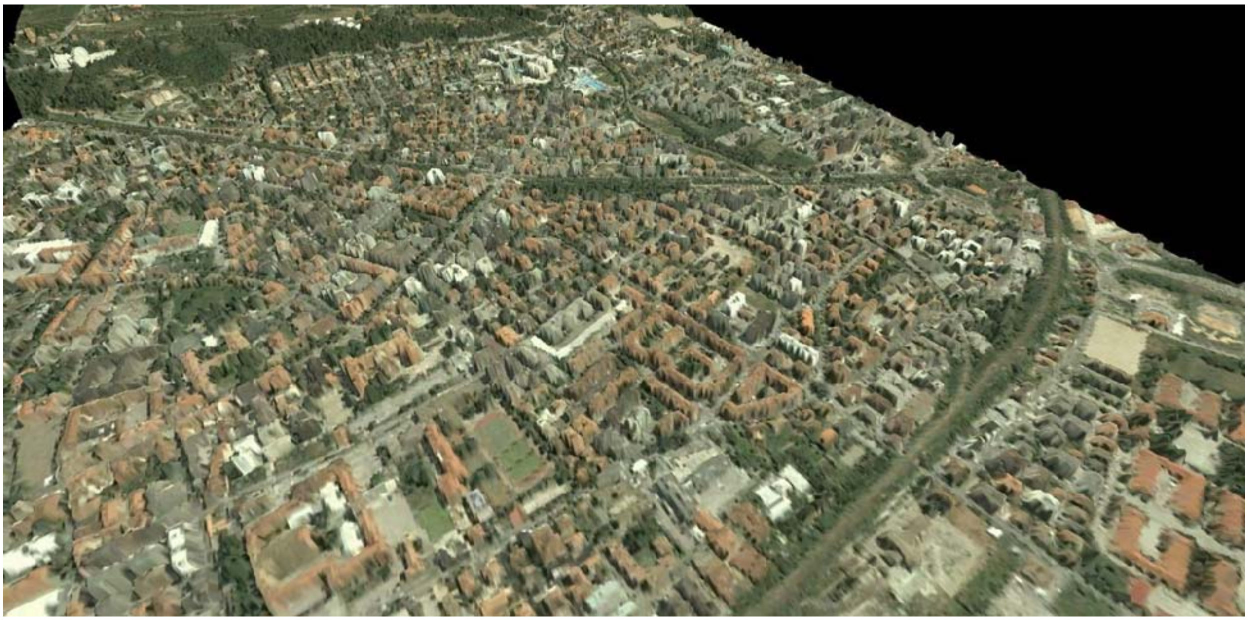
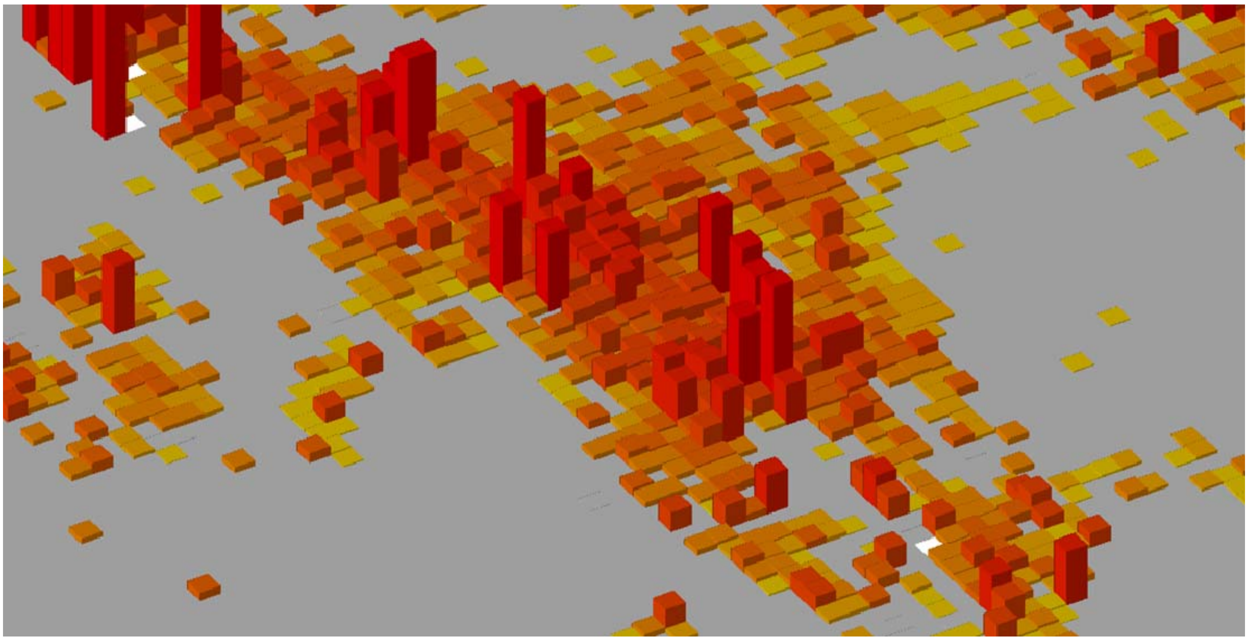


Figure 19. Trento center area: 3D render of buildings (height), extracted by the LiDAR survey.

Figure 20. Trento southern area: 3D render of Floor to Area Ratio (FAR).



However, there are also drawbacks and limitation related to the use of LiDAR sensor. Some difficulties, for example, were reported when determining the level of precision of LiDAR measurements for some surveys.
The post-processing of data seems to be, so far, the main problem of LiDAR. While the LiDAR technology continues to advance, the algorithms required and the amount of data that they have to process is significantly more. A better development of software to keep up with the demand for new application is necessary. 3D urban modeling, automated classification and vegetation mapping are three sectors to be deeply developed yet. The LiDAR market is growing all around the world, but LiDAR handling software is not.

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Chapter 5

5. Test of the method on a case study

5.1 The case study area: Trento-Pergine-Valsugana

The study area (Figures 21, 22 and 23) is the urban system composed by Trento, Pergine and the Valsugana Valley. It is located northern Italy and is an alpine urban system. The area is characterized by two narrow valleys floor surrounded by mountains reaching about 2200 m a.s.l.. Urban morphology reflects the complexity of the geomorphology. The main settlements are located on the valley floors while other towns developed by occupying both the portions of the valley floor not affected by floods and the most gently sloped alluvial fans. For ease of elaboration the study area was selected using an altitude criteria. All the areas exciding 1400 m a.s.l. are excluded. The resulting area shows to contain the 95% of the buildings. Diamantini [5.2] provided a complete characterization of the area for the economic and social point of view.

Figure 21. Case study area location within Italian territory.

Figure 22. Digital Elevation Model of the case study area.

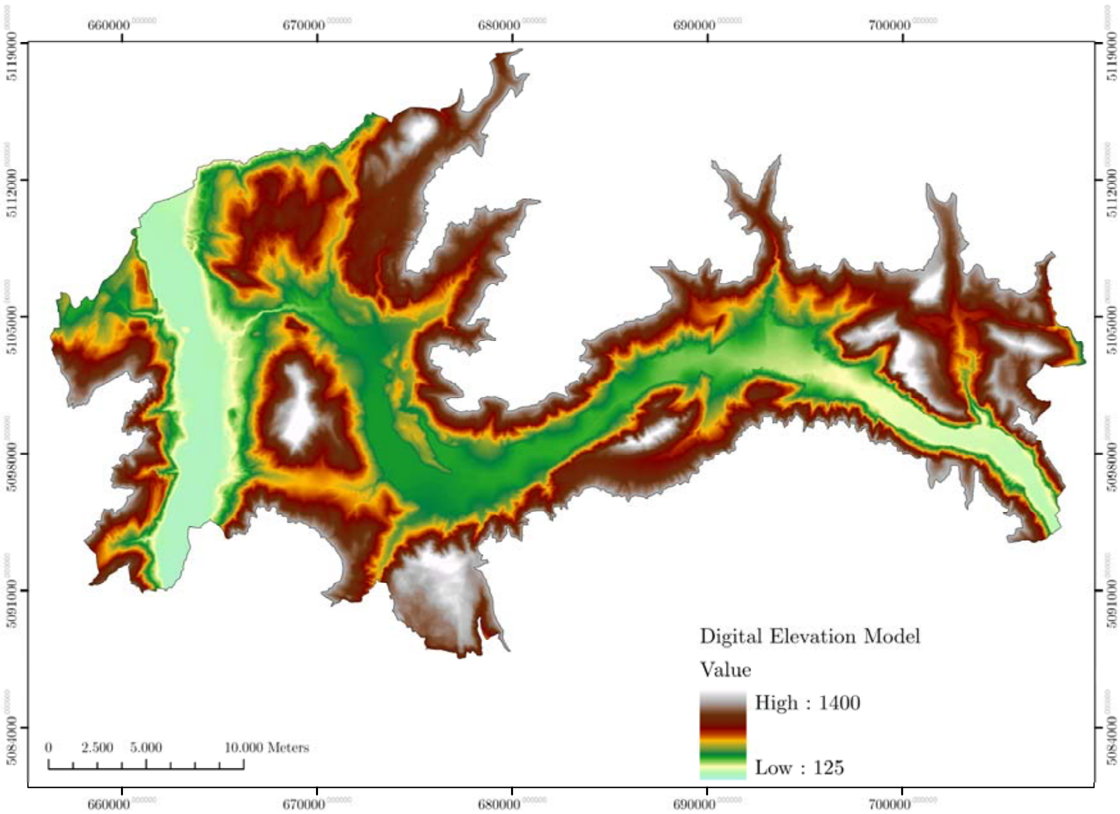
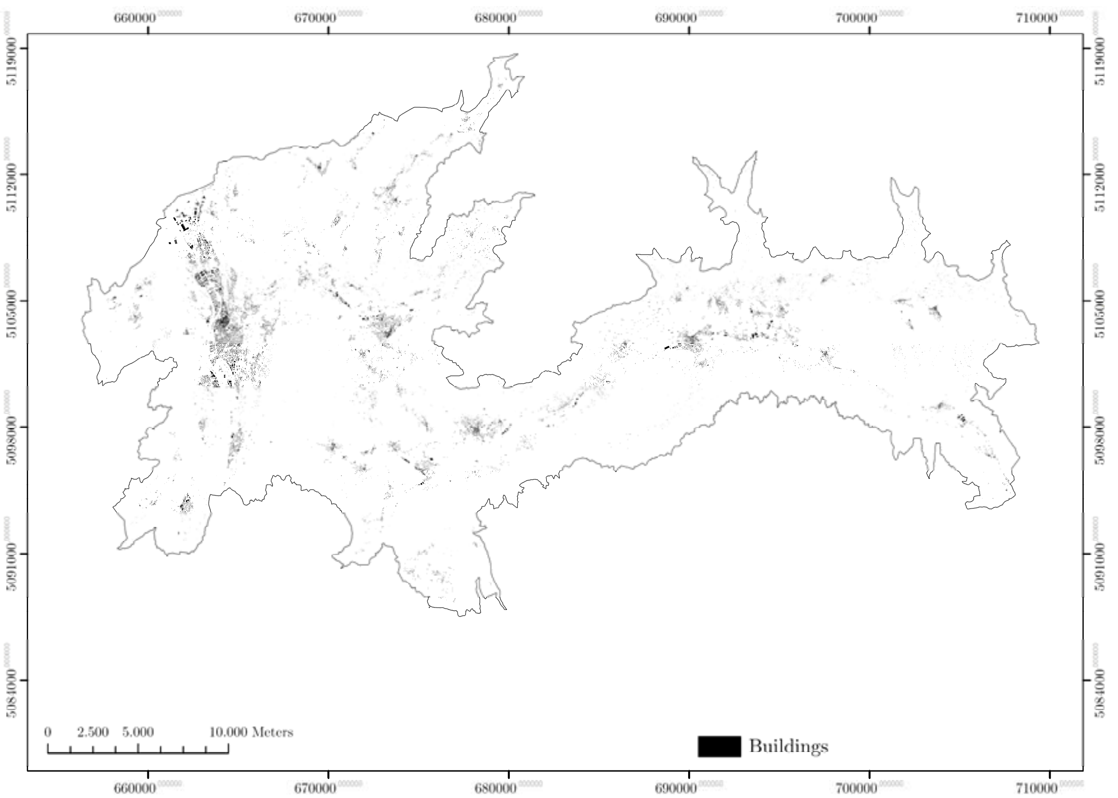


Figure 23. Buildings location within the case study area.



5.2 The geo-dataset

Data about climate zones are obtained from Sergio Los [5.1] that performed a climate analysis for the Autonomous Province of Trento in 1990.

The Digital Elevation Models are provided by the Autonomous Province of Trento. In particular a 10 meter resolution DEM generated in 2000, and a 1-m horizontal resolution and 25 cm vertical resolution, point cloud of the area obtained by a LiDAR (Light Detection and Ranging) survey carried out in the winter of 2007. From the Lidar survey are derived all the data about buildings' height, volume and 3D shape.

The road networks are provided by the Autonomous Province of Trento. The layers are provided in vector format and extracted from the "Carta Tecnica Provinciale" 2009-2010 edition.

Hydropower potentials are provided by RSE - Ricerca sul Sistema Energetico [5.8] in form of thematic map. No information about spatial resolution are included.

Wood biomass dataset is extracted from the *"Piano di assestamento forestale 2007"* [5.3], provided by the Environmental Service of Autonomous Province of Trento, Trento.

The used LANDSAT ETM+ [5.10, 5.11] scene has been downloaded from edcsns17.cr.usgs.gov and was captured on the 26th of August 2001. The recording time was estimated from the Sun elevation and Azimuth on 10:45am. Digital Numbers values are recoded according with the operational manual provided by Landsat.

The dataset about job density and population density is provided by the Statistical Service of the Autonomous Province of Trento and derived by the ISTAT national census performed in 2001.

Public transport service dataset is provided by Trentino Trasporti.
Survey of geologic layers is provided by the Geological service of the Autonomous Province of Trento.

The urban services location have been exported via a recursive query on the Google-Maps server in Lat/Lon coordinates and for the following categories of urban services:

- Food shops, groceries and supermarkets;
- Bars;

- Schools: nursery, primary, secondary, high, university;
- Post offices;
- Pharmacies;
- Banks;
- Entertainment centres: cinemas, theatres, sporting centres;
- Hospitals and clinics;
- Municipal services.
- Libraries

All the datasets have been re-projected to the UTM WGS84 zone32N coordinate system.

The following software is used in the elaboration of the data:

- The open source package SAGA GIS v.2.2 , and the commercial ArcGis v.9.3 for the raster and vector data elaboration.
- The open source package GRASS GIS v. 6.4 for the sun irradiation models. [5.5, 5.6]
- The commercial ERDAS IMAGINE 9.3, for the Landsat ETM+ 7 scene elaboration.
- The commercial StatSoft STATISTICA package for the Principal Component Analysis.

5.3 Procedure

In this chapter the procedure is described.

Adaptation of the spatial pattern metrics relevant for energy aspects (SPM-RE) list to the case study

According to the available data, the available resources and time, and according to the regional characteristics of the case study [5.2], the interaction matrix is adapted and the following spatial pattern metrics are included in the study:

Table 4. Interactions matrix adapted to the case study area

Interaction	Spatial Pattern Metrics	Code
Local climate conditions	Climate zones	001_R_CLIMATE
Natural sun exposition / lighting	Available hours of light / m2 /day	002_R_INS
Road network slope	Land slope in degrees	003_R_SLOPE
Main road network density	Spatial density of main road network	004_R_PRN
Solarpower potential of land	Incident sun beam irradiation in W/ m2/day	005_BEAM_IRR
Hydropower potential of land	Gwh/year/basin	
Biomasspower potential of land	Potential m3/ha/year	006_R_W_BIOM
Urban Heat Island aptitude	Overheating aptitude of surfaces	007_U_UHI_APT
Building thermal conservation	Building compactness	008_U_BUILD_COM
Housing and urban services proximity	Spatial proximity of urban services	009_U_SERV_PROX
Housing and job proximity	Job density	010_U_JOB_D
Secondary road network density	Spatial density of secondary road network	011_U_SRN
Public transport accessibility	Public transport stops density/ frequency of public transport	012_U_BUS_SD
District Heating and Cooling suitability	Building density (floor to area ratio FAR)	013_U_FAR
Ground Source Heat Pump (GSHP) potential	GSHP suitability	014_U_GSHP
Natural illumination of buildings	Avaliable h/light/m2 on building surface	015_N_INS_BUILD
Green area factor	Normalized Difference Vegetation Index (NDVI)	016_N_NDVI
Walkability and bikeability	Spatial density of tertiary road network	017_N_TRN
Photovoltaic and thermal potential energy of roofs and facades	Incident sun beam irradiation on buildings surfaces (roofs and facades) in w/ m2/day	018_N_BEAM_ROOF

The description of the procedure to obtain each SPM-RE follows.

Local climate conditions - Climate zones – code: 001_R_CLIMATE

Climate zones are obtained from modified version of the procedure and the data published in [5.1]. The classification of the land in different climate zones follows this scheme:

Cold: -5 / 5 °C (minimum temp.)
Cool: 5 / 17 °C (average temp.)
Mild: 17 / 29 °C (maximum temp.)
Warm: 29 / 33 °C (maximum temp.)
Hot: > 33 °C (maximum temp.)

Zone 1: between 0m and 250m a.s.l.
Zone 2: between 250m and 500m a.s.l.
Zone 3: between 500m and 1000m a.s.l
Zone 4: between 1000m and 1500m a.s.l.

Zone 1

	Cold	Cool	Mild	Warm	Hot
Jan	■				
Feb	■				
Mar		■			
Apr		■			
May			■		
Jun			■		
Jul			■		
Aug			■		
Sep			■		
Oct		■			
Nov	■				
Dic	■				

Zone 2

	Cold	Cool	Mild	Warm	Hot
Jan	■				
Feb	■				
Mar	■				
Apr		■			
May			■		
Jun			■		
Jul			■		
Aug			■		
Sep			■		
Oct		■			
Nov	■				
Dic	■				

Zone 3

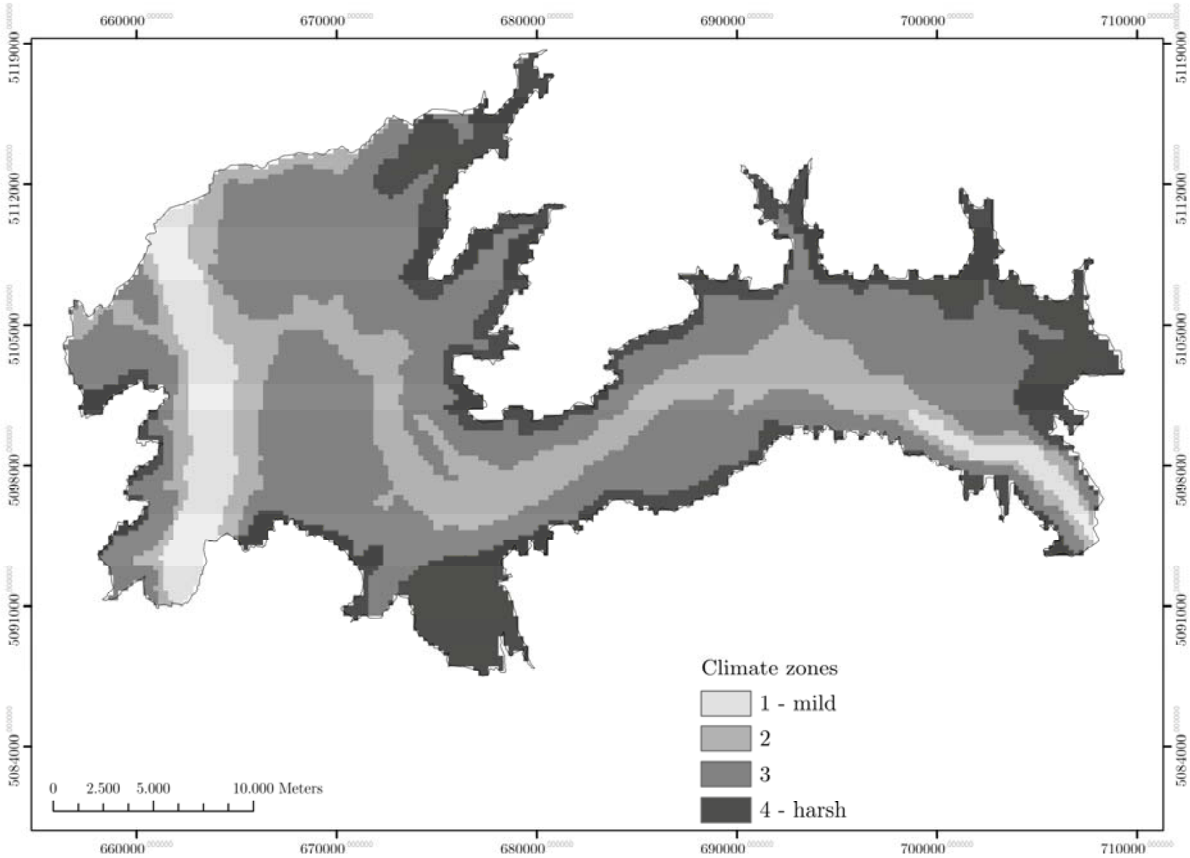
	Cold	Cool	Mild	Warm	Hot
Jan	■				
Feb	■				
Mar	■				
Apr	■				
May		■			
Jun			■		
Jul			■		
Aug			■		
Sep		■			
Oct		■			
Nov	■				
Dic	■				

Zone 4

	Cold	Cool	Mild	Warm	Hot
Jan	■				
Feb	■				
Mar	■				
Apr	■				
May	■				
Jun		■			
Jul			■		
Aug		■			
Sep		■			
Oct	■				
Nov	■				
Dic	■				

The map of climate zones SPM is presented in Figure 24.

Figure 24. Map of climate zones SPM

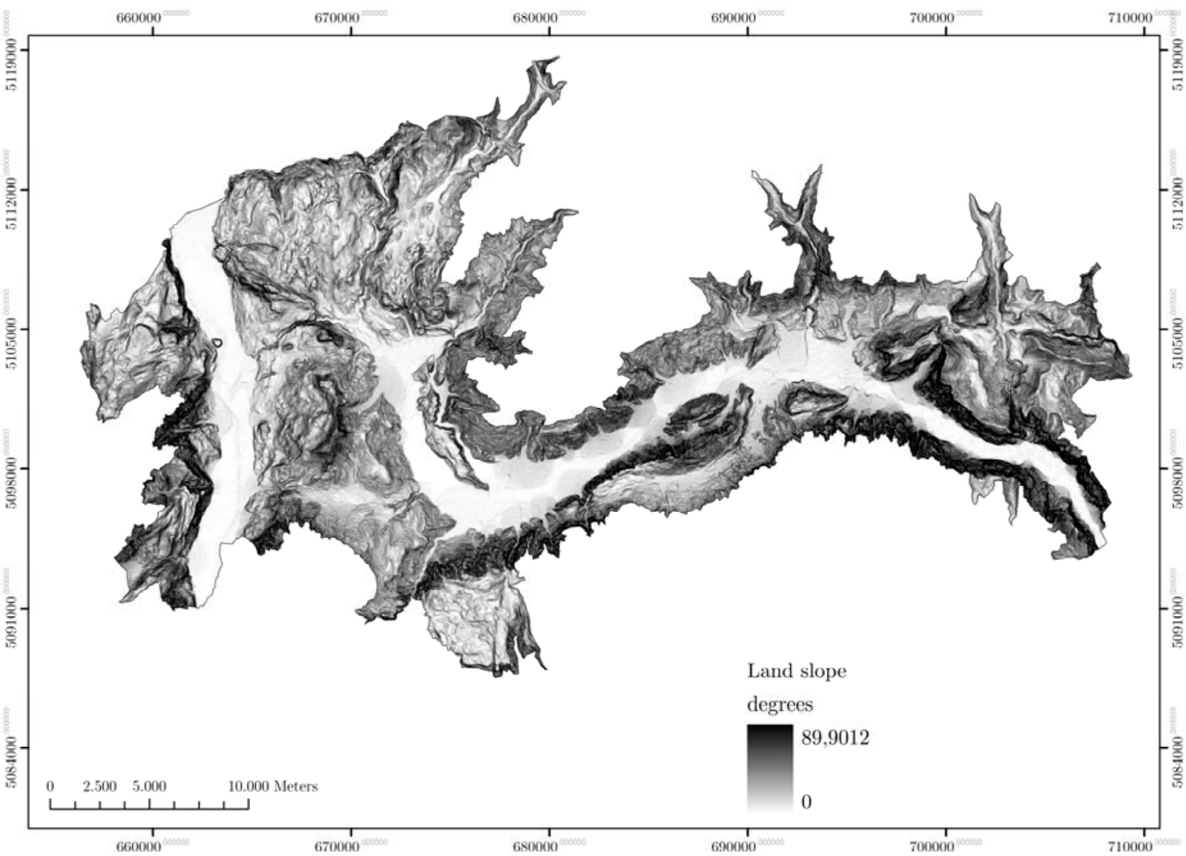


Road network slope. Land slope in degrees – code: 003_R_SLOPE

Coping with the available data, the estimation of this SPM is simplified to the calculation of the land slope in degree with a variation between 0 to 90 deg.
The slope is calculated using the open source software GIS GRASS 6.4 and a 10 meters resolution Digital Elevation Model (DEM) generated in 2000 and provided by the Province of Trento.

The land slope map for the case study area is presented in Figure 25.

Figure 25. Land slope map in degrees.



Prymary road network density. Spatial density of primary road network. Code: 004_R_PRN

Secondary road network density. Spatial density of secondary road network. Code: 011_U_SRN

Walkability and bikeability. Spatial density of tertiary road network. 017_N_TRN

The SPM for primary, secondary and tertiary road network are calculated using the Inverse Distance Weight function from the primary, secondary and tertiary road networks as defined in the Carta Tecnica Provinciale of Trentino Province, published in 2008.

A general form of finding an interpolated value u at a given point $\mathbf{x}$ based on samples $u_i = u(x_i)$ for $i = 0,1,...,N$ using IDW is an interpolating function:

$$u(\mathbf{x}) = \sum_{i=0}^{N} \frac{w_i(\mathbf{x})u_i}{\sum_{j=0}^{N} w_j(\mathbf{x})},$$

where

$$w_i(\mathbf{x}) = \frac{1}{d(\mathbf{x}, \mathbf{x}_i)^p}$$

is a simple IDW weighting function, as defined by Shepard [5.7] $\mathbf{x}$ denotes an interpolated (arbitrary) point, $\mathbf{x}_i$ is an interpolating (known) point, d is a given distance (metric operator) from the known point$\mathbf{x}_i$ to the unknown point $\mathbf{x}$, N is the total number of known points used in interpolation and p is a positive real number, called the power parameter.

The resulting maps show the Euclidean distances from the networks and are considered as proxy for the density and the accessibility. The produced maps are presented in Figure 26, 27 and 28.

Figure 26. Main road network

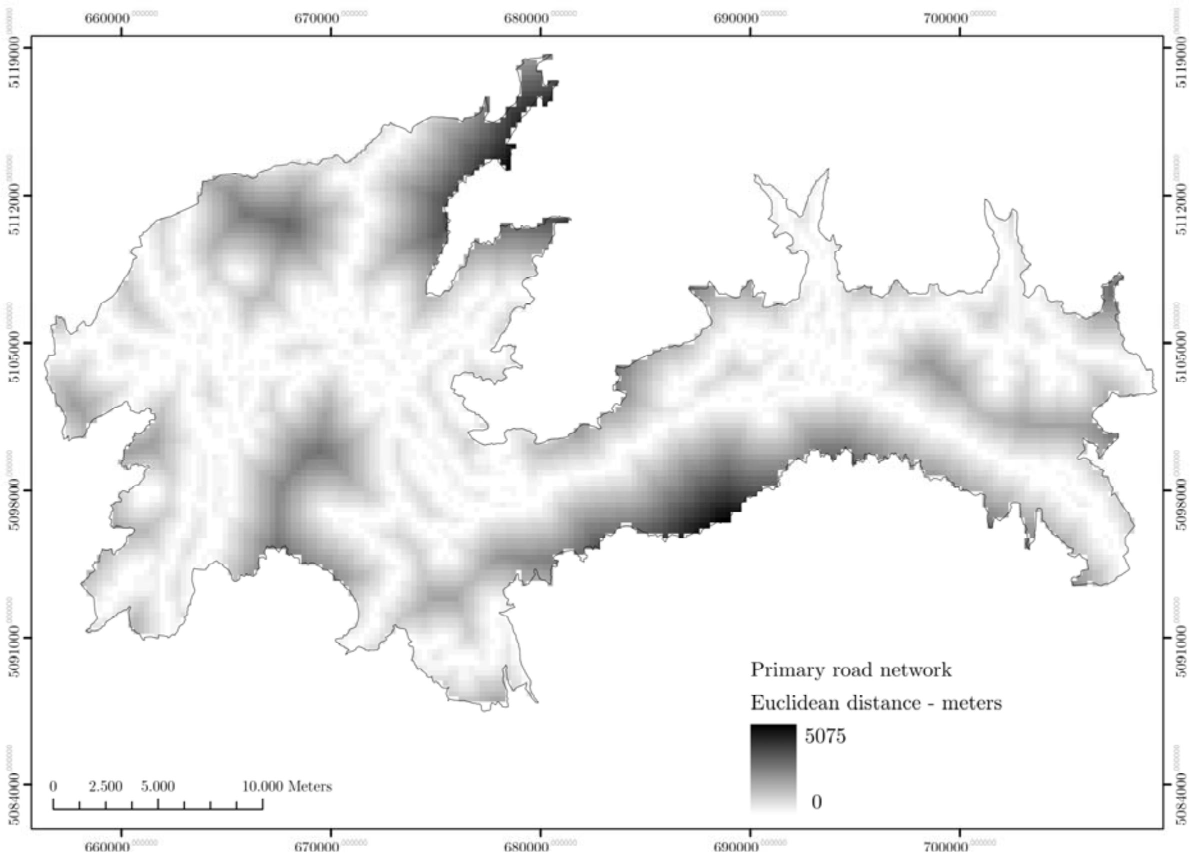


Figure 27. Secondary road network

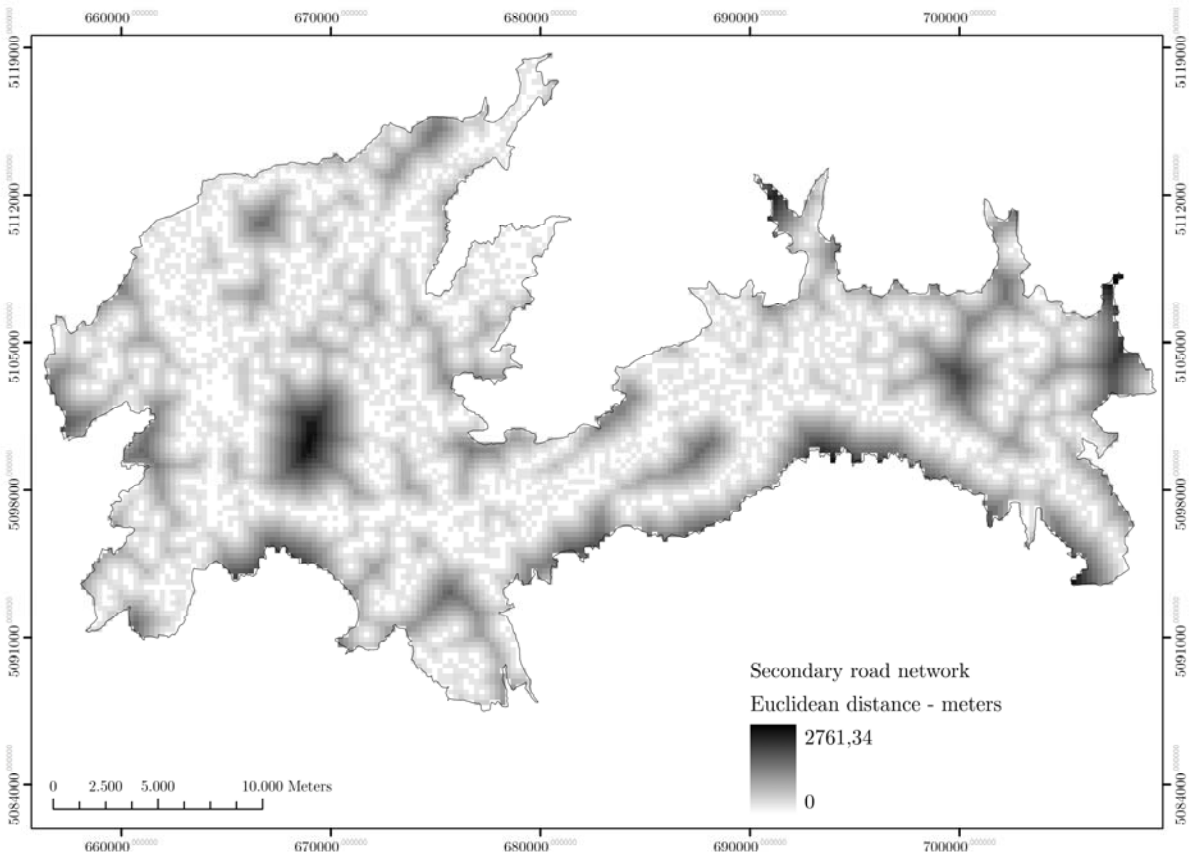
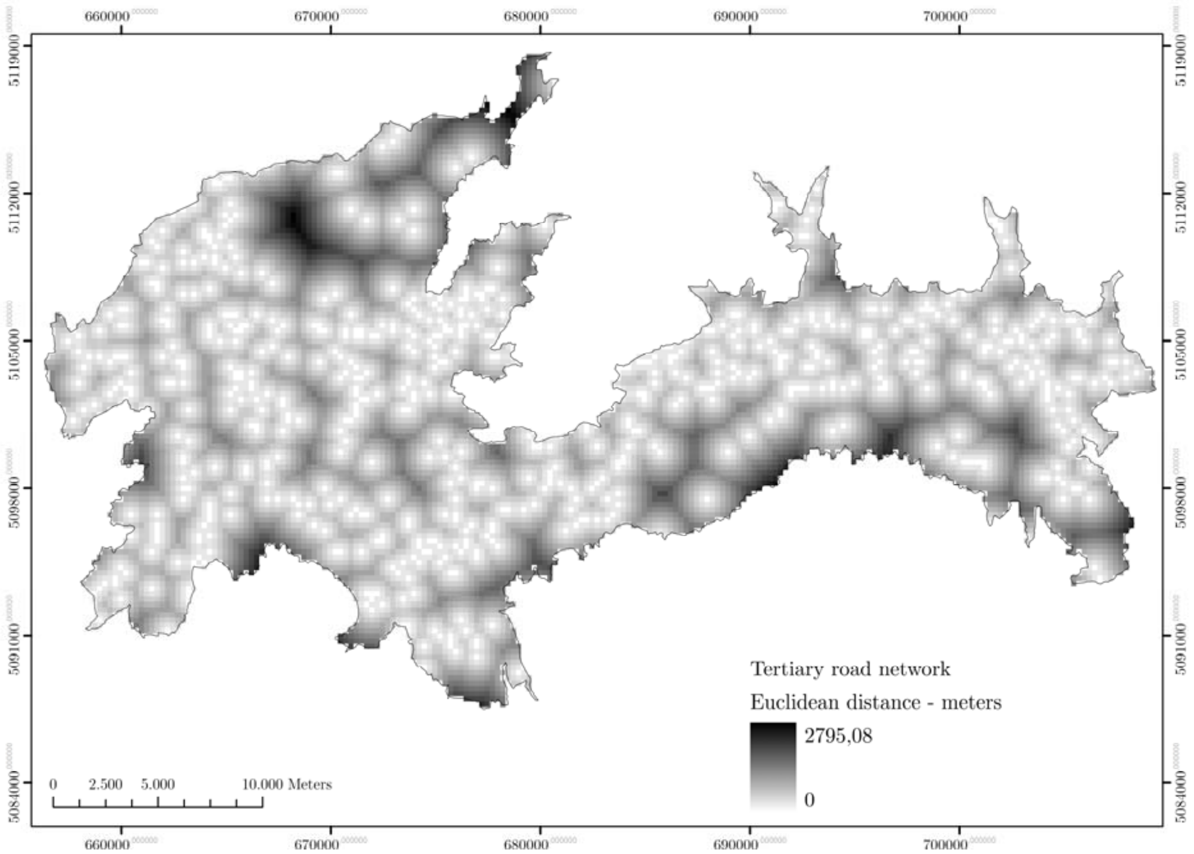


Figure 28. Walkability and Bikeability.

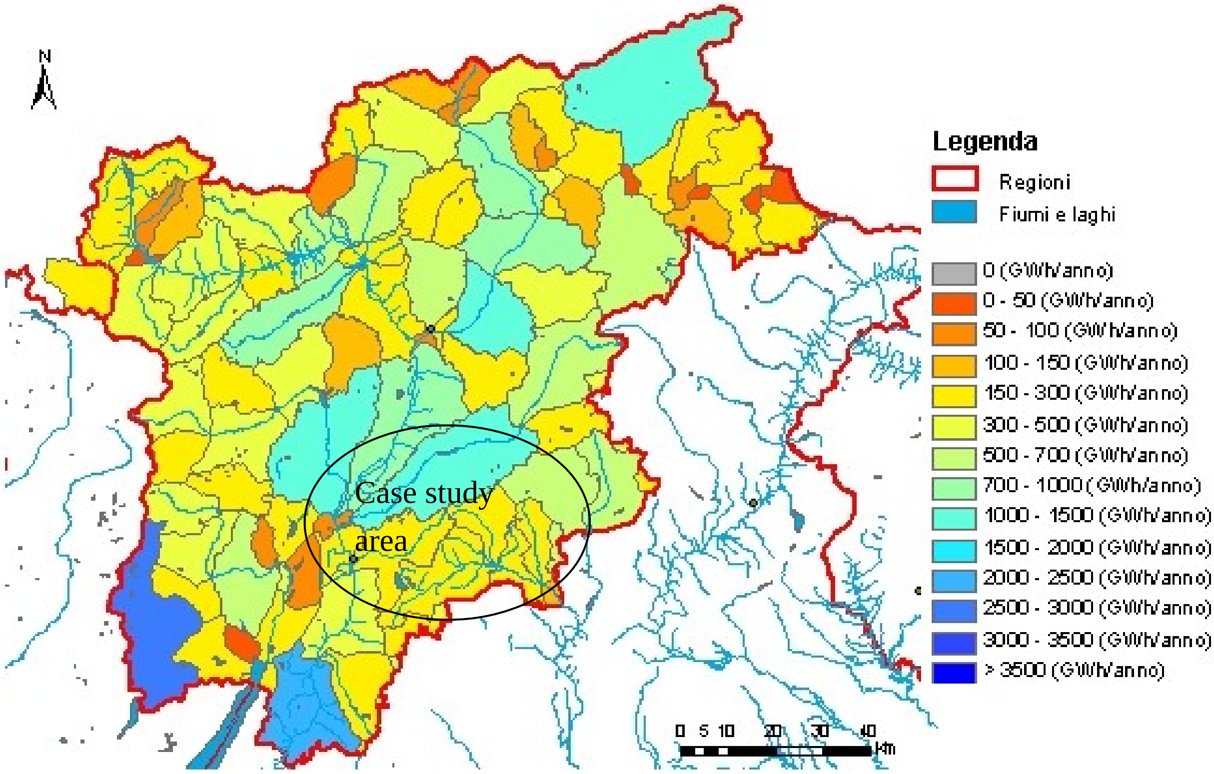


Hydropower potential of land—Gwh/year/basin

Data about the hydropower potential of land for the case study area are published by [5.8]. Due to the low spatial resolution of the estimation, the potential is the same for the whole area. It means that the hydropower potential for the case study area shows no variability. This SPM is not included, a priori, in the further analysis because it is considered irrelevant for the correlation analysis and the ranking.

The hydropower potential in Gwh/year/basin for the whole Trentino Province area is presented in Figure 29.

Figure 29. hydropower potential in Gwh/year/basin for the whole Trentino Province area [5.8].



Biomasspower potential of land. Potential m3/ha/year. Code: 006_R_W_BIOM

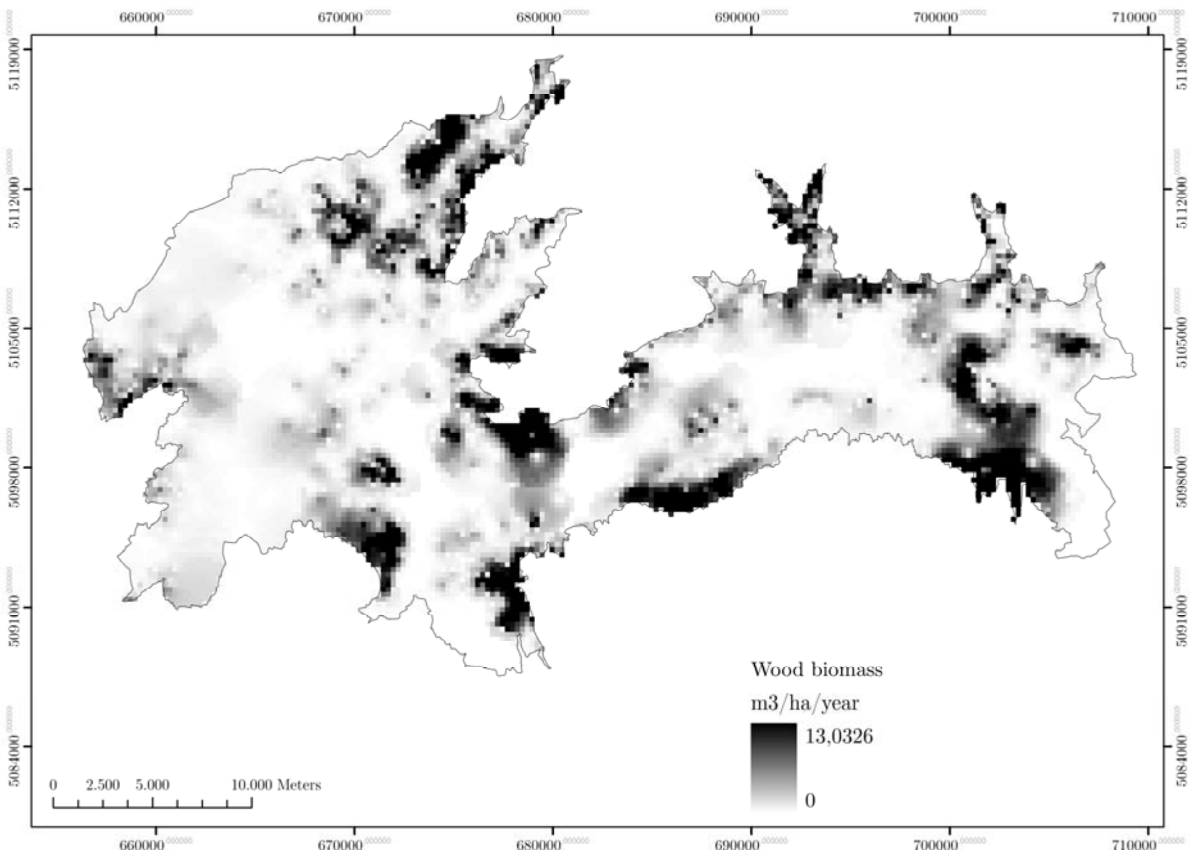
The biomass power potential of land is estimated in m3/ha/year of produced biomass. A mature forest usually has a positive annual net productivity (biomass) that can be extracted without affecting the ecosystem internal equilibrium. Consistently with Röser et al. (2008), the estimation of the potential energy from wood biomass was based on the following parameters:

- Annual average net productivity;
- Accessibility to the area;
- Distance between production and consumption area;

A Forest Inventory (PAT, 2007c) is used to obtain information about the net production of wood biomass for the case study area. The IDW function (see above) is used to elaborate an interpolated map. Afterward this map is multiplied for a factor of conversion according to the slope of the pixel: 1 for slopes between 0° and 15° (0% to 26,8% slope); 0,5 for slopes between 15° and 20° (26,8% to 36,3% of slope) and 0,1 for slopes over 20°.

The resulting map of wood biomass production potential for the case study area is presented in figure 30.

Figure 30. Wood biomass production of land

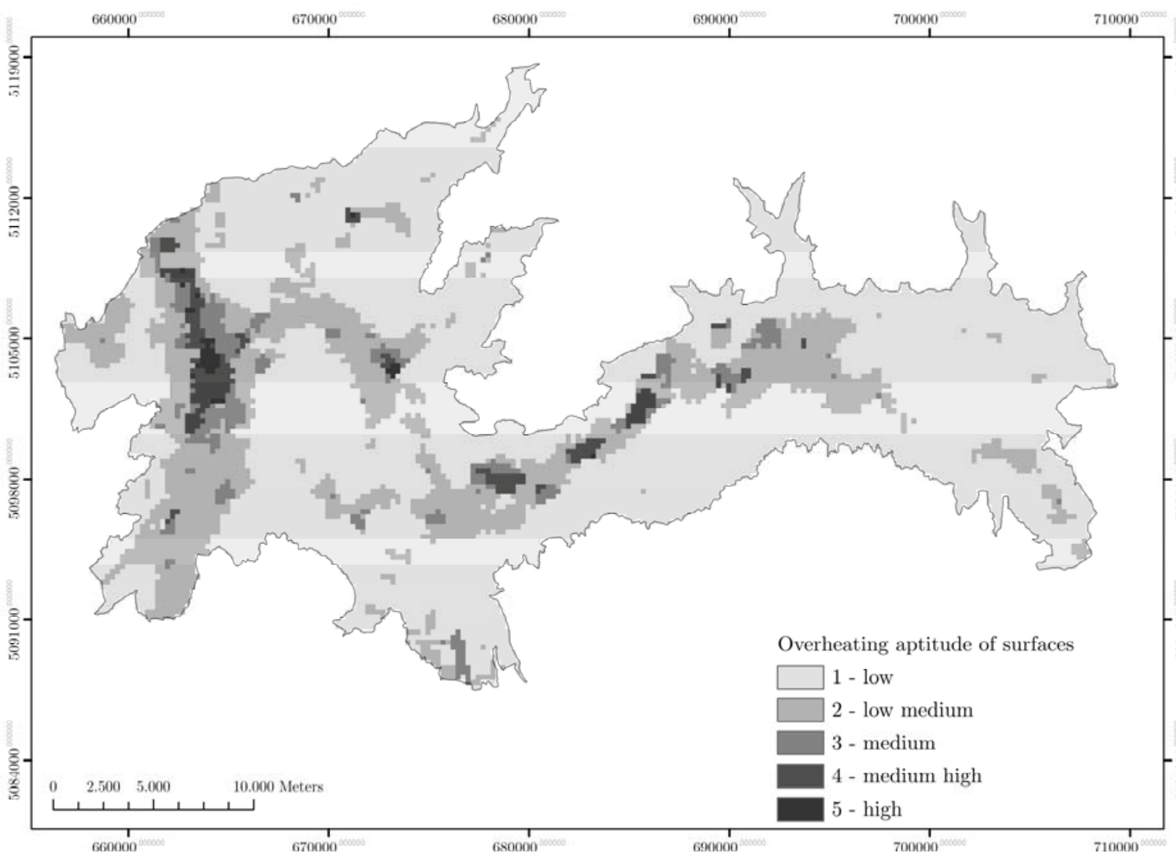


Urban Heat Island aptitude. Overheating aptitude of surfaces. Code:

007_U_UHI_APT

I already presented in [5.13] a method to correlate urban morphologies with surface temperature of land. This contribution demonstrates that, for the case study area, can be found a good correlation between surface temperature and characteristics of urban morphology. In this research I use the results of that study to produce a map of Overheating aptitude of surfaces. The Landsat 7 ETM+ infrared thermal band (with bias gain 2) is used to estimate the surface temperature for the case study area at a spatial resolution of 60m/pixel. The segmentation in quantiles permits the classification of the resulting map in 5 classes of overheating aptitude of surfaces (high, medium-high, medium, medium-low, low).
The resulting map of overheating aptitude of surfaces for the case study area is presented in Figure 31.

Figure 31. Overheating aptitude of surfaces.

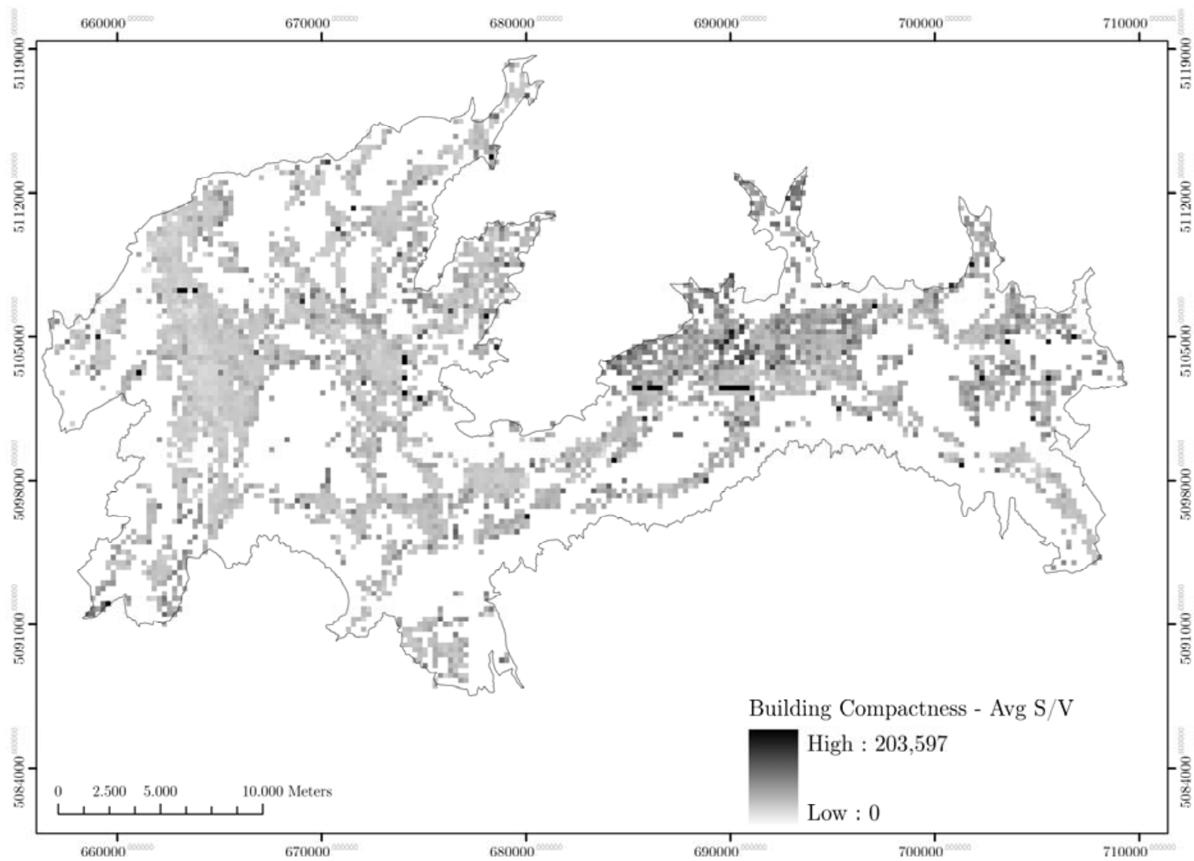


Building thermal conservation. Building compactness. Code: 008_U_BUILD_COM

According to the assumption of chapter 3, the compactness of buildings is used as a proxy for the building thermal conservation aspect. Thanks to a high resolution LiDAR survey, provided by the Autonomous Province of Trento , the heights of the buildings are calculated. The point cloud LiDAR survey is rendered in a 1mX1m grid for the Digital Surface Model (DSM) and the Digital Terrain Model (DTM). In particular the procedure uses the vector map of building shapes to calculate the average value of the nDSM within the buildings areas. The nDSM is the difference between the DSM and the DTM (for the details please refer to [5.14, 5.15] published by the author of this dissertation). The estimated height and the buildings shapes areas and perimeters are used in the calculation of the Surface/Volume ratio of buildings, assuming all buildings with a parallelepiped form.

The building compactness index map for the case study area is presented in Figure 32.

Figure 32. Building compactness index map.



Housing and urban services proximity. Spatial proximity of urban services. Code: 009_U_SERV_PROX

The IDW function is used again to estimate the spatial density of urban services.

This urban services categories have been grouped following these criteria and assigning a score to each group:

Daily urban services (Food shops, groceries and supermarkets; Schools: nursery, primary secondary): 10 points

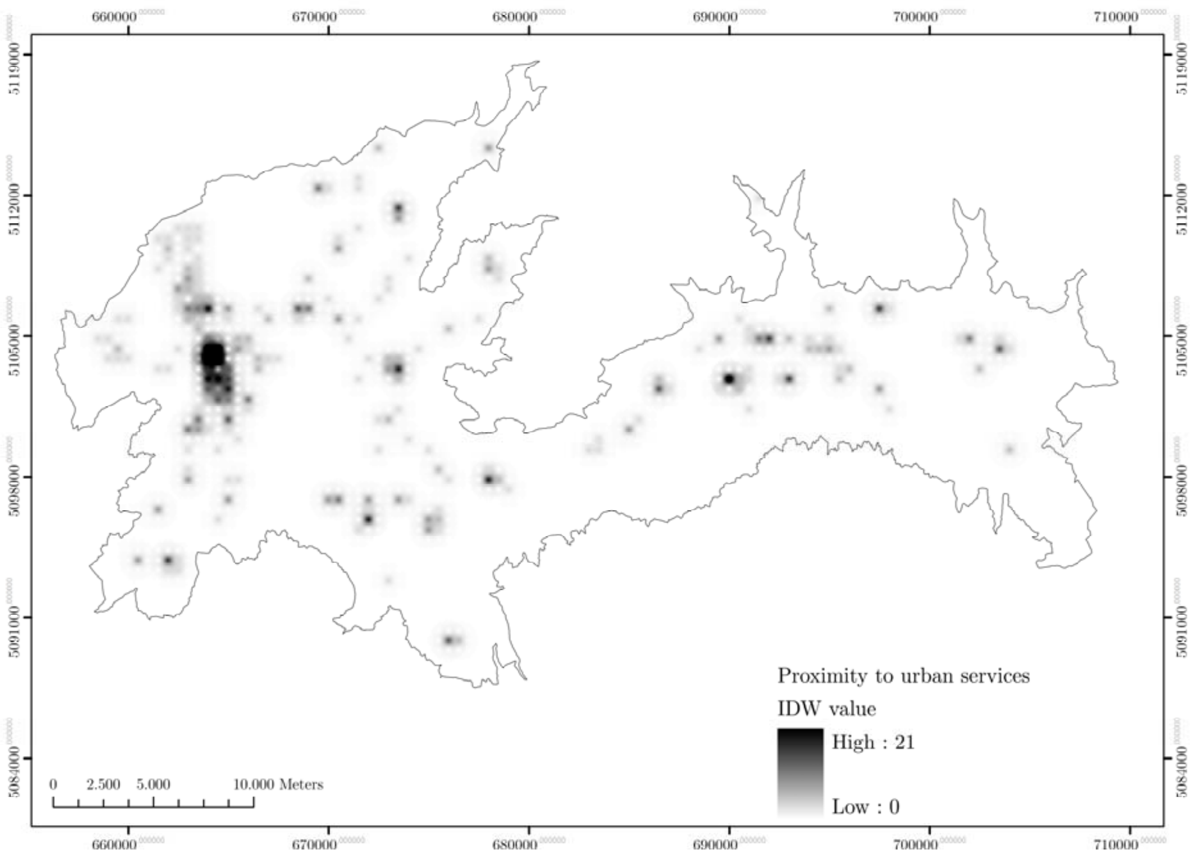
Daily metropolitan services (Schools: high, university;): 20 points

Not-daily urban and metropolitan services (Municipal services; Post offices; Banks; Hospitals and clinics; Libraries; Entertainment centres: cinemas, theatres, sporting centres; Pharmacies;) : 5 points

The case study zone is divided in squared areas using a 100X100 m grid and the sum count of the points is calculated for each area and then the IDW function, with resolution of 100 m and power of 2, is applied to interpolate the values according to the Euclidean distance.

The resulting map of spatial proximity of urban services is presented in Figure 32.

Figure 32. Spatial proximity of urban services.



Housing and job proximity. Job proximity. Code: 010_U_JOB_D

Job proximity map is calculated using again the IDW function, with resolution of 250 m and power of 2, on the job/km^2 index. ISTAT provided the census map and the number of jobs per unit of census. The original census map is recalculated in jobs/km2. The resulting map of job density for the case study area is presented in Figure 33.

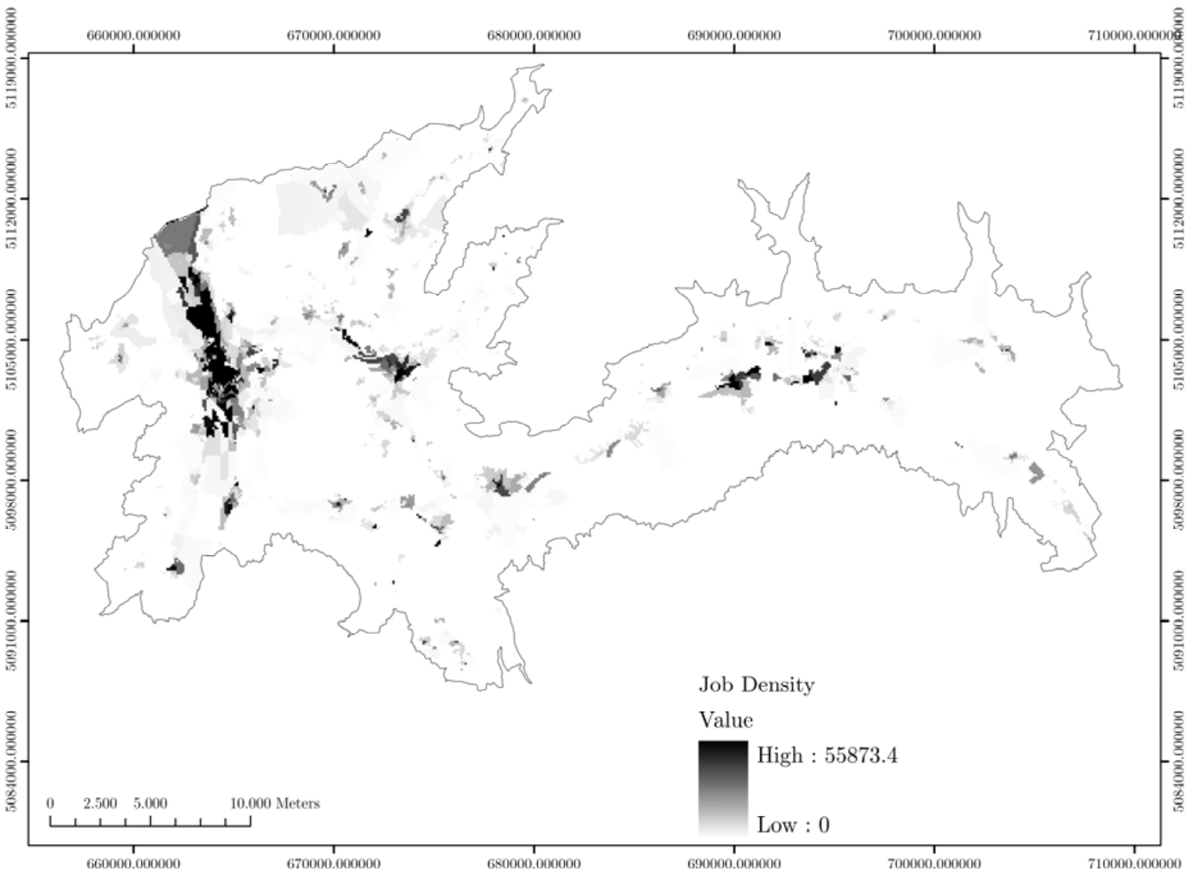


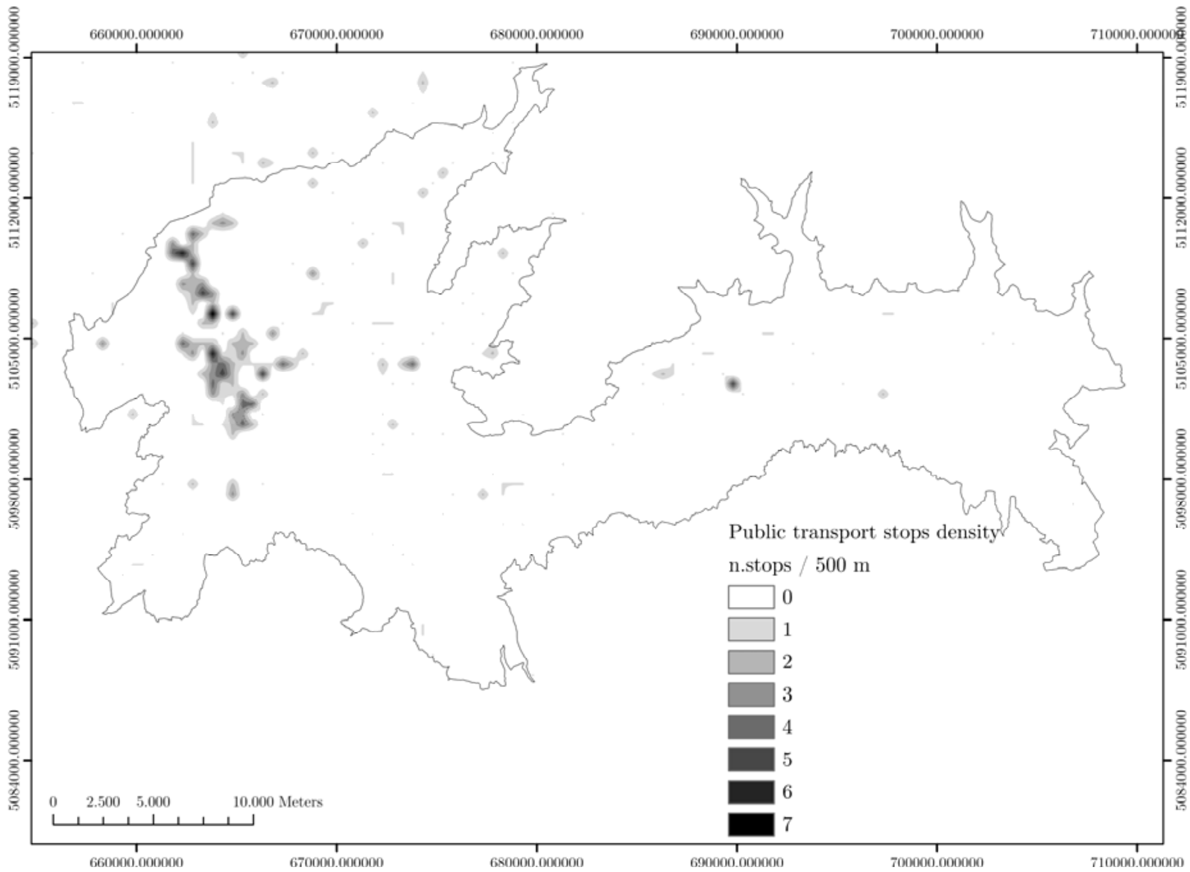
Figure 33. Job density.

Public transport accessibility. Public transport stops density/ frequency of public transport 012_U_BUS_SD

The public transport accessibility index could not be calculated because data on frequencies were not available. The public transport density is used instead. The map is calculated from the scattered point map of public transport stops. The point are counted over a 500 m2 grid resolution. The resulting map represents the number of public transport stops / 500 m^2.

The map of public transport stops density is presented in Figure 34.

Figure 34. Public transport stops density.

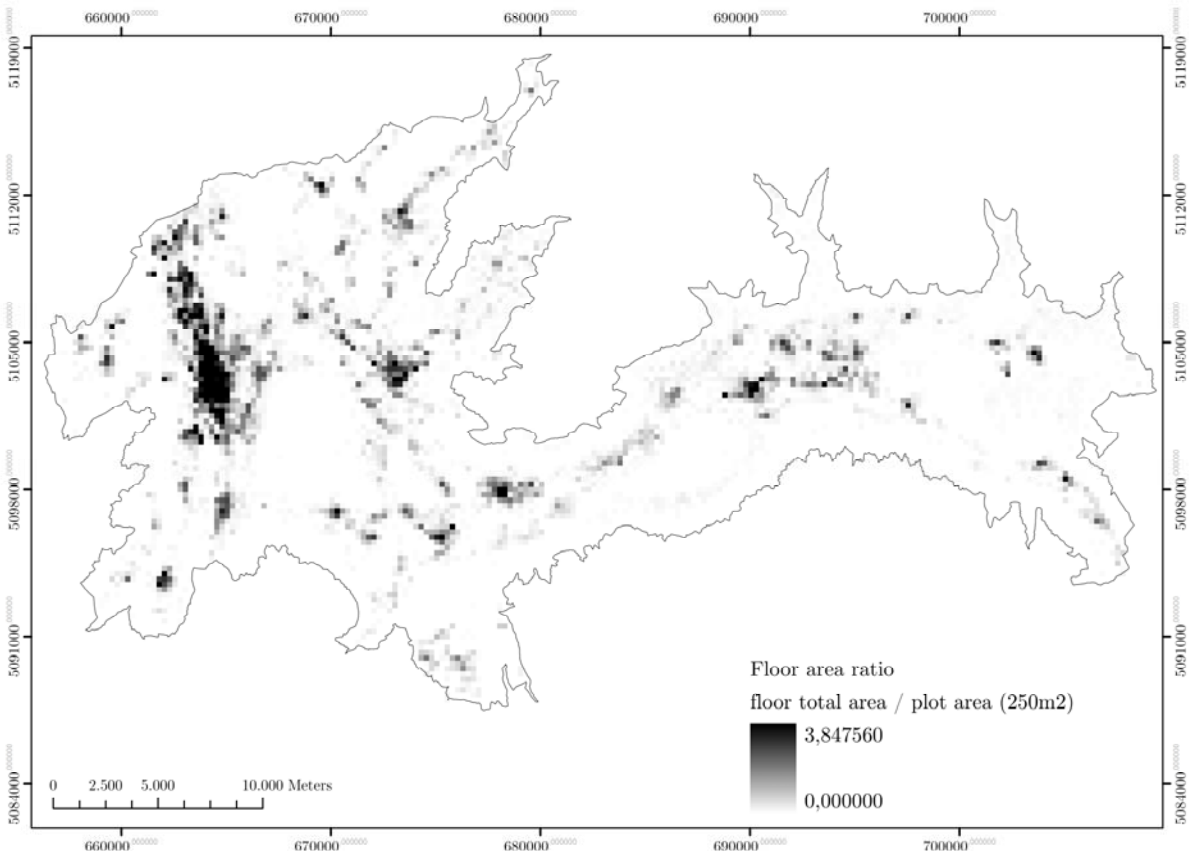


District Heating and Cooling suitability. Building density (floor to area ratio - FAR). Code: 013_U_FAR

The FAR (total built floors area/ plot area) index is used as a proxy for the district heating and cooling suitability. Thanks again to the LiDAR survey, the buildings' height is calculated and related to the vector map of buildings' shapes. The distance between floors is decided in 3 meters and the number of floors per building is estimated. Afterward the total built floor area is calculated and divided by the plot area (250 m^2).

The resulting map of FAR for the case study area is presented in Figure 35.

Figure 35. Floor to Area Ratio.



Ground Source Heat Pump (GSHP) potential. GSHP suitability. Code: 014_U_GSHP

GSHP suitability is used as a proxy for Ground Source Heat Pump (GSHP) potential.
Ground-source geothermal energy is exploitable with Ground Source Heat Pumps (GSHP) [5.17]: a central heating and/or cooling system that pumps heat to or from the ground. It uses the Earth as a source of heat (in the cold season), or as source of cool (in the hot season). The heat storage capacity of the ground can be used as an earth-heat sink because the temperature at depths between 15 and 200 m remains fairly constant (12 to 14°C) all year round (IEA/OECD, 2009). This design reduces the costs of heating and cooling systems, and can be combined with solar heating to form a geo-solar system [5.18]. According to Busby et al. [5.19], the efficiency of a GSHP system depends on local geological conditions. Factors that need to be considered in the estimation are: surface temperature, subsurface temperatures at a depth of 100–200 m, thermal conductivities and diffusivities of the soil and bedrock layers, groundwater levels and flows, and aquifer properties. Ground thermal conductibility depends on soil

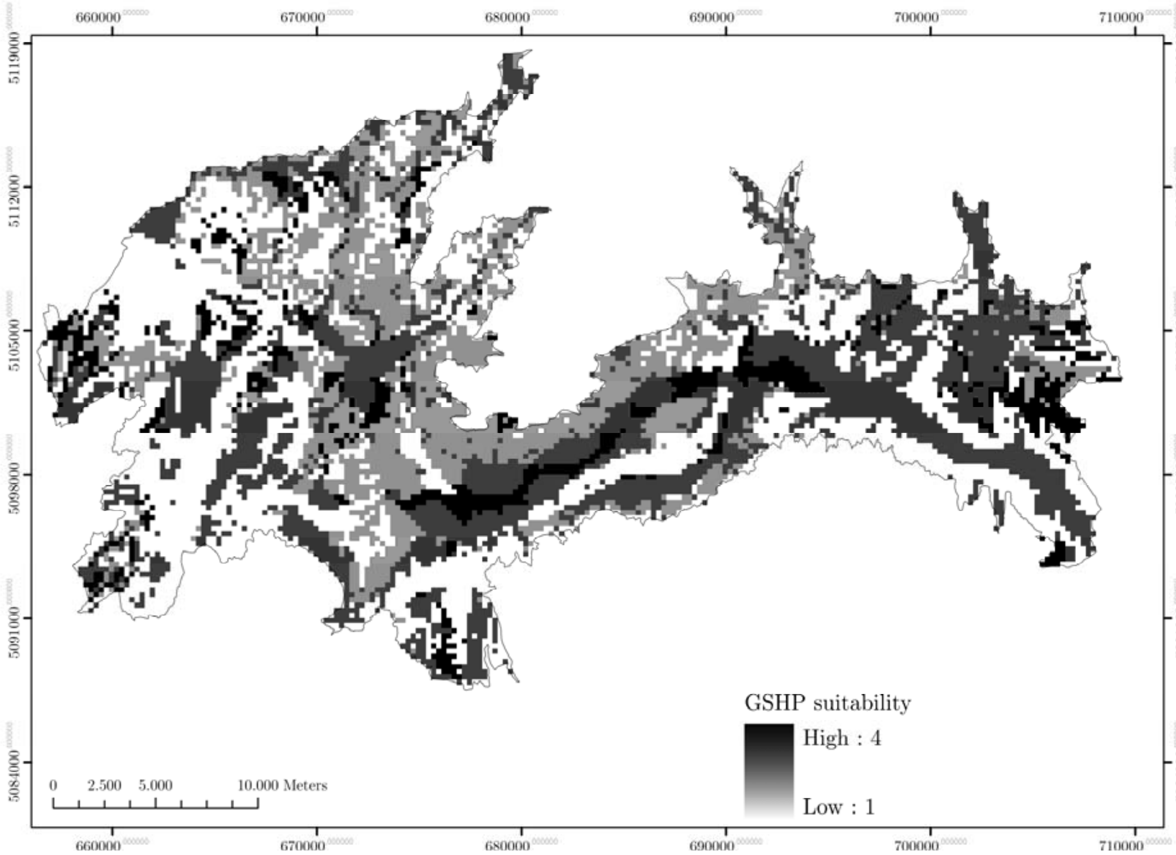
composition and it increases in presence of water. Thermal conductivity of soils are qualitatively estimated from available geological maps and geological sections, by referring to Busby et al [5.19]. Qualitative estimation of groundwater levels and flows are obtained from local hydro-geological maps and surveys. Ground thermal conductibility is considered a proxy for the GSHP installation suitability. Data scarcity does not allow to carry out a fully quantitative analysis. However the magnitude of the thermal conductibility of soil is approximated through representative values of thermal conductivity of porous materials (Anderson, 2005). The geological map is provided by the Geological service of the Autonomous Province of Trento. The classification of GSHP suitability for the case study area is shown in Table 5.

Table 5. Classification of GSHP suitability

Geological layer	**Thermal conductivity (W/ m°C)**	**Suitability class**
Dry sediments (e.g., sand, loam clay)	0.18-0.26	Very Low - 1
Saturated sediments (e.g. sand, loam, clay)	1.4-2-2	Medium - 3
Shale	1 - 2	Low - 2
Sandstone	2 - 4.5	High - 4
Limestone	2 - 3	Medium - 3
Granite	3 – 4	High - 4
Basalt	1.5 – 2.5	Low - 2

The resulting map of GSHP suitability for the case study area is presented in Figure 35.

Figure 35. GSHP suitability.



Natural sun exposition / lighting.Available hours of light / m2 /day. Code: 002_R_INS

Solarpower potential of land. Incident sun beam irradiation in W/m2/day. Code: 005_BEAM_IRR

Potential insolation, commonly measured in h/light/day, and potential solar irradiation, commonly measured in kWh/m^2/day, are a function of [5.4]:

- Terrain morphology;
- Atmospheric turbidity factor

As to the first factor, a 10-m Digital Elevation Model (DEM) generated in 2000 and provided by the Province of Trento is used . Information on the atmospheric turbidity factor, that approximates the radiation absorption by atmosphere, is provided by freely available atmospheric databases, (JRC, 2009). The solar insolation and irradiation maps are calculated assuming clear-sky conditions.

The dataset is loaded into the open source software GIS GRASS 6.4 [5.5]. The solar insolation map (expressed in hours of light/m2/day) and the land beam irradiation (in w/m2/day) are computed by taking into account also the shadow effects, using the r.sun module [5.6]. The procedure follows the method published in [5.3] by the author of this dissertation

The insolation map for the case study area is presented in Figure 36 while the sun irradiation map for the case study area is presented in Figure 37.

Figure 36. Insolation map in hours of light/m2/day.

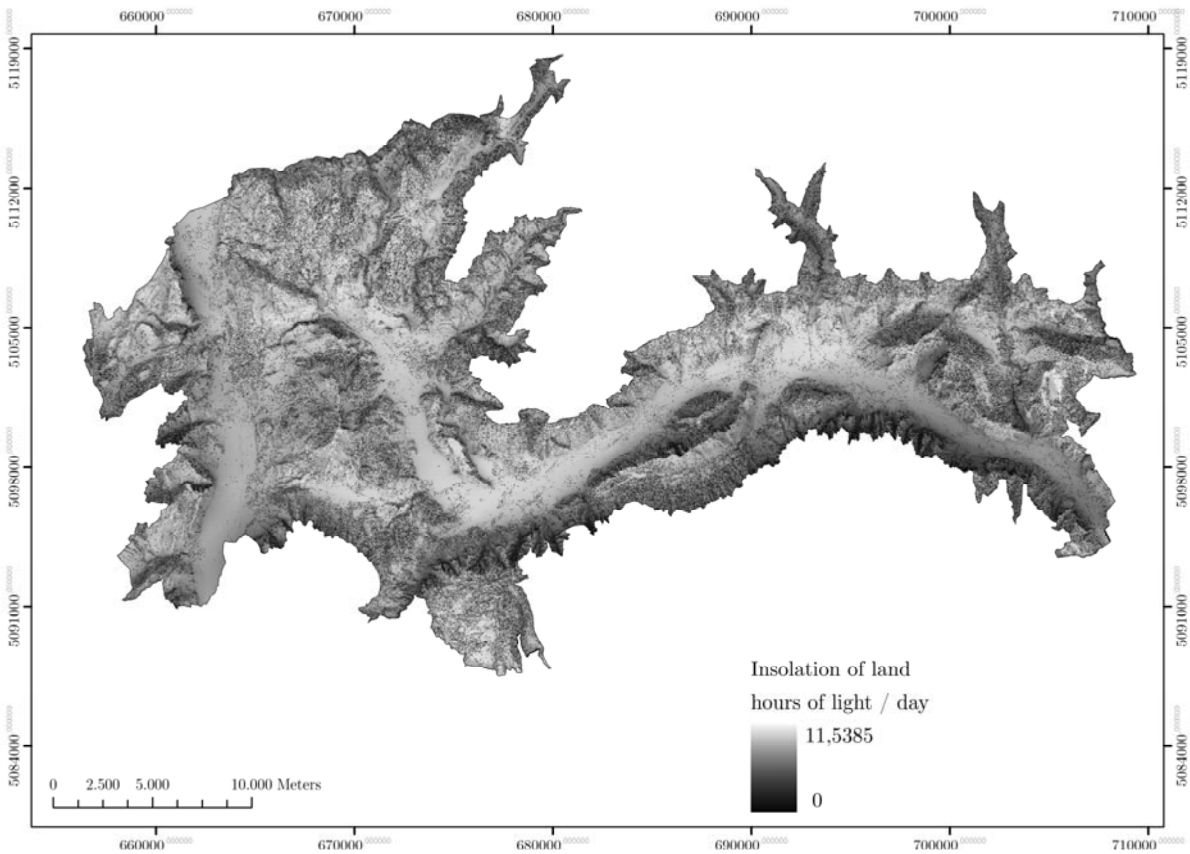
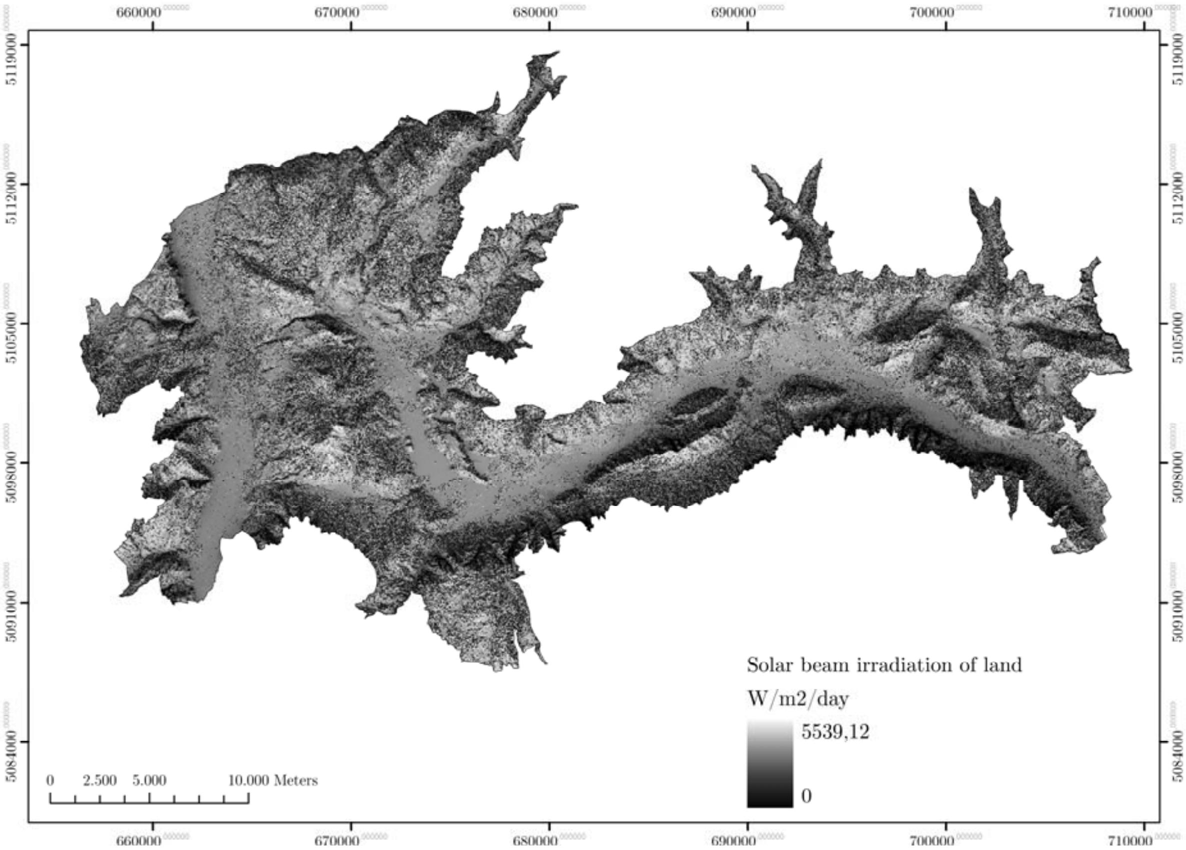


Figure 37. Sun irradiation map in W/m2/day.



Natural illumination of buildings. Avaliable h/light/m2 on building surface. Code: 015_N_INS_BUILD

Photovoltaic and thermal potential energy of roofs and facades .Incident sun beam irradiation on buildings surfaces (roofs and facades) in w/ m2/day . Code: 018_N_BEAM_ROOF

The procedure followed for the calculation of the natural illumination of buildings and Photovoltaic and thermal potential energy of roofs and facades is similar to the procedure followed to calculate the insolation (**002_R_INS**) and beam irradiaton (005_BEAM_IRR) of land. The procedure includes 3 more factors:

- Building orientation;
- Roof form and inclination;
- Interaction between buildings and urban vegetation, that can produce shadow zones;

The LiDAR survey is used again to obtain a high resolution representation of buildings

and of the other urban objects (i.e. trees) that can affect the insolation and the sun irradiation on buildings, producing shadow zones.
Using a map with the location of all the buildings, it is possible to extract the insolation and the solar irradiation values of each building's facades and roof surfaces.
Calculated values are then resampled at a resolution of 100m/pixel.
The map of insolation of buildings for the case study area is presented in Figure 38, while the map of sun irradiation of buildings for the case study area is presented in Figure 39.

Figure 38. Insolation of buildings in hours of light/m2/day.

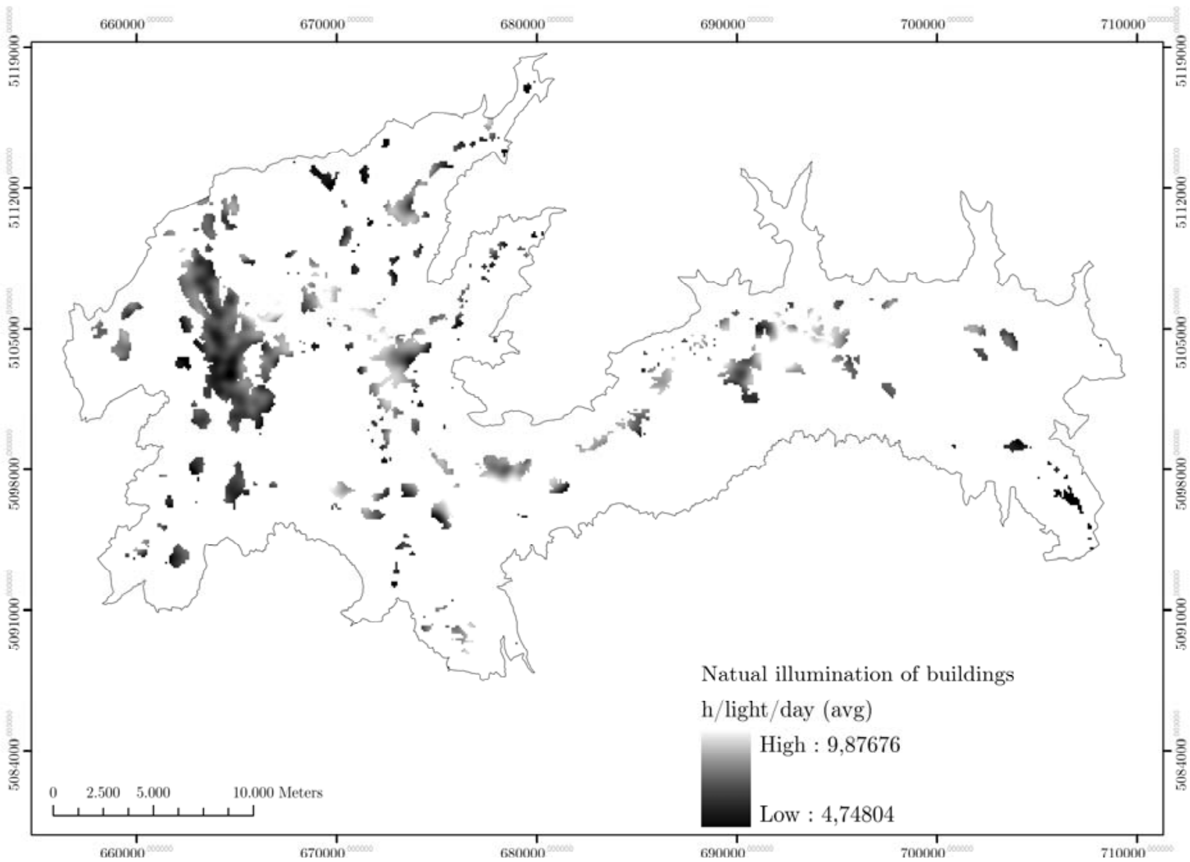
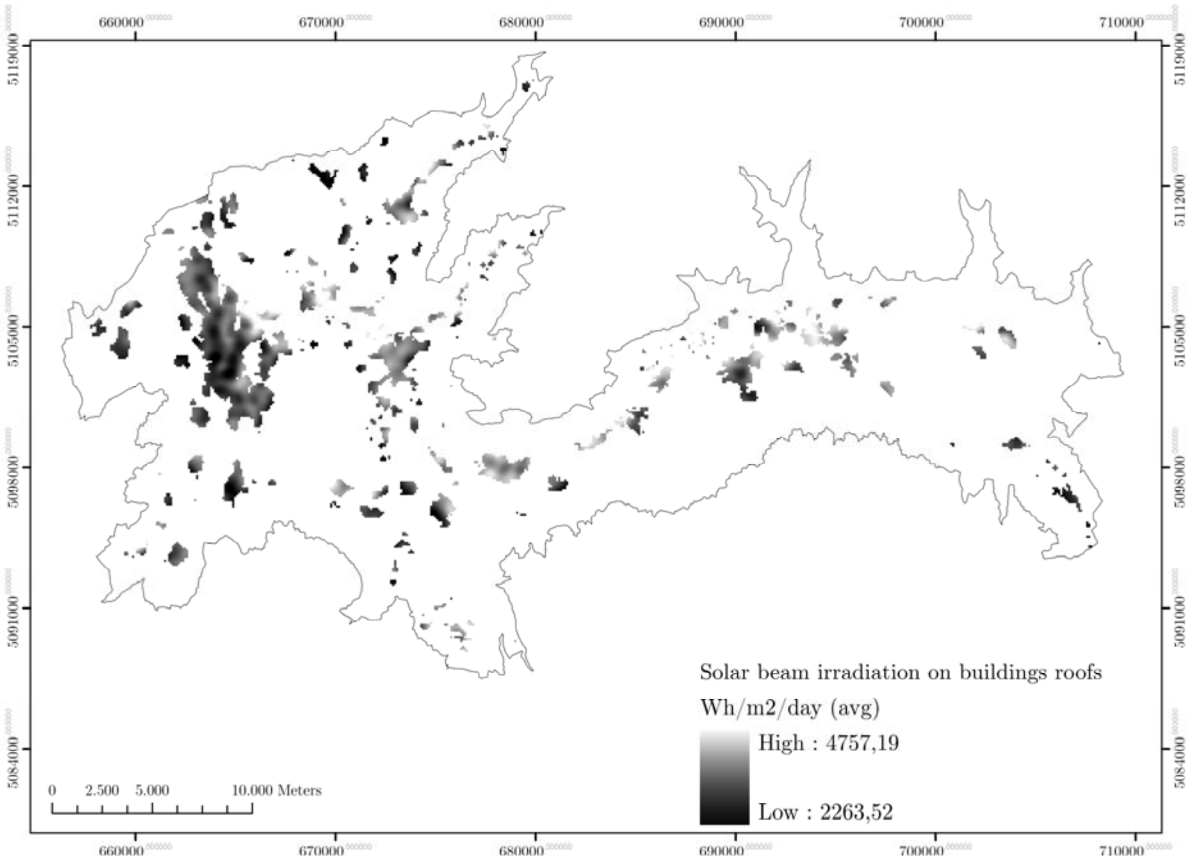


Figure 39. Sun beam irradiation of buildings in W/m2/day.



Green area factor. Normalized Difference Vegetation Index (NDVI) . Code: 016_N_NDVI

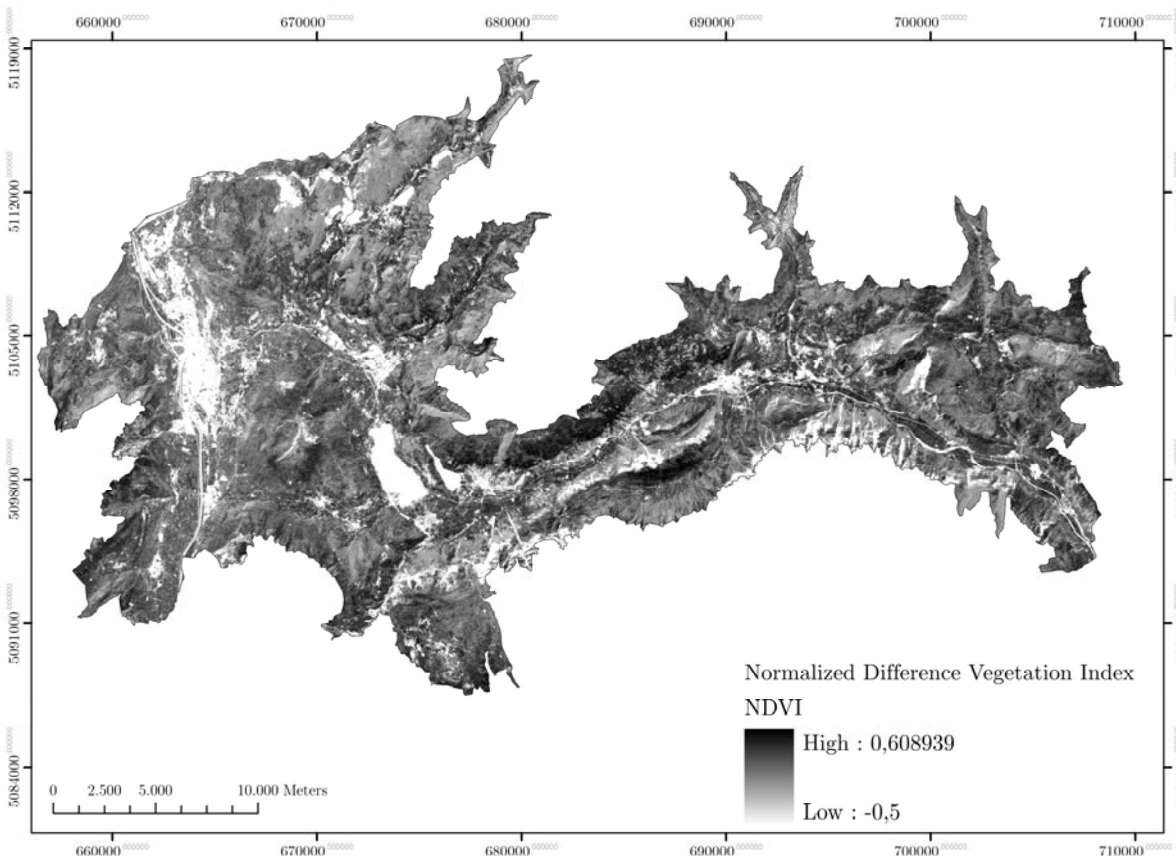
The green area factor is estimated using the NDVI method and the same Landsat ETM+ scene mentioned before.

The NDVI is calculated using the Landsat ETM+ bands 3 (Red, 30 m/px) and 4 (Near InfraRed, 30 m/px) and applying the formula published in literature by several authors (for example, Tucker, 1979):

$$\text{NDVI} = \frac{\frac{\text{Red}}{\text{NIR}} - 1}{\frac{\text{Red}}{\text{NIR}} + 1}$$

The resulting NDVI map for the case study area is presented in Figure 40.

Figure 40. Normalized Difference Vegetation Index.

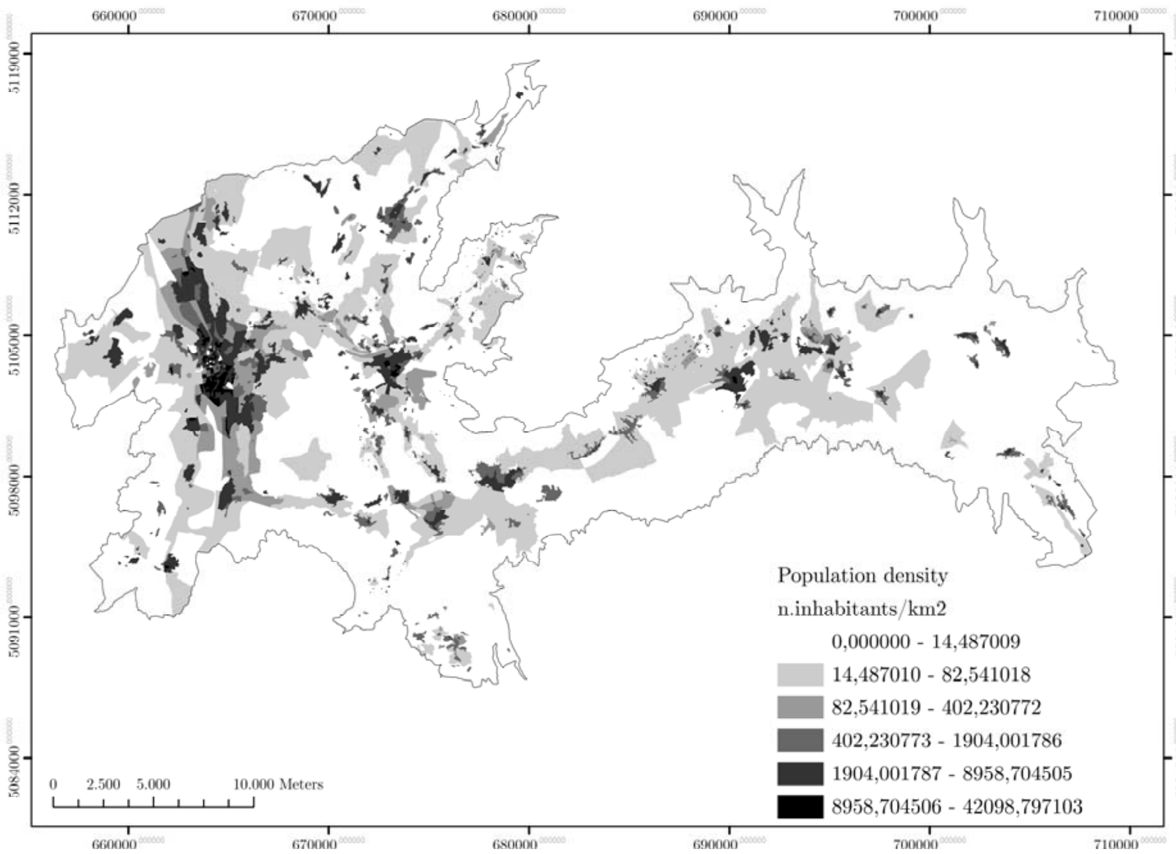


Urban Compactness gradient (UCG)

The UCG is calculated thorough the Urban Compactness Indicator. The procedure uses two factors:

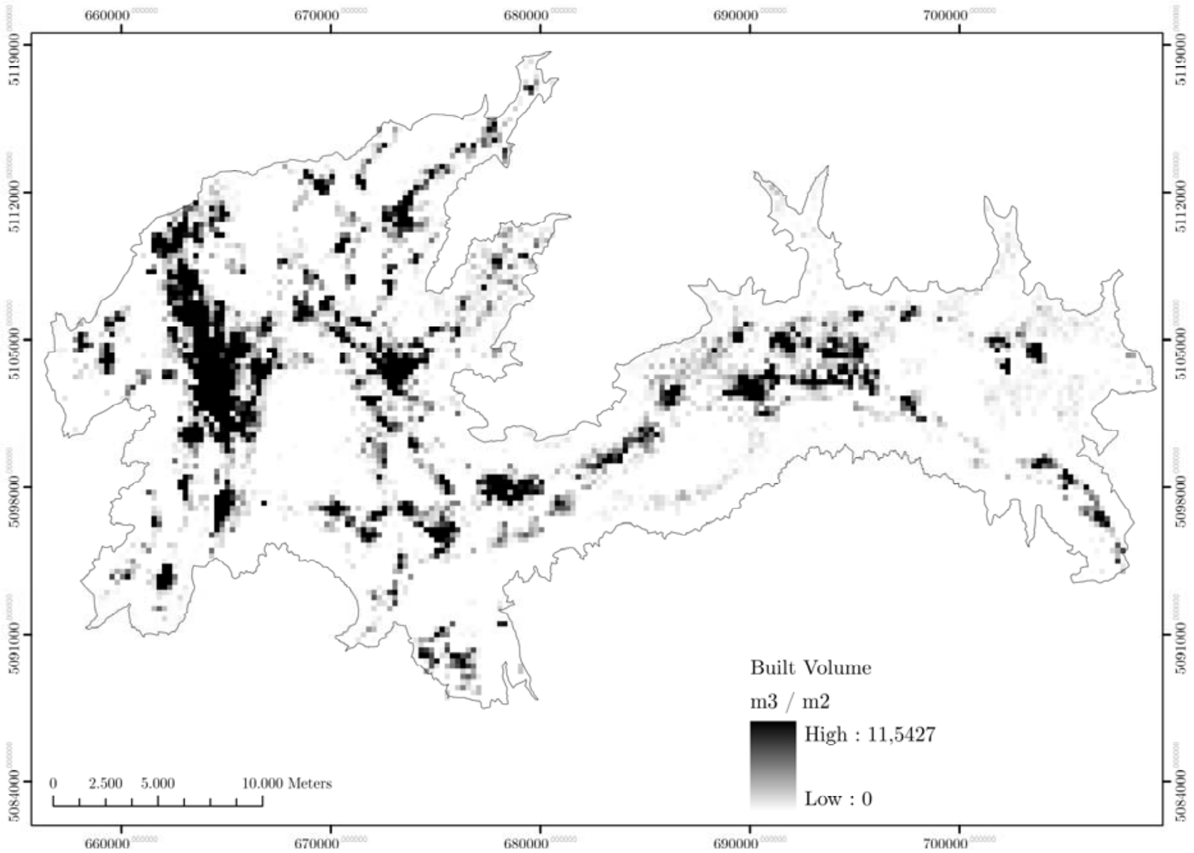
- Population density
- Built-up density
- Population density is derived from the population census provided in 2001 by ISTAT. The population density is calculated in inhabitants/km^2 with a resolution of 100m/pixel. The resulting map is presented in Figure 41.

Figure 41. Population density map.



Built-up density is derived again by the LiDAR survey and calculated in m^3/m^2 with a resolution of 100m/pixel. The resulting map is presented in Figure 42

Figure 42. Built-up density.



The correlation analysis performed for the two maps shows a very low correlation between the variables.

Table 6. Table of correlations between polulation density and bult up density

	POPDENS	VOL
POPDENS	1,000000	0,045818
VOL	0,045818	1,000000

The cluster analysis using the Hill-Climbing method [9] is performed on the two variables in order to obtain 5 classes (Urban Compactness Classes - UCC) representing the UCG:

- High compactness urban area
- Medium compactness urban area
- Low compactness urban area
- Very low compactness urban area
- Rural area

The output of the cluster analysis is presented in Table 7

Table 7. Output of the UCG cluster analysis.

CLUSTER ANALYSIS - UCG

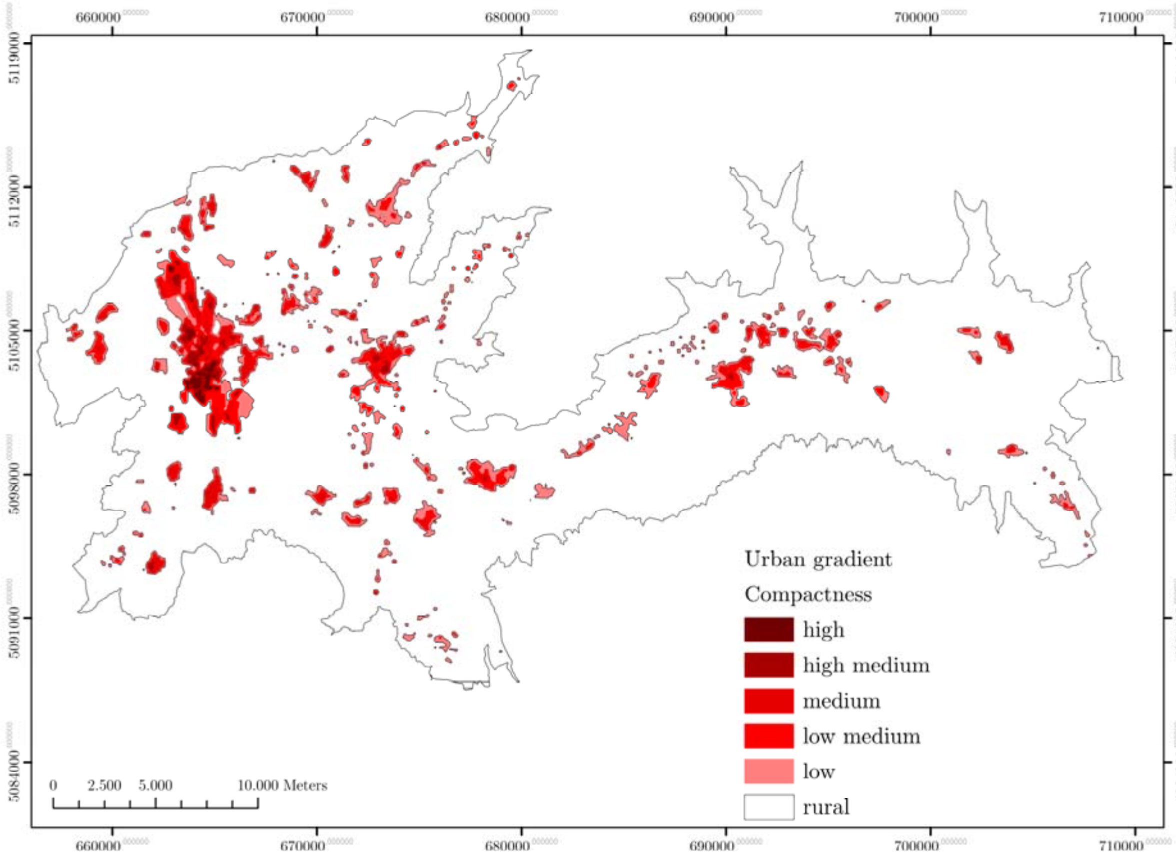
Number of Elements: 1122910
Number of Variables: 2
Number of Clusters: 6
Value of Target Function: 67059179728.685989

Cluster	Elements	Std.Dev.	m3_m2_250	population_density25
0	1038063	62037.296294	0.079325	22.640626
1	37726	76856.669589	0.570727	1255.047593
2	26882	76856.669589	0.570727	1255.047593
3	13368	92976.169073	1.234549	5166.662791
4	5181	112854.891351	2.261138	8895.560264
5	1690	166916.598751	3.471354	16843.518304

0=rural; 1=low; 2= low medium; 3=medium; 4=medium high; 5=high

The UCG map is presented in Figure 43.

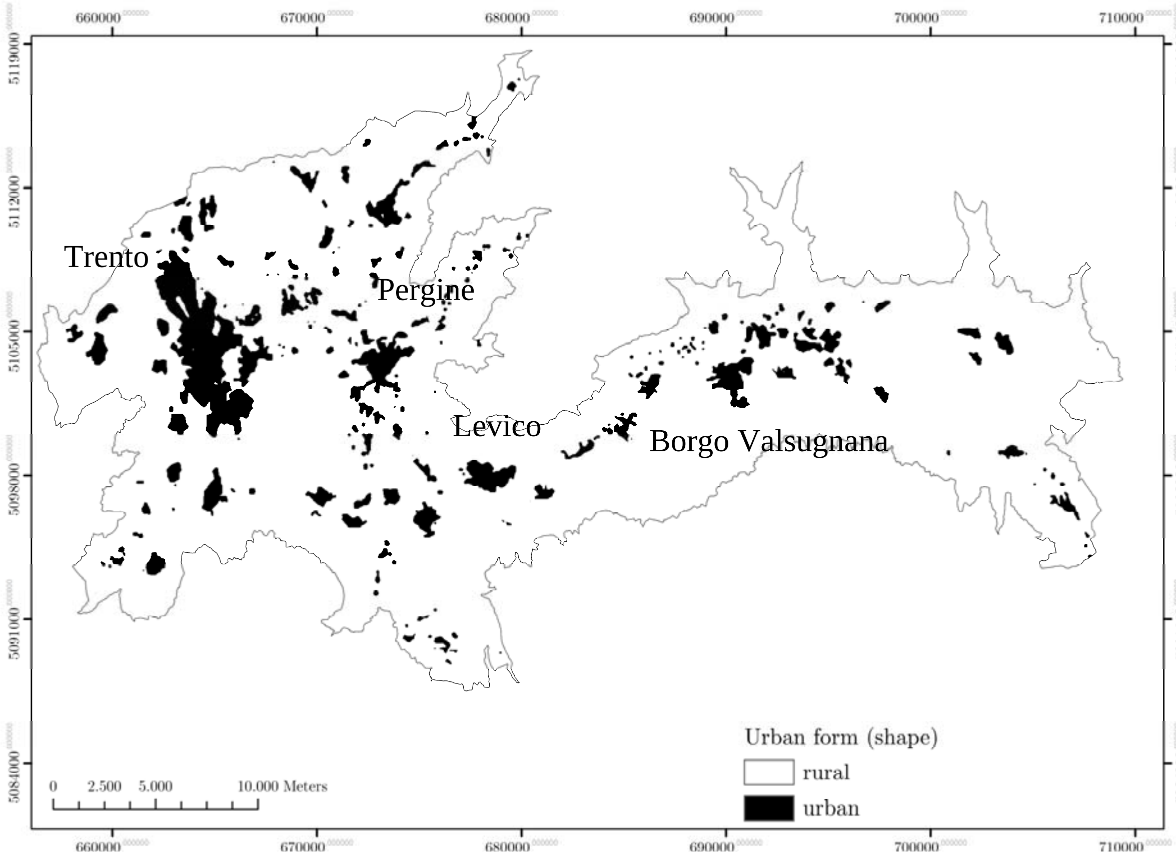
Figure 43. Urban Compactness Gradient map.



From the UCG map the Urban Shapes (US) are derived aggregating spatially contiguous areas.

The map of US is presented in Figure 44.

Figure 44. Urban Shapes.



Multivariate Statistical Analysis – Principal Component Analysis – Correlation Matrix

The produced SPM-RE maps and the UCG map are resampled at a resolution of 100m/pixel on a common grid and transformed in a matrix where the columns contain the values of each raster and the rows represents the pixels.
Afterwards a Principal Component Analysis is performed on the dataset.

Ranking

According to the available literature, the thresholds for the reclassification of the variables in 3 performance classes (high, medium, low) are assigned as follows (Table 8)

Table 8: Thresholds for the reclassification

	SPM	Reclassification Value High	Medium	Low	Literature references for thereshold
Local climate conditions	001_R_CLIMATE	Zone 1	Zone 2	Zone 3 and 4	[5.1]
Natural sun exposition / lighting	002_R_INS	Over 8 h/day	between 5 and 8 h/day	under 5 h/day	[5.19, 5.21, 5.34]
Road network slope	003_R_SLOPE	under 10°	between 10° and 15°	over 15°	[5.24], [5.35]
Main road network density	004_R_PRN	between 500 and 1000 m	between 1000 m and 2000 m	under 500m and over 2000m	[5.24], [5.34]
Solarpower potential of land	005_BEAM_IRR	Over 4000 wh/m2/day	Between 2500 and 4000 wh/m2/day	Under 2500 wh/m2/day	[5.19, 5.21, 5.34]
Biomasspower potential of land	006_R_W_BIOM	over 10 m3/ha/year	between 5 and 10 m3/ha/year	under 5 m3/ha/year	[5.19], [5.28]
Urban Heat Island aptitude	007_U_UHI_APT	low and low-medium	medium	medium and medium-high	[5.29, 5.30, 5.31, 5.32, 5.33]
Building thermal conservation	008_U_BUILD_COM	over 100	between 50 and 100	under 50	[5.27, 5.34]
Housing and urban services proximity	009_U_SERV_PROX	over 15	between 10 and 15	under 10	[5.27, 5.34]
Housing and job proximity	010_U_JOB_D	over 35000 jobs/km2	between 20000 and 35000 jobs/km2	under 20000 jobs/km2	[5.27, 5.34]
Secondary road network density	011_U_SRN	over 1000m	between 500m and 1000	under 500m	[5.24], [5.35]
Public transport accessibility	012_U_BUS_SD	over 5 stops/500m2	between 3 and 5 stops/500m2	under 3 stops/500m	[5.24], [5.35]], [5.24], [5.35]
District Heating and Cooling suitability	013_U_FAR	over 3	between 2 and 3	under 2	[5.27], 5.19]
Ground Source Heat Pump (GSHP) potential	014_U_GSHP	over 3	between 2 and 3	under 2	[5.27]
Natural illumination of buildings	015_N_INS_BUILD	Over 8 h/day	between 5 and 8 h/day	under 5 h/day	[5.27],[5.19]
Green area factor	016_N_NDVI	over 0,4	between 0,1 and 0,4	under 0,1	[5.28]
Walkability and bikeability	017_N_TRN	under 100m	between 100m and 250m	over 250m	[5.35]
Photovoltaic and thermal potential energy of roofs and facades	018_N_BEAM_ROOF	Over 4000 wh/m2/day	Between 2500 and 4000 wh/m2/day	Under 2500 wh/m2/day	[5.19]

Afterward a score is assigned to each class: 3 points for High, 2 points for Medium, 1 point for Low.

For each pixel and for each SE aspect (saving and conservation, efficiency and renewable energy sources) the score are summed up. The resulting maps show the sustainable energy performances for each land unit and for the three SE aspects.

For visualization purpose the three resulting maps are summed up to show the "total SE performances". Each SE aspect map is reclassified in 3 classes (again high=3 points, medium=2 points, low=1 point) with the Jenks Natural Break method [5.36] in order to obtain a composite map with values between 3 to 9. The map is then reclassified in 3 classes, assigning the class "Virtuos" to the land units between 3 and 4 scores, "Medium" to the pixels between 5 and 7 scores, "Low" to the pixels between 8 and 9 scores.

Due to the multiple reclassifications, the arbitrary thresholds assigned to the classes and the lack of a common physical scale and unit, the resulting maps can just be used for visual appreciate differences in SE performances of land units.

Again to visually compare the SE performances of different US, the average values for the pixels belonging to each US are calculated for the each SE aspect. Following the same procedure explained above the maps are summed up into a "composite SE performances" of urban shapes.

5.4 Results presentation and discussion

The organization of the results aims to answer these questions:

- Which intrascale relationships exists between the SPM-REs ?
- Which relationships exist between SPM-REs and UCG?
- Is it possible to characterize the US by SPM-REs?
- Which relationships exist between the US and the SPM-REs?

The results are divided in two sections:

The first presents the output of the Multivariate Statistical Analysis describing the differences between SPM-REs within the case study area and compare them with UCG.

The second presents the ranking of urban areas from the EPUM point of view and makes some considerations about energy sustainability of urban footprints within the case study area.

Multivariate Statistical Analysis results

The aims of the task are:

- To analyse the intra scale correlations between SPM-RE;
- To analyse the correlations between SPM-RE within SE aspects (saving and conservation, efficiency and RES) and UCG.

The correlation matrix for SPM-RE and UCG is shown in Table 9. Table 10,11,12, reproposes the content shown in table 9 aggregating the results by SE aspects.; Tables 13, 14, 15 by scales .

The relationships are shown graphically in the following tables through the use of a red (negative correlation) to green (positive correlation) colour scale.

Table 9. Correlation matrix for SPM-RE and UCG

	RBEAM_IR	RCLIMATE	RINS	RPRN	RSLOPE	RWBIOM	UBUSSD	UFAR	UJOBD	USERPROX	USRN	UUHIAPT	UBCPT	UGSHP	NBROOF	NINSBUIL	NNDVI	NTRN	*URBCPT
RBEAM_IR	1,00	0,26	0,82	0,01	-0,14	0,15	-0,22	-0,20	-0,18	-0,20	0,05	-0,04	-0,01	-0,02	0,47	0,44	0,16	-0,05	-0,19
RCLIMATE	0,26	1,00	0,25	0,37	0,10	0,27	-0,46	-0,48	-0,33	-0,36	0,13	-0,61	0,03	-0,06	0,26	0,25	0,39	-0,05	-0,32
RINS	0,82	0,25	1,00	-0,05	-0,27	0,10	-0,22	-0,24	-0,20	-0,25	0,06	-0,02	0,01	0,02	0,55	0,67	0,15	-0,11	-0,21
RPRN	0,01	0,37	-0,05	1,00	0,02	0,23	-0,11	-0,12	-0,08	-0,12	-0,19	-0,28	-0,06	-0,15	-0,06	-0,10	0,14	0,25	-0,10
RSLOPE	-0,14	0,10	-0,27	0,02	1,00	0,00	0,09	0,19	0,17	0,23	-0,03	0,03	-0,04	-0,02	-0,33	-0,45	-0,09	0,05	0,16
RWBIOM	0,15	0,27	0,10	0,23	0,00	1,00	-0,22	-0,11	-0,13	-0,14	-0,08	-0,03	-0,04	0,01	0,09	0,05	0,12	0,10	-0,12
UBUSSD	-0,22	-0,46	-0,22	-0,11	0,09	-0,22	1,00	0,59	0,51	0,52	-0,10	0,56	0,06	-0,20	-0,19	-0,20	-0,42	0,11	0,34
UFAR	-0,20	-0,48	-0,24	-0,12	0,19	-0,11	0,59	1,00	0,75	0,82	-0,16	0,69	-0,02	0,06	-0,24	-0,23	-0,61	0,21	0,47
UJOBD	-0,18	-0,33	-0,20	-0,08	0,17	-0,13	0,51	0,75	1,00	0,71	-0,07	0,49	-0,02	0,02	-0,19	-0,20	-0,45	0,16	0,29
USERPROX	-0,20	-0,36	-0,25	-0,12	0,23	-0,14	0,52	0,82	0,71	1,00	-0,11	0,56	-0,01	0,05	-0,19	-0,20	-0,47	0,16	0,38
USRN	0,05	0,13	0,06	-0,19	-0,03	-0,08	-0,10	-0,16	-0,07	-0,11	1,00	-0,19	0,04	-0,03	0,06	0,06	0,14	-0,08	-0,12
UUHIAPT	-0,04	-0,61	-0,02	-0,28	0,03	-0,03	0,56	0,69	0,49	0,56	-0,19	1,00	0,00	0,07	-0,02	0,01	-0,52	0,07	0,39
UBCPT	-0,01	0,03	0,01	-0,06	-0,04	-0,04	0,06	-0,02	-0,02	-0,01	0,04	0,00	1,00	0,05	-0,01	0,02	-0,01	0,01	0,00
UGSHP	-0,02	-0,06	0,02	-0,15	-0,02	0,01	-0,20	0,06	0,02	0,05	-0,03	0,07	0,05	1,00	0,00	0,03	-0,02	0,01	0,01
NBROOF	0,47	0,26	0,55	-0,06	-0,33	0,09	-0,19	-0,24	-0,19	-0,19	0,06	-0,02	-0,01	0,00	1,00	0,82	0,18	-0,14	-0,18
NINSBUIL	0,44	0,25	0,67	-0,10	-0,45	0,05	-0,20	-0,23	-0,20	-0,20	0,06	0,01	0,02	0,03	0,82	1,00	0,15	-0,16	-0,20
NNDVI	0,16	0,39	0,15	0,14	-0,09	0,12	-0,42	-0,61	-0,45	-0,47	0,14	-0,52	-0,01	-0,02	0,18	0,15	1,00	-0,11	-0,43
NTRN	-0,05	-0,05	-0,11	0,25	0,05	0,10	0,11	0,21	0,16	0,16	-0,08	0,07	0,01	0,01	-0,14	-0,16	-0,11	1,00	0,09
*URBCPT	-0,19	-0,32	-0,21	-0,10	0,16	-0,12	0,34	0,47	0,29	0,38	-0,12	0,39	0,00	0,01	-0,18	-0,20	-0,43	0,09	1,00

Table 10. Correlation matrix for SPM-RE and UCG - Energy Saving and Conservation aspect

Energy saving and conservation

	R-CLIMATE	R-INS	R-SLOPE	U-FAR	U-JOBD	U-SERPROX	U-UHIAPT	N-INSBUIL	N-NDVI	*U-RBCPT
R-CLIMATE	1,00	0,25	0,10	-0,48	-0,33	-0,36	-0,61	0,25	0,39	-0,32
R-INS	0,25	1,00	-0,27	-0,24	-0,20	-0,25	-0,02	0,67	0,15	-0,21
R-SLOPE	0,10	-0,27	1,00	0,19	0,17	0,23	0,03	-0,45	-0,09	0,16
U-FAR	-0,48	-0,24	0,19	1,00	0,75	0,82	0,69	-0,23	-0,61	0,47
U-JOBD	-0,33	-0,20	0,17	0,75	1,00	0,71	0,49	-0,20	-0,45	0,29
U-SERPROX	-0,36	-0,25	0,23	0,82	0,71	1,00	0,56	-0,20	-0,47	0,38
U-UHIAPT	-0,61	-0,02	0,03	0,69	0,49	0,56	1,00	0,01	-0,52	0,39
N-INSBUIL	0,25	0,67	-0,45	-0,23	-0,20	-0,20	0,01	1,00	0,15	-0,20
N-NDVI	0,39	0,15	-0,09	-0,61	-0,45	-0,47	-0,52	0,15	1,00	-0,43
*U-RBCPT	-0,32	-0,21	0,16	0,47	0,29	0,38	0,39	-0,20	-0,43	1,00

Table 11. Correlation matrix for SPM-RE and UCG - Energy Efficiency aspect

Energy efficiency

	R-PRN	U-BUSSD	U-SRN	U-BCPT	N-TRN	*U-RBCPT
R-PRN	1,00	-0,11	-0,19	-0,06	0,25	-0,10
U-BUSSD	-0,11	1,00	-0,10	0,06	0,11	0,34
U-SRN	-0,19	-0,10	1,00	0,04	-0,08	-0,12
U-BCPT	-0,06	0,06	0,04	1,00	0,01	0,00
N-TRN	0,25	0,11	-0,08	0,01	1,00	0,09
*U-RBCPT	-0,10	0,34	-0,12	0,00	0,09	1,00

Table 12. Correlation matrix for SPM-RE and UCG - Renewable energy potential aspect

Renewable energy sources

	R-BEAM_IR	R-WBIOM	U-GSHP	N-BROOF	*U-RBCPT
R-BEAM_IR	1,00	0,15	-0,02	0,47	-0,19
R-WBIOM	0,15	1,00	0,01	0,09	-0,12
U-GSHP	-0,02	0,01	1,00	0,00	0,01
N-BROOF	0,47	0,09	0,00	1,00	-0,18
*U-RBCPT	-0,19	-0,12	0,01	-0,18	1,00

Table 13. Correlation matrix for SPM-RE and UCG - regional scale

Regional scale	R-BEAM_IR	R-CLIMATE	R-INS	R-PRN	R-SLOPE	R-WBIOM	*U-RBCPT
R-BEAM_IR	1,00	0,26	0,82	0,01	-0,14	0,15	-0,19
R-CLIMATE	0,26	1,00	0,25	0,37	0,10	0,27	-0,32
R-INS	0,82	0,25	1,00	-0,05	-0,27	0,10	-0,21
R-PRN	0,01	0,37	-0,05	1,00	0,02	0,23	-0,10
R-SLOPE	-0,14	0,10	-0,27	0,02	1,00	0,00	0,16
R-WBIOM	0,15	0,27	0,10	0,23	0,00	1,00	-0,12
*U-RBCPT	-0,19	-0,32	-0,21	-0,10	0,16	-0,12	1,00

Table 14. Correlation matrix for SPM-RE and UCG - urban scale

Urban scale	U-BUSSD	U-FAR	U-JOBD	U-SERPROX	U-SRN	U-UHIAPT	U-BCPT	U-GSHP	*U-RBCPT
U-BUSSD	1,00	0,59	0,51	0,52	-0,10	0,56	0,06	-0,20	0,34
U-FAR	0,59	1,00	0,75	0,82	-0,16	0,69	-0,02	0,06	0,47
U-JOBD	0,51	0,75	1,00	0,71	-0,07	0,49	-0,02	0,02	0,29
U-SERPROX	0,52	0,82	0,71	1,00	-0,11	0,56	-0,01	0,05	0,38
U-SRN	-0,10	-0,16	-0,07	-0,11	1,00	-0,19	0,04	-0,03	-0,12
U-UHIAPT	0,56	0,69	0,49	0,56	-0,19	1,00	0,00	0,07	0,39
U-BCPT	0,06	-0,02	-0,02	-0,01	0,04	0,00	1,00	0,05	0,00
U-GSHP	-0,20	0,06	0,02	0,05	-0,03	0,07	0,05	1,00	0,01
*U-RBCPT	0,34	0,47	0,29	0,38	-0,12	0,39	0,00	0,01	1,00

Table 15. Correlation matrix for SPM-RE and UCG - neighbourhood scale

Neighborhood scale	N-BROOF	N-INSBUIL	N-NDVI	N-TRN	*U-RBCPT
N-BROOF	1,00	0,82	0,18	-0,14	-0,18
N-INSBUIL	0,82	1,00	0,15	-0,16	-0,20
N-NDVI	0,18	0,15	1,00	-0,11	-0,43
N-TRN	-0,14	-0,16	-0,11	1,00	0,09
*U-RBCPT	-0,18	-0,20	-0,43	0,09	1,00

Intra scale correlations between the spatial patterns of SPM-RE

The analysis of the correlations between the SPM-RE can be summarized as follow:

- Most of the correlations between regional scale and urban scale are negative (increasing the regional variables the urban decrease);

- Most of the correlations between urban scale and neighbourhood scale is negative;
- Most of the correlations between regional scale and neighbourhood scale are positive;

As expected a positive correlation, but not very high, is observed between “regional beam sun irradiation”, “regional insulation” and the corresponding “beam irradiation of roofs” and “insolation of buildings” at a neighbourhood scale.

Correlations between SPM-RE grouped by SE aspects (saving and conservation, efficiency and RES) and UCG.

Energy saving and conservation

- Urban compactness is negatively correlated with the variables climate zones, land irradiation and insolation, NDVI and insolation and irradiation of buildings;
- while it is positively correlated with the variables building density, job proximity, overheating aptitude of surfaces, urban services proximity.

Energy efficiency

- UCG is negatively correlated, but weakly, with the variables primary and secondary road network distance.
- It is positively correlated with the public transport stops density.
- No correlations can be observed with the building compactness and tertiary road network distance.

Renewable energy sources

- Negative correlations are observed between UCG and land beam irradiation, *Wood biomass availability*, beam irradiation on buildings.
- The correlation between “beam irradiation on buildings and UCG is stronger than the correlation between land irradiation and UCG.

Correlations between the SPM-RE and the UCG.

As expected different SPM-RE show differences when related to UCG.
These relationships can be summarized as follow:

- UCG is positively correlated with FAR, job proximity, urban services proximity, public transport stops density;
- It is positively correlated with overheating aptitude of surfaces;
- It is also characterized by a negative correlation with NDVI.

Characterization of the UCG by scales and SE aspect

Drawing from these empirical observations it is possible to formulate some hypothesis for the case study area:

At the regional scale the spatial patterns of SPM-RE determine the suitability for the regional localization of urban settlements from the energy point of view. The compact urban settlements in this region are typically located in the valley floors or on the conoides with gently slope to the valley floor. These areas are more accessible and with a mitigate climate but are often shadowed by surrounding mountains that reduce the incoming solar irradiation and the available hours of natural light. Very rarely the settlements are located on the mountain slopes where the sun irradiation and the proximity to the forests are higher and the climate is more harsh. The prevalent localization of urban settlement can affect the production of energy from the sun source and the use of wood biomass in compact urban area. It is clear that the re-localization of existing urban settlement within the region is not possible but the localization parameter should be considered at least in the choice of the strategies for the renewal urban projects and for the localization of new settlements.

The negative correlations between SPM-RE at urban and neighbourhood scales can explain the separation between the urban and the neighbourhood design processes from the point of view of energy. This empirical observation could sustain the hypothesis that a stronger relationship between urban and neighbourhood design should be developed taking into account the consequences for the energy system through an intra scale integrated strategy.

The positive correlations between SPM-RE at regional and neighbourhood scales underline again the importance of the regional localization of urban settlements and the direct connection between these two scales, partially intercepted by the urban one. It is important to highlight the positive but not strong correlation between sun irradiation (on land and on the roofs and buildings) at regional and neighbourhood scales. This difference, explained also by the correlations of these variables with the UCG, can be easily connected with the interference and the interaction between some urban morphology (disposition and layout of urban object like buildings and trees) and the sun irradiation. The sun irradiation on the roofs and the hours of light ,in fact, decrease with the increase of urban compactness.

From the energy saving and conservation point of view UCG determines high values of building density, job proximity and urban services proximity. This positive correlation underlines the aptitude of compact urban areas to save energy especially reducing the internal mobility needs.

A positive correlation is observed also between UCG and the overheating aptitude of surfaces. This could lead to the consideration that compact urban area are more af-

fected by the Urban Heat Island phenomenon than the dispersed one but analyzing other variables it is possible to observe that the Overheating aptitude of surfaces is negatively correlated with the NDVI and with the Climate Zones. It is possible to state that the location and the green factor can play a role to reduce the overheating aptitude of surfaces in compact urban areas.
From the energy efficiency point of view UCG shows a good and positive correlation with public transport stops density. The observation suggests that public transport is more accessible in the compact urban area than in the dispersed one. An interesting observation comes from the road network density indicators. UCG in this case is negatively but weakly correlated with the distance from primary road network and the distance from secondary road network while it is not correlated with the distance from tertiary road network. This lead to consider that compact urban areas have the same road network density than the more dispersed ones. The reduction especially of the secondary road network and the improvement of tertiary roads network in compact areas could increase the walkability and bikeability levels in this areas. Compact areas are, moreover, the most flat and then suitable for the sustainable mobility .
Jumping to the renewable energy sources negative correlations can be observed between UCG and the RES potentials. Wood biomass availability is positively correlated with Climate Zones that means that forests have been relegated in the more harsh climate zones. As expected the sun irradiation is highly correlated with the insolation and negatively correlated with UCG. Continuing the considerations started above it is possible to observe that the potential solar energy in urban areas is function of two main variables: regional localization and urban compactness.

Ranking results

The aims of the task are:

- To transform SPM-RE in Sustainable Energy Performances (SEPs);
- To visualize SEPs within urban areas;
- To visualize the SEP of different Urban Shapes ;
- To classify US in “virtuous” and “bad” settlements from the SE point of view.

SPM-RE ranking and visualisation of Sustainable Energy Performances (SEP) of urban areas.
The ranked maps are show in Figures 45, 46 and 47.
The sum of the points with the pixel-by-pixel method rendered the results with the following points ranges:

- From 14 (worst) to 27 (best) for the Energy Saving and Conservation aspect (figure 45);

- From 5 (worst) to 13 (best) for the Energy Efficiency aspect (figure 46);
- From 5 (worst) to 18 (best) for the Renewable Energy Sources aspect (figure 47).

A red (worst) to green (best) legend is used to visualize the maps.

Figure 45. Energy saving and conservation ranking map.

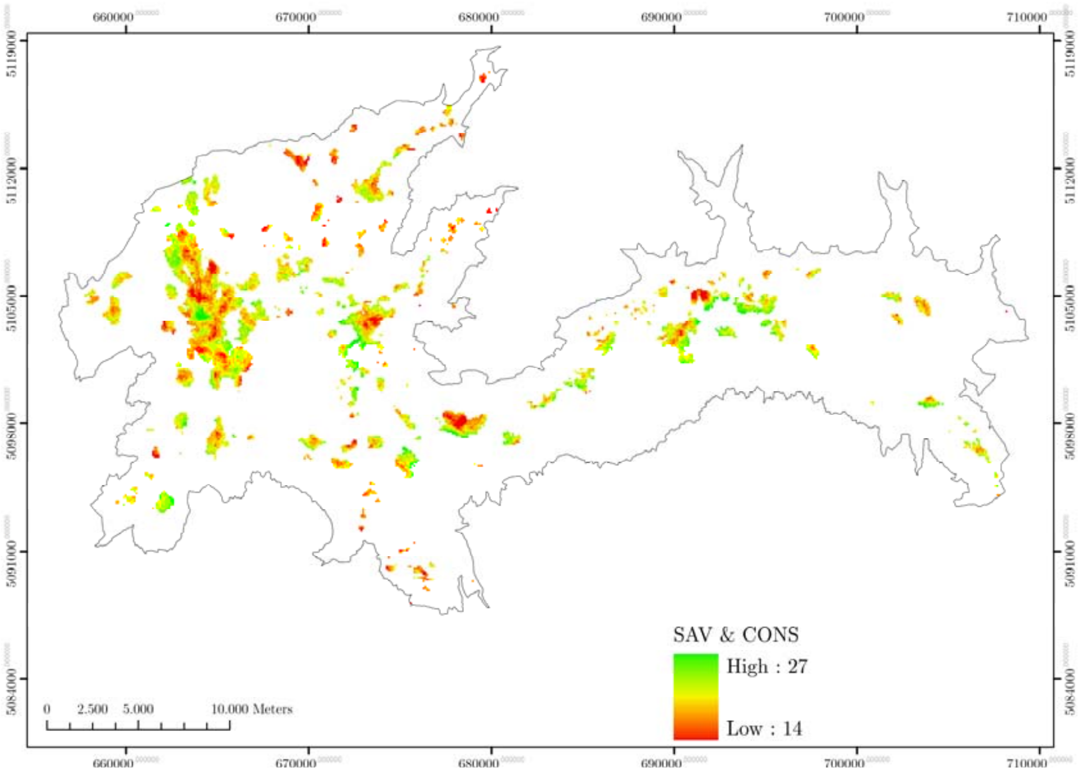


Figure 46. Energy efficiency ranking map.

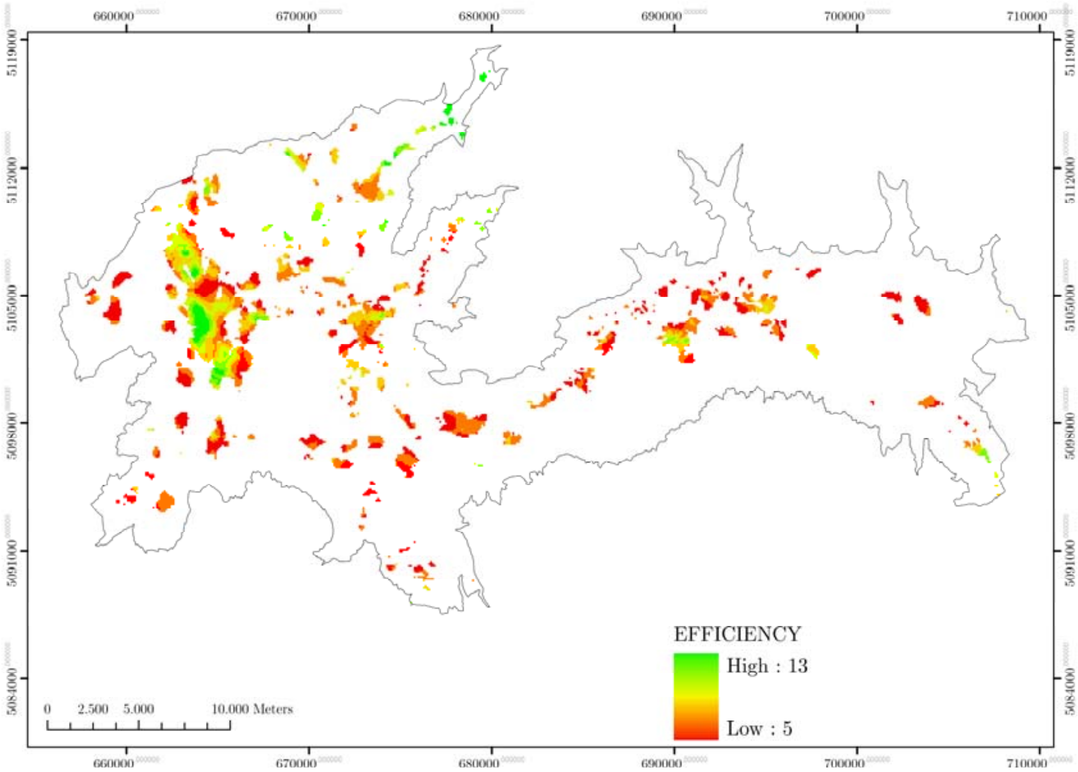
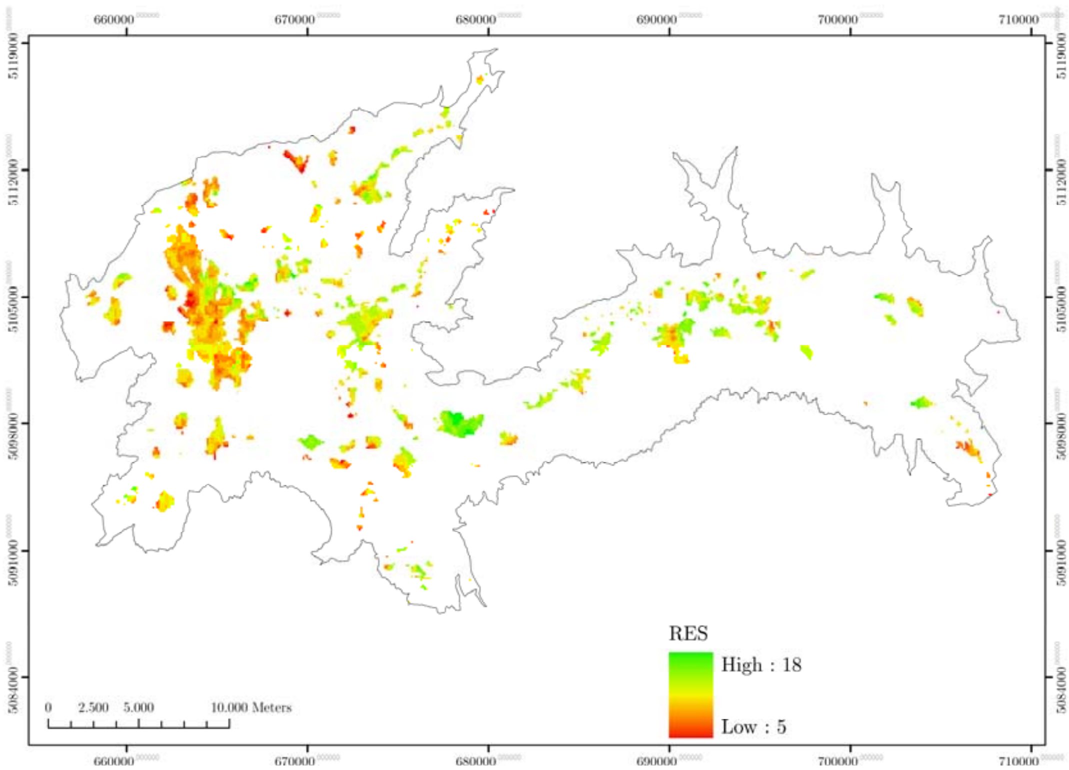


Figure 47. Renewable Energy Sources ranking map.



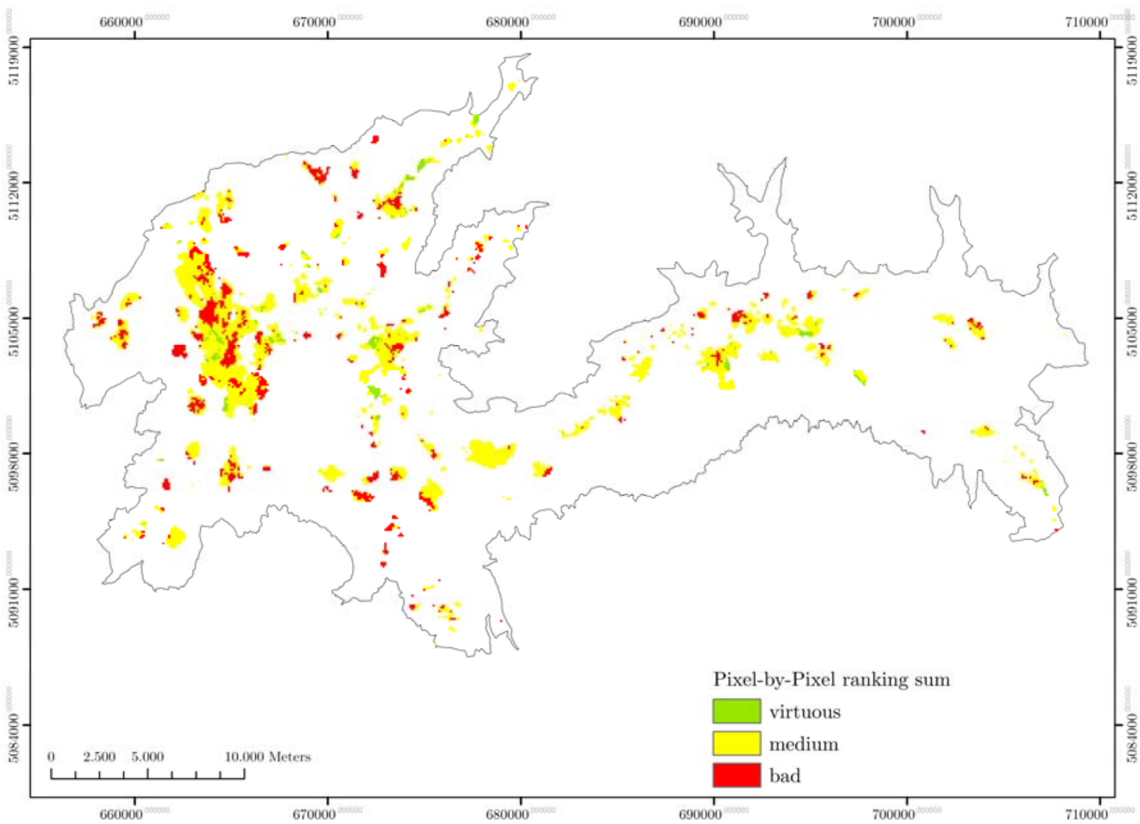
As expected the spatial patterns highlighted by the pixel-by-pixel rank are heterogeneous but zones with similar Energy Performances are identifiable.
For a visualization propose the 3 SEP maps are reclassified in 3 classes each (virtuous, medium, bad) with the natural break method [5.36], and summed up following the reclassification scheme in table 16 to obtain the map of "virtuous" and "bad" zones from the SEP point of view.

Table 16. Jenks natural break reclassification and sum

Jenks natural break reclassification points	
Virtuous	3
Medium	2
Bad	1
Reclassification of the points sum	
From 8 to 9	Virtuous
From 5 to 7	Medium
From 3 to 4	Bad

The resulting "total SE performances" map per pixel is presented in figure 48 . It is just for a visualization purpose assuming the 3 aspects of SE (saving and conservation, efficiency and RES) perfectly equivalents.

Figure 48. Pixel—by– pixel reclassification in Virtuous to Bad energy performances.



Visualisation of SEP for Urban shapes.

From the 3 ranking maps presented above the urban shapes ranking maps are derived (figures 49,50 and 51).

The average of the points within the urban footprints areas rendered the following points range:

From 15 (worst) to 26 (best) for the Energy Saving and Conservation aspect (figure X);

From 5 (worst) to 13 (best) for the Energy Efficiency aspect (figure X);

From 6 (worst) to 15 (best) for the Renewable Energy Sources aspect (figure X).

Figure 49. Energy saving and conservation ranking map—urban shape average.

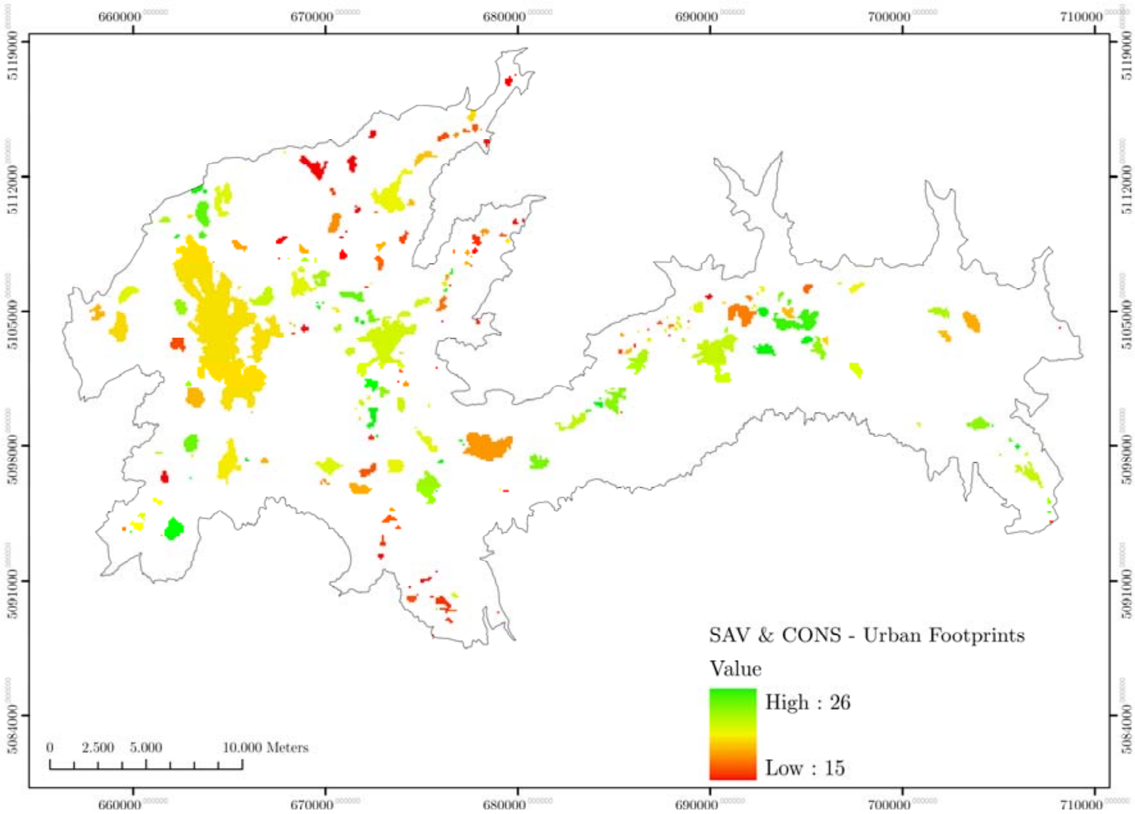


Figure 50. Energy efficiency ranking map—urban shape average

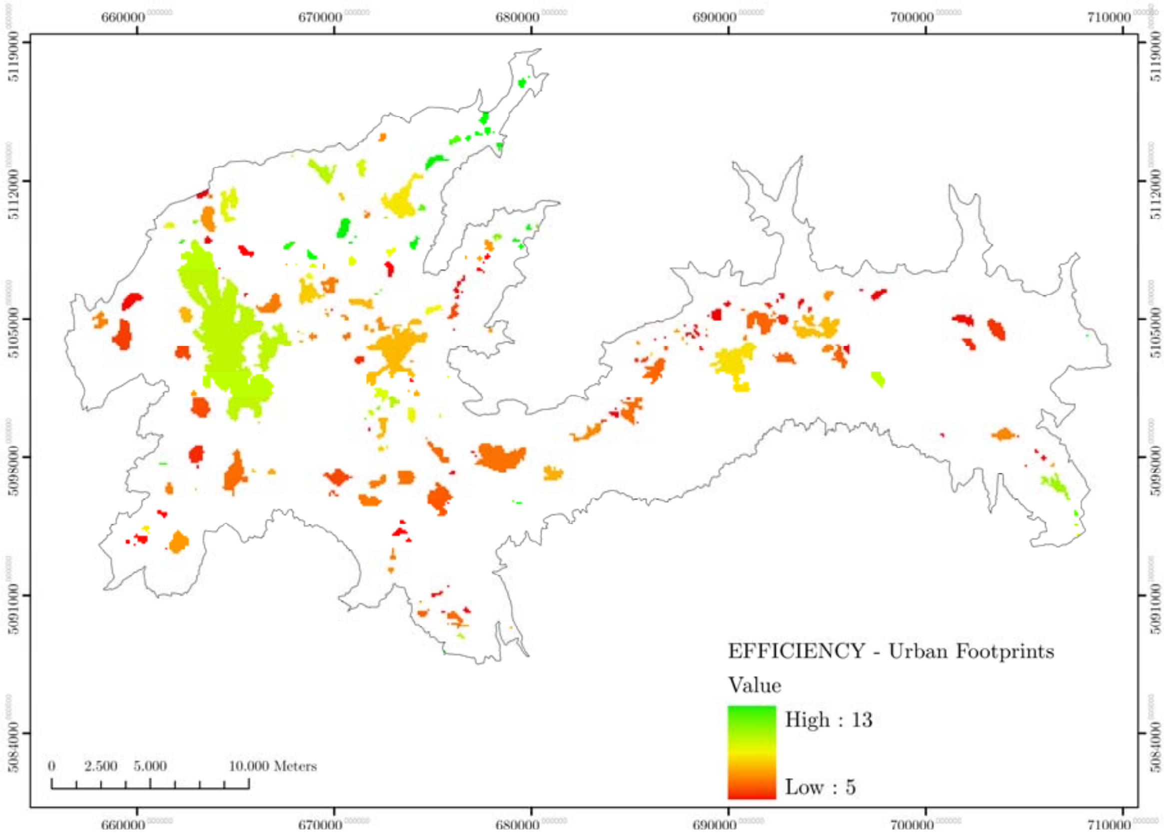
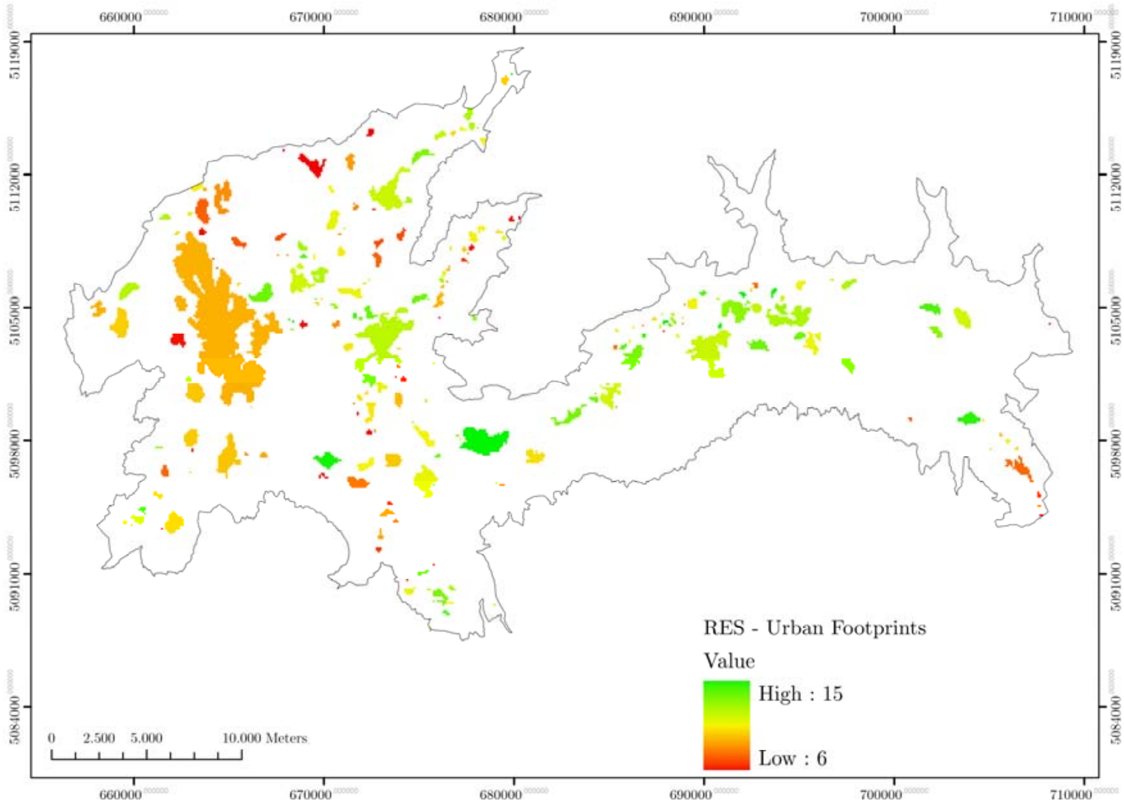


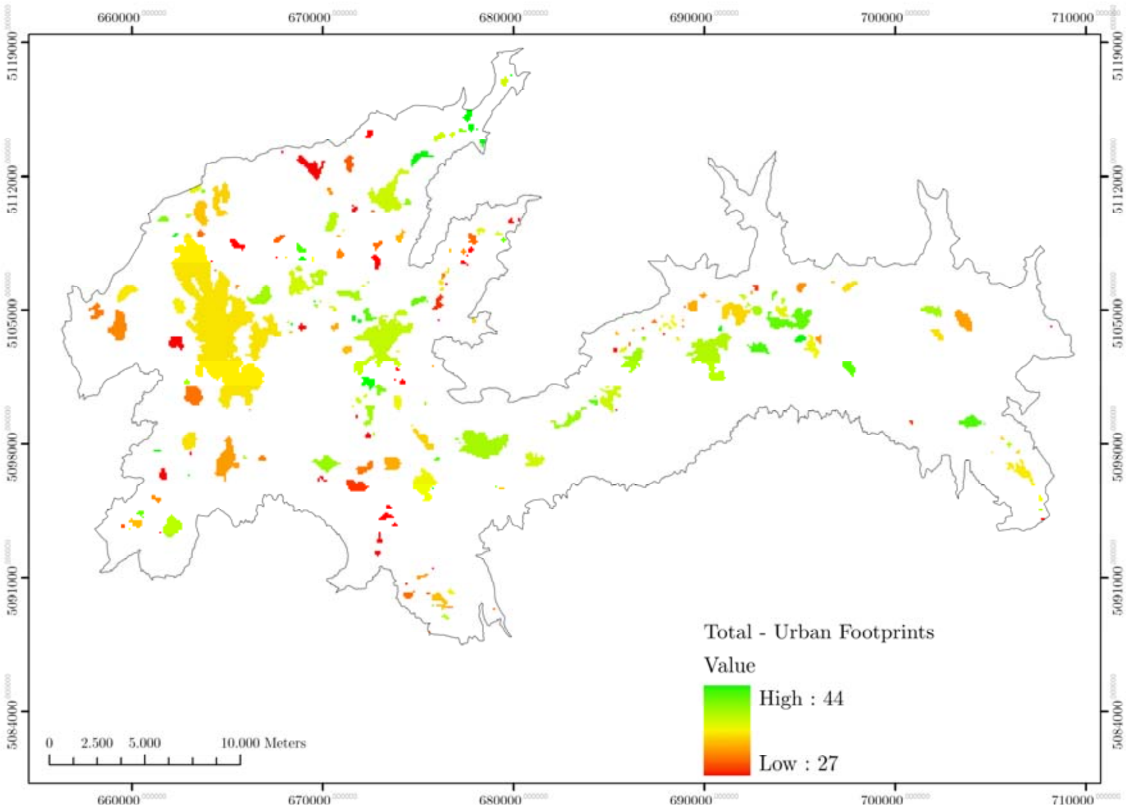
Figure 51. Renewable Energy Sources ranking map– urban shape average.



For a visualization propose the 3 SEP maps are reclassified in 3 classes each (virtuous, medium, bad) with the natural break method (RIF) and summed up, following again the reclassification scheme in table 16, to obtain the map of "virtuous" and "bad" Urban shapes from the SEP point of view.

The results of the sum is presented in Figure 52.

Figure 52. Reclassification of urban shapes in Virtuous to Bad energy performances.



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Chapter 6

6. Discussion of the results

The proposed methodology can contribute to the debate on the role of the urban morphology on the sustainable energy performances of settlements. In particular the spatial perspective of the analytical framework allows direct considerations of the spatial distribution of the Energy Performances of Urban Morphologies (EPUM).
On the technical end the proposed approach can be further improved, by considering in particular the following issues:

- the multivariate statistical analysis applied to raster images shows to work properly and to be a powerful analytical instrument but the results need to be interpreted by the analyst adding subjectivity to the final assessment;

- the availability of some open-source GIS software that embedded several spatial analysis tools reduce the elaboration time.

The LiDAR survey provided a very good set of derived products. The availability of these 3D and high resolution datasets strongly helped to improve the estimation of some urban morphology indicators as well solar irradiance on buildings. However, the calibration of the theoretical model can be improved by using sensors to collect data about solar beam irradiation and natural illumination;

- The dataset used for the estimation of potential geothermal energy was incomplete, requiring the use of proxy variables. Field surveys are needed to better characterize geology and the distribution of groundwater. Additionally, groundwater protection areas need to be mapped and excluded from the analysis, because GSHP technology can alter groundwater levels and temperature;

- Detailed maps of forest trails can be used to integrate the analysis of the accessibility to wood biomass;

- Further development of the proposed approach should also consider the performance of the different technologies available on the market to exploit RES;

- The reclassification of SEP maps used arbitrary thresholds. Sensitivity analysis can be performed to assess to what extent the final results are affected by the use of different thresholds;

- Available datasets and methods did not allow to carry out a fully quantitative analysis. Consequently, qualitative classes were used in the output maps. This affected the interpretability of the results, and in particular of the comparison analysis, because the classes were not associated to any physical energy unit. At this stage the selection of threshold criteria can be performed according to several qualitative factors (i.e. economic, social and environmental factors) that better fit the characteristic of the studied area.

- The case study shows that urban growth occurred incrementally around existing centres, the most efficient and energy savers, but disregarding patterns of RES distribution, which tended to be dispersed within the territory. This result cannot be generalised to other cases, but it sustains the hypotesis that sustinable energy development of urban morphologies implies complex re-organisation of the territory with, probably, increases decentralisation of energy production and the use of widely-diffused energy resources. This should be taken into account when drawing reccomendations for sustainable urban development that promotes urban density and the use of RES.

At a more general level, there appear to be three empirical results that, while specific to the case study area, shed some light on the relationship between urban morphologies and sustainable energy development. These are:

- The energy saving and conservation performances of the urban settlements have a positive correlation with the compactness to, while compactness is negatively correlated with renewable energy sources potentialities;

- Even if an energy strategy for sustainable development of urban settlements could follow a logic of compactness, other factors show to be equally important and they should be taken into account: the settlement localization at a regional scale that determines “a priori” the maximum levels of energy sustainability reachable by the settlements (especially regarding RES), the internal urban design and the dimension/shape of the urban footprints;

- Any urban area shows to reach the best ranking in all the three aspects of sustainable energy. It is possible to conclude that, for the case study area and for the energy performances analyzed, any urban area shows to be in absolute better than another;

- The methodologies, procedures and tools available in literature for the sustainable energy performances assessment of urban morphologies show to be few, sectorial, sometime inaccessible and outdated. As well (the same consideration can be made) for the datasets available for the case study area. Investments in a “culture” and a “tradition” to collect and elaborate energy variables within urban design and planning processes should be urgently promoted to reach more results in terms of sustainable energy;

- The conceptual models available in literature for the integration between environmental and human processes are not optimized for the sustainable energy concept and should be revised;

- The complexity of urban/energy system needs to be analyzed with proper instruments. The Pattern Oriented Modelling approach shows to fit the complexity of urban morphologies /energy performances interaction. It also suggests to focus the analysis on the “state” of the urban environment instead t than on the “pressures” to the urban environment, as traditional approaches propose.

The test of the proposed methodology on the case study suggests several strategies for urban planning and design. Zooming to a specific urban area permits to specify some guidelines for interventions. Some examples follow.

For the Trento urban area (for the spatial reference see Figure 44):
Trento shows to have a general good performance in energy efficiency, medium performances in energy saving and low aptitude in renewable energy sources exploitation. This performances levels are not equally distributed inside its urban shape but are well identifiable by clear spatial patterns. Some guidelines could be :

- To improve the energy saving and conservation conditions. Considering that the most affected field is the overheating aptitude of surfaces, an urban greening strategy should focus on those areas that show low scores in this aspect;

- To enhance the investiments on renewable energies only in those areas with medium-high potential, limiting the interventions in those with less potential;

- To increase the mobility energy efficiency in the northern area improving , for example, the public transport accessibility, the walkability and the bikeability;

For the Levico Terme urban area some guidelines are (for the spatial reference see Figure 44):

- To improve the energy saving and conservation increasing the proximity to urban services;

- To invest in energy production from renewable sources (Levico shows to have high RES potentials);

- To improve the energy efficiency optimizing the public transport connections.

For each analyzed urban settlements it is possible to make this kind of considerations. The use of the proposed methodology permits to identify virtuous and bad urban settlements from the energy performances point of view and to make hypothesis on the possible strategies for their improvement.

Chapter 7

7. Conclusions

The starting hypothesis has been confirmed: a relationship exists between "urban morphology" and "sustainable energy performances" of settlements and it can be spatially visualized and systematized.
This dissertation has attempted to answer the question: "does urban morphology play a role in sustainable energy performances of settlements?". Answering this "sample" question ends up being a challenging enterprise. Not a clear and broadly accepted definition of "sustainable energy" exists. Furthermore, the interactions of urban morphology on sustainable energy performances take place in a complex system environment, the urban metabolism, that is very difficult to model.
The dissertation has structured the discussion in four basic categories: (1) the presentation of the state of the art about sustainability, energy and urban systems; (2) the presentation of the conceptual framework; (3) the presentation of the methodology, the analytical framework and database; (4) the test of the methodology on a case study area.
In synthesis:
The state of the art on sustainable energy design of urban morphologies has been presented and discussed.
A brief review of the sustainability concept shows that today this word has become so commonplace to be meaningless. In that regard, the basic definition given by the Bruntland commission is a useful reference to pose the fundamental challenge of balancing the needs of today with the needs of the future. In this sense the Strong sustainability paradigm shows to better fit the concept of "sustainable energy in post carbon era" considering that the natural stock, in this case the energy sources, should not decrease over time.
A definition of sustainable energy in urban systems has been proposed and discussed. Again no agreement in literature is found. The "Trias Energica", proposed by the Delft University, has been used in this research. Afterwards a definition of sustainable en-

ergy of urban morphologies has been derived and connected to the debate on “compact vs sprawl”. Literature shows no scientific agreement on the definition of the most sustainable urban morphology from the sustainable energy’s point of view, even if, mainly due to high political priorities, the compact form has been elected. For this reason the research has been developed on the framework of urban compactness. The definition of “compact” form itself shows to be unclear in literature. In this sense the “urban compactness gradient” approach can help to define and compare different levels of compactness according to the selected indicators.

A methodology to assess urban morphologies from the sustainable energy point of view has been presented. In particular:
A conceptual model based on the Pressure, State, Responses to relate the sustainable energy concept with urban morphology design has been presented and discussed. Again literature did not help a lot: PSR conceptual model shows to be very general. A PSR model focused on energy and urban morphology was then developed and presented by the research.
An new analytical framework to analyze the multi-scale spatial interactions between urban morphology and their energy performances has been presented; it is based on considerations derived from urban ecology and adapted to fit the issues of the research.A procedure for the definition of an urban compactness gradient has been presented;
A set of tools to spatially describe the interactions between urban morphology and their energy performances has been proposed. It is composed by:

- A set of spatial indicators; particularly relevant is the geo-database issue. A new remote sensor, the LiDAR, shows to be very useful in the construction of the morphological database related to energy aspects. The available LiDAR datasets for the case study area have been tested with advanced software engines and used in the elaboration of several Spatial Pattern Metrics, for both urban morphology metrics and solar irradiation modeling analysis;

- A pixel-by-pixel approach and Pattern Oriented Modelling (POM); This approaches show to be very powerful in the description of the complex system composed by the interactions between urban morphology and energy performances. In particular the POM with the medawar zone strategy suggests a procedure to manage the complexity of urban systems without simplifying the model too much;

- The multivariate statistical analysis; this technique applied to raster images shows to work properly and to be a powerful analytical instrument. In particular this technique, developed for the analysis of multiband satellite images, shows to be useful also in the analysis of custom raster datasets;

- A ranking system; even if the proposed ranking system is very simple and with an quite high grade of approximations, the results suggest many answers to the research questions. This leads to the conclusion that, with the necessary improvements, tests and validations, the method can provide reliable and useful results;

A test of the proposed methodology on a case study has been performed.
The results of the test demonstrate that the proposed method can be effectively used to assess urban morphologies from the sustainable energy point of view. The main findings are that:

- No urban area in particular shows to reach the best score in each sustainable energy aspect. This leads to new hypotheses. For the case study area, maximum performances on each aspect of sustainable energy performances cannot be reached at the same time. No urban area within the case study is optimized from the sustainable energy point of view;

- Existing urban settlements could be optimized to reach an higher level of sustainability in the energy field but three conditions are needed for the re-design: a good assessment of the energy conditions of the settlement, the identification of "virtuous" and "bad" urban areas from the energy performances point of view and the maximization of the specific characteristics of a settlement according to factors like location, land potentialities, internal design and structure, proximity to other settlements, etc;

- A general strategy for the optimization of urban morphologies from the sustainable energy point of view can be the maximization of the three aspects of sustainable energy: saving and conservation, efficiency and renewable energy production. Each of them finds out a set of spatial patterns that permit to measure and compare the energy performances of different urban areas.

Limits of the research and further developments

Data scarcity and available methods do not allow to carry out a fully quantitative analysis. This results in a qualitative comparison between Sustainable Energy Patterns (SEP). Even if the thresholds selection criteria is given for the SEP, the high subjectivity in the thresholds selection makes this research difficult to be reproduced with other datasets.

This affects the interpretability of the results and in particular of the comparison between Spatial Pattern Metrics – Relevant for Energy (SPM-RE) and SEP because they are not associated to any physical common energy unit. A strategy to solve this limitation is suggested by Jorgensen with the concept of "emergy" [7.1] : "Emergy expresses the cost of a process or a product in solar energy equivalents. The basic idea is that solar energy is our ultimate energy source and by expressing the value of products in emergy units, it becomes possible to compare apples and pears". Unfortunately any reliable conversion tables between "processes" and "emergy" is given so far.

At this stage the selection of threshold criteria can be performed according to several qualitative factors (i.e. economic, social and environmental factors) that better fit the characteristic of the studied area. The research and the study of analogous case areas can also provide useful information about SEP in similar territorial contexts. A Delphi survey can also help to better define thresholds and spatial indicators because literature has shown to be unclear. Particular attention should be given to a sensibility analysis of thresholds of SEP-RE.

In general, the lack of datasets, methods and tools to assess specific interactions between urban morphology and sustainable energy aspects has influenced the quality of the results. Too many approximations in the procedures can produce a cumulative effect error in this sense.

A set of indicators to validate the results has to be developed and integrated in the procedure. In particular spatial pattern metrics of final energy consumption for buildings and mobility can help in this sense. A multidisciplinary approach to the problem, instead of the traditional mono-disciplinary approach (i.e. transport, technical physics, urban planning, engineering, etc.), could be the way.

The items above show that the proposed approach is affected by uncertainty factors and that approximations have been introduced to achieve the final outputs but that some strategies are available to improve the method.

The main contribution of this research, however, resides in the proposal of a sequence of analytical steps to support sustainable energy urban design and renewal.

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Chapter 8

8. References

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