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2.5D maps supporting energy policy in Turin

Geomatics for energy transition applications and analyses in a portion of District 6

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Summary

Acronyms

AGL	Above Ground Level
APE	Attestato di Prestazione Energetica
AT	Aerial Triangulation
CEC	Citizen Energy Community
CGR	Compagnia Generale Ripresearee S.p.A.
COP	Coefficient of Performance
DB	DataBase
DBMS	DataBase Management System
DEM	Digital Elevation Model
DSM	Digital Surface Model
DT	Digital Twin
DTM	Digital Terrain Model
ER	Entity Relationship
GCP	Ground Control Point
GDB	GeoDataBase
GEPI	Global Energy Performance Index
GIS	Geographic Information System
GHG	GreenHouse Gas
GML	Geography Markup Language
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IFSAR	InterFerometric Synthetic Aperture Radar
ICT	Information and Communication Technologies
IMU	Inertial Measurement Unit
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection And Ranging
LoD	Level of Detail
MD	Ministerial Decree
NIR	Near InfraRed

NZEB	Nearly Zero Energy Building
OGC	Open Geospatial Consortium
PA	Public Administration
PED	Positive Energy District
REC	Renewable Energy Community
RES	Renewable Energy Source
RGB	Red Green Blue
SAR	Synthetic Aperture Radar
SDG	Sustainable Development Goal
SDI	Spatial Data Infrastructure
SQL	Structured Query Language
TIN	Triangulated Irregular Network
TP	Tie Point
UML	Unified Modelling Language
VGI	Volunteered Geographic Information
WFS	Web Feature Service
WMS	Web Map Service

Abstract (EN)

The present thesis works on the concept of energy transition, providing analyses aimed to orient energy policies in a portion of the City of Turin. In particular, it focuses on the building sector, recognising its high impact and the potential for renovation. It takes advantage of 2.5D data, which include elevation information in a bi-dimensional representation, but keeps the option of tridimensional representations open.

The work aims to provide a theoretical background to the concepts of digital cartography and energy transition before going into the practical application. This is structured along two axes, one about energy renovation and the other concerning photovoltaic potential. Different combinations are explored to find the most balanced scenario, potentially mitigating the investments with proportioned savings. The first step is energy classification, carried out by analysing thermal dispersion; then, alternative retrofitting scenarios are analysed, comparing the savings not only in terms of kilowatt-hour but also computing the CO_2 emissions which can be prevented. Solar radiation is calculated through a tool in ArcGIS Pro software for assessing the potential photovoltaic productivity, considering three alternative technologies (monocrystalline, polycrystalline, thin film). Finally, an electrification scenario integrates the two sections about renovation and solar potential to define an optimal reference.

The thesis demonstrates that integration is the key for improving the sustainability of the building sector, targeting the least performing buildings and the most productive roofs for renovation and photovoltaic panels installation, respectively. Considering the dated building stock and the good amount of solar radiation, both solutions have a high potential, it is the policymakers' job to define a suitable strategy for balancing social, economic and environmental costs and benefits.

Abstract (IT)

La presente tesi elabora il concetto di transizione energetica, fornendo analisi volte ad orientare le politiche energetiche in una parte della Città di Torino. In particolare, si concentra sul settore edilizio, riconoscendone l'elevato impatto e i benefici potenziali derivanti da ristrutturazioni. Vengono utilizzati dati in 2.5D, che includono informazioni sull'altitudine in una rappresentazione bi-dimensionale; tuttavia non è stata esclusa a prescindere l'opzione di una rappresentazione tridimensionale.

Lo scopo della ricerca è di fornire un'introduzione teorica ai concetti di cartografia digitale e transizione energetica, prima di entrare nel merito dell'applicazione pratica. Questa è strutturata secondo due assi principali, il miglioramento energetico e il potenziale fotovoltaico. Diverse combinazioni vengono esplorate per definire lo scenario più bilanciato, che possa mitigare l'investimento con risparmi proporzionati. Il primo passo è la classificazione energetica, realizzata analizzando la dispersione termica; vengono poi analizzati scenari di ristrutturazione alternativi, che comparano i risparmi non solo in termini di chilowattora, ma anche calcolando le emissioni di CO_2 che vengono evitate. Uno strumento nel software ArcGIS Pro permette di calcolare la radiazione solare, per poi definire il potenziale fotovoltaico considerando tre tecnologie alternative (monocristallino, policristallino, film sottile). Infine, uno scenario di elettrificazione integra le due sezioni su ristrutturazioni e potenziale solare per definire un riferimento ottimale.

La tesi dimostra che l'integrazione è la chiave per migliorare la sostenibilità del settore edilizio, mirando agli edifici meno performanti e ai tetti più produttivi rispettivamente per ristrutturare e installare pannelli fotovoltaici. Considerando il patrimonio edilizio datato e la buona radiazione solare, entrambe le soluzioni hanno un alto potenziale, sta ai decisori politici definire una strategia che possa bilanciare costi e benefici sociali, economici ed ambientali.

I

Introduction

Contemporary cities are facing a number of challenges connected to sustainable development and its three dimensions. Recently, the political debate has focused on environmental aspects, but the gas crisis and the consequent increases in the energy price have put the accent on economical and social aspects, too. The building sector, considering its relevant energetic and environmental footprint, has huge impacts on such problems, thus requiring a paradigm shift.

This thesis, applying the geomatic instruments to the energy sector, aims to provide a method for an efficient and comprehensive assessment on the possibilities for targeted renovations and the energetic transition. In particular, after having recognised the potential and the limits of traditional representations, it will point out the applications which use the elevation component as a key information. The complexity of 3D modelling resulted in the choice of 2.5D data for a comprehensive analysis which, at the same time, keeps efficiency as a principal goal. 2.5D implies a diffuse indication of the elevation in a 2D representation: it is different from traditional 2D expedients (contour lines and height points) for the homogeneity, from 3D models because it does not imply extrusions. The whole process was carried out with ArcGIS Pro, a software by ESRI for the elaboration of spatial data and their attributes.

In particular, aerial data are taken into account: photogrammetry allows a fast and precise survey which does not require to touch the object, making it one of the most common surveying methods currently. At the same time, it allows tridimensional reconstruction, enabling precision representation in different forms (2D, 2.5D, 3D). Data can be acquired in different spectral bands: thermal infrared records the temperature of the surfaces, providing accurate information on dispersion. Such information can be used for evaluating the energy performance.

The process was pivoted on a portion of Turin (Italy): *Barriera di Milano* is a peripheral area, characterised by social distress and a heterogeneous urban fabric. Therefore, it is a perfect case study, requiring something to unlock its potential.

Chapter 2 provides an overview on photogrammetry, 2D and 3D methods for representing reality; the focus would be in particular on the background information enabling 3D representation, starting from the tools to quantify heights to open standards and hard and soft enablers. The chapter is wrapped up by a brief introduction to GeoDataBases, the “containers” of geographical information. Chapter 3 focuses on the other component of the research, energy: it introduces possible energy renovation by starting from the current situation and proposing the most common solutions, considering in the second part the legislative framework and existing technologies in the photovoltaic field. These two macro-topics flow into the last paragraph, which takes into account energy communities, based on efficient buildings and Renewable Energy Sources. The application, described in chapter 4, explains step by step the process, starting from the problem and the available data and moving on by showing the methods and tools used throughout the procedure. Finally, some conclusions are drafted, pointing out possible future work.

2

2D and 3D cartography

Cartography is the discipline concerning the conception, production, diffusion and study of maps, representations of the real world based on surveying and documentation. Maps are flat, selective, scaled and symbolic representations (Amadio, 2012): in the modelling, only the necessary characteristics are represented, with a ratio between the dimensions on the map and in reality, and some of them are schematised or indicated by conventional symbols.

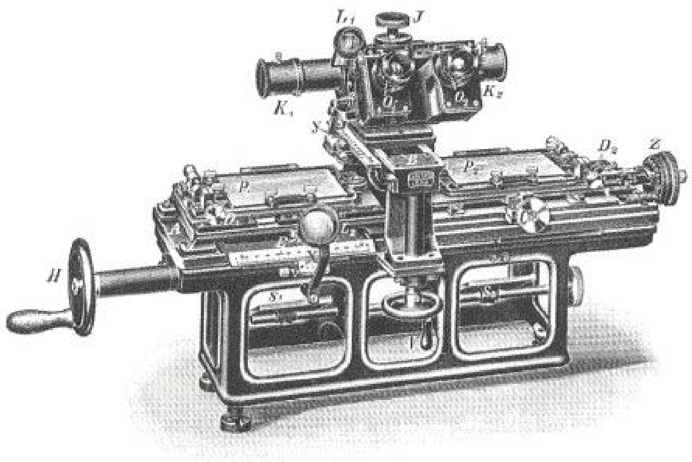
Apart from base maps, which provide simple geometrical information, there are several other cartographic products: thematic maps (showing the distribution of a given phenomenon), digital elevation models (providing the basic data for the solid modelling), orthophotos (pictures geometrically corrected but still to be interpreted) and tridimensional models.

The whole mapping process is evolving: the advent of IT innovated not only surveying tools and methodologies but also the storage and processing of geographical data. A revolution occurred with the advent of the Geographical Information System (GIS), a system which models entities (objects) as made up of geometrical, alphanumerical and relational components, allowing spatial analyses on them (Amadio, 2012). In other words, a GIS is a system to acquire, elaborate, manage and represent geographical data. (Biallo, 2005). As for storage, archives are now translated into Geo DataBases (GDBs); the higher amount of storable data led to the storage of geographical information with the maximum accuracy, then activated or not depending on the scale and theme of the digital map to be produced (Amadio, 2012).

2.1 Photogrammetry

Photogrammetry can be defined as «the science of obtaining reliable information about the properties of surfaces and objects without physical contact with the objects, and of measuring and interpreting this information» (Schenk, 2005). It allows one to get metrical information about tridimensional objects through the registration, measurement and interpretation of photographic images. Digital photogrammetry introduced tridimensional reconstruction, with algorithms based on the theoretical principles of traditional photogrammetry: collinearity, intersection of projection rays and camera calibration (Monteforte, 2021). Compared to direct surveys, it has some advantages: it is not needed to touch the objects, simultaneity (multiple points are acquired at the same time), affordability (after the data acquisition all the work is carried on in the office), quickness, uniformity in the precision, the possibility of working on historical data. However, it is the operator who recognises visually geographical objects and memorises them as primitives (Amadio, 2012). Moreover, photogrammetric products can have errors or information holes with a stereo obstruction or lack of texture, as for shadowed areas or glass structures: this leads to wrong 3D modelling and texture misprojection (nFrames, n.d.).

Image 2.1



Stereo comparator of Dr Carl Pulfrich (Zeiss Jena, 1901)
Source: researchgate.net

Photogrammetry history is strictly related to technological and process innovations. Its early phases, pioneering, immediately followed the advent of photography in 1839. At the beginning of the XX century, Pulfrich's stereo photogrammetry marked the beginning of the second generation, the analogical photogrammetry; in the same period, the first planes were realised: aerial techniques were perfected so that their bases are still considered valid today. Analytical photogrammetry, the third generation, depended on the invention of the computer: Aerial Triangulation became ten times more accurate. The one we're using today is the fourth generation, digital photogrammetry: digital pictures are elaborated by software in a semi-automatic way (Schenk, 2005).

As mentioned, photogrammetry gives 3D information; therefore, the outputs are several, falling into three main categories. Photographic products are the result of rectification, a process by which a diapositive becomes parallel to the ground, but not necessarily without projection errors. Computational results consist of elaborations based on points restituted in ground coordinate systems by Aerial Triangulation. Finally, maps can be produced based on photo interpretation.

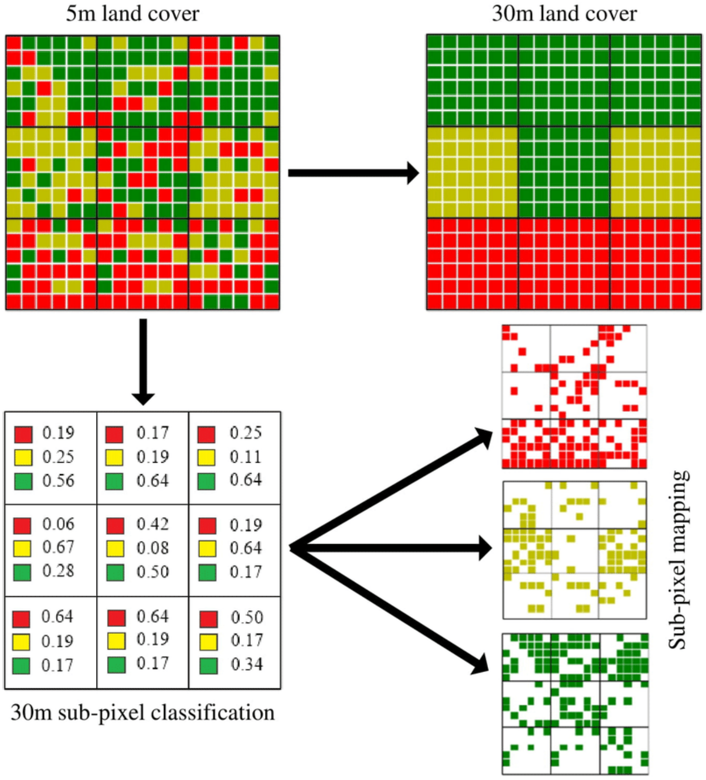
(Schenk, 2005).

The photogrammetric process can be divided into three principal steps: data acquisition (with adequate planning), orientation (operation for allowing measuring on the model, through determined points) and restitution (control, editing and production of the final output).

Data acquisition can be performed both terrestrial and aerial. To produce topographical information, most times the aerial survey is the method to acquire the necessary information (Monteforte, 2021): this information, which has to be reliable, is therefore acquired without physical contact with the object, through a sensor mounted on a platform (Schenk, 2005).

The actual flight must be preceded by proper planning. First, the scale has to be considered: given that the lenses of the photogrammetric cameras are fixed, without zoom, it is necessary to define a medium scale of the photos and modify the height accordingly. In digital photogrammetry, this concept was overcome by the one of spatial resolution: it depends on the portion of the image occupied by a pixel, quantified in metres per pixel; the higher the value is, the less the picture is detailed (Monteforte, 2021).

Image 2.2

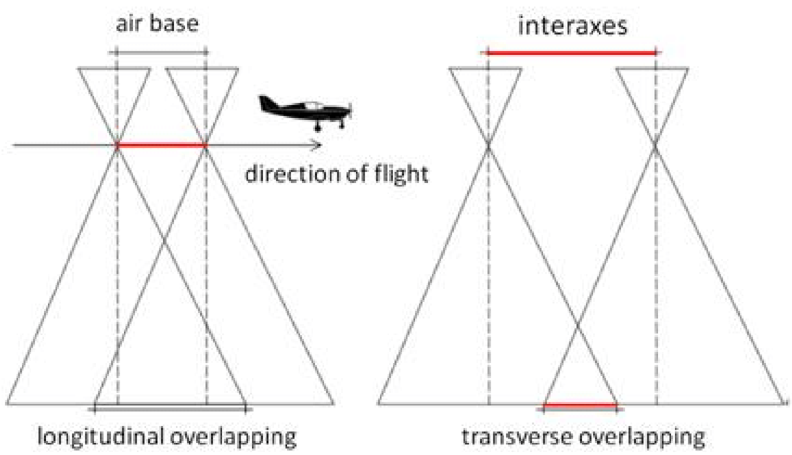


Spatial resolution
Source: researchgate.net

Another aspect of the resolution is the radiometric one, which indicates the number of grey levels within a dynamic scale or intensities of luminous radiation which the sensor can detect, expressed in the bit number. These aspects depend not only on the height above ground but also on the quality of the lens. Other important parameters which depend on the camera and its settings are sharpness, exposition and blur. Time of exposure and aperture affect them: the histogram should be centred (not over nor underexposed picture), the ISO should be the least possible, the aperture values should be comprised between 5,6 and 8 and the exposure time should be approximately 1/100 s. Problems which can emerge are aberration and vignetting: the former causes the emergence of fringes on the border of white elements and can be corrected by calibration and the latter leads to darker regions in the corners of the picture (nFrames, n.d.).

In addition to the settings necessary to obtain the required accuracy for every picture, it is necessary to plan the tiling too. To model an area properly, an overlap between adjacent frames is required. Two overlaps are identified: the longitudinal (among pictures of the same strip) shouldn't be less than 60% or even 80% in urban areas and the transversal (among different strips) 30%. Diminishing the take base, quantified by the metres between two subsequent frames, the overlap increases.

Image 2.3



Photogrammetric flight, longitudinal overlap
Source: researchgate.net

The moment of the flight is determined based on the sun rays inclination (it must not be lower than 35°), the presence of snow and other disturbing elements, such as tree crowns, clouds or snow. To follow the determined flight path and meet the required standards for the pictures, the plane is equipped with a set of necessary technologies:

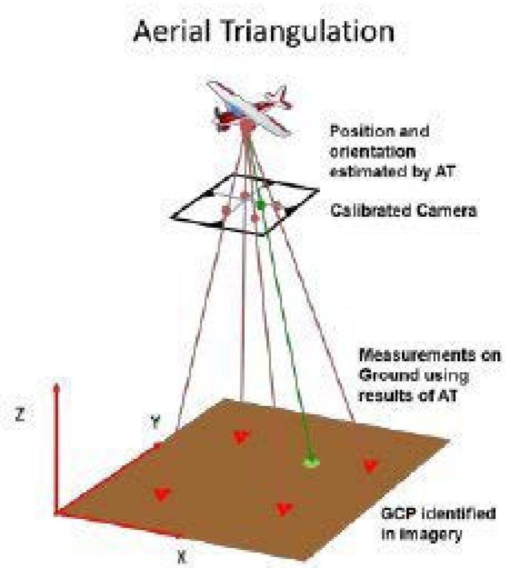
- navigation and flight software;
- GNSS system, the combination of GPS and IMU to realise a dataset that provides each picture with tags indicating position and orientation;
- gyro-stabilised support to contrast the effects of roll, pitch and yaw of the plane;
- camera and memory for saving the acquired data (Monteforte, 2021).

The orientation is the process by which a picture is corrected, scaled and oriented to produce a model and allow measures on it. It is divided into interior and exterior orientation: the latter is further split into relative and absolute.

The interior orientation corrects the distortions caused by the lenses (Monteforte, 2021). It establishes the relationship between a measuring system and the photo coordinate system by determining the translation vector, the scale factor and the rotation angle. It is also known as image refinement since it corrects systematic errors such as radial distortion, reflection and Earth curvature (Schenk, 2005). For cancelling the parallax (the phenomenon by which an object seems to move in space when changing the point of observation), camera calibration data are used: they are the same for each picture. These data are especially the offset between the fiducial centre and the principal point of auto collimation: so, the determination of the projection centre and of the plane on which the image is formed allows the reconstruction of projection rays and therefore of the central projection.

After having recomposed the projection lines with interior orientation, the frames have to be located in the object space with Aerial Triangulation: six parameters, one for each movement of an object in space (three translations and three rotations), are integrated into the collinearity model. This model puts on the same line the perspective centre, the image point and the object point (Schenk, 2005). The spatial position of the camera in the moment of data acquisition is reconstructed, using Tie Points and Ground Control Points, in the coordinates of the output. High-quality orientation brings higher geometrical accuracy. The relative orientation output is a photogrammetric block (or stereo model), on an arbitrary scale and in an undefined space. The block is a model constituted by the whole set of frames, overlapped in correspondence of homologous points, oriented in a fictitious reference system (Monteforte, 2021). Therefore, relative orientation can be defined as the process by which the relative position of the frames concerning one another is determined intersecting the projecting rays. Tie Points, homologous points, are located on two or more photograms in the overlapping area; the parameters derived from them improve the accuracy of the model, ensuring the sub-pixel parallax removal (nFrames, n.d.). The absolute orientation, by contrast, orients the stereo model to the ground control system (Schenk, 2005), properly dimensioned: the model is moved and scaled. Ground Control Points coordinates (determined through direct survey) are used as known terms in the orientation equations, while Control Points allow the calculation of the residual errors. At the end of the process, the pictures are transformed in orthogonal projection, being therefore comparable to cartography (CGR S.p.A., 2022).

Image 2.4



External orientation
Source: researchgate.net

Despite the technologies generally allowing very high accuracy, still, the model can have some problems or difficulties in being interpreted (it is to be remembered that photo interpretation is necessary). Recognition includes metrical integration (direct survey for the portions of the territory lacking information), informative integration and toponymic survey. The editing, during which the recognition data are integrated into the model, follows, ending with a correct photogrammetric model. The outputs are then finalised in the restitution phase: according to needs and requirements, the photogrammetric product is delivered to the client.

2.1.1 Elevation component

Traditional maps can include elevation information, representing altimetry through height points and contour lines. The former are localised points with a known quota, the latter are unions of height points of the same quota (with inter distance, called equidistance, generally equal to 1/1000 of the scale denominator). Digital cartography can perfect this representation, localising each point of the model through a set of coordinates XYZ (Schenk, 2005).

Elevation, determined according to the reference system used, is set according to specific rules: artificial structures quota corresponds to the intersection with the terrain; only when there is no intersection (e.g. electrical lines) the real elevation is used. Moreover, for the height of volumetric entities two elements are introduced: volumetric units are defined by a dividend and their quota is measured in the centroid.

Photogrammetry, to determine the tridimensional position of the objects, takes advantage of an effect present in human vision, the stereoscopic sense. The underlying principle is that it is impossible to take measures on a picture, considering it is a central perspective; on the contrary, taking two images from slightly different points of view and making each eye see only one of them creates a sense of depth. Our eyes are located at a distance of about 7 cm (binocular vision); increasing the inter-distance increases the sense of depth, too. A computer cannot work like our brain, so it needs the definition of the TPs and GPCs for the recreation of the homologous rays and therefore for the superimposition of two or more images, thus creating a 3D model through collimation; the model is generated in 3D cartesian coordinates (Schenk, 2005).

Image 2.5

Stereoscopic sense
Source: researchgate.net

A dense point cloud is created through the 3D points deriving from the collimation of single pixels: this, filtered for ensuring accuracy, correct exposure and noise reduction, allows proper modelling of the surveyed area. However, even if a stereo pair (a couple of photographs showing the same area taken from two slightly different points of view) is sufficient, multi-stereo triangulation increases the reliability of the output: some programs, such as SURE, recommend that the surface of interest appears at least in five frames. Dense image matching requires, as briefly mentioned in the previous paragraph, in-strip and cross-strip overlaps: increasing them reduces the possibility of stereo occlusions, from which data gaps and the need for interpolation derive. For example, urban areas, even if they don't have skyscrapers, are to be photographed with 80% of longitudinal overlap and 60% transversal. So, the accuracy of the modelling depends not only on the orientation parameters but also on the number of overlapping images and their common areas (nFrames, n.d.).

In modern photogrammetric sensors, cameras are often coupled with active sensors, registering the 3D position of a varying set of points. The active sensory survey consists of the measurement of the distance of points on the Earth's surface through the analysis of the return of electromagnetic pulses, generated by a source on the plane itself. The needed inputs are the exact distance between the sensor and the terrain, the position of the sensor and its setup (Amadio, 2012).

One of the most common active sensor technologies is the Light Detection and Ranging (LiDAR). Developed in the Sixties, it consists of a system using the principles of the radar: it is a ranging system, measuring the range between an instrument and an object. It does so by generating a brief laser pulse and registering the reflection (Cronenborg et al., 2015): data are punctual, thus creating a point cloud. Its main pros and cons are synthesised in Table 2.1.

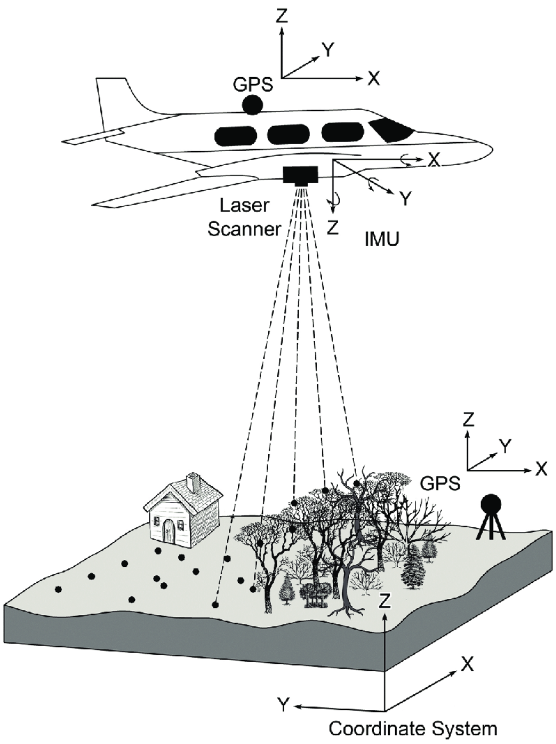
Table 2.1

Advantages	Disadvantages
• high spatial resolution: up to 20 points per square metre; • good accuracy: 15 cm vertically, 50 cm horizontally; • flexibility and density in the point coverage, resulting in high data acquisition speed; • possibility to work in adverse conditions; • multiple applications.	• irregular spacing, which can be corrected through interpolation; • high costs; • large data volume, depending on the high resolution.

Advantages and disadvantages of LiDAR technology.
Sources: Cronenborg et al., 2015; Teodoro, 2021.

Airborne Laser Scanning (ALS) consists of LiDAR technology brought on planes, flying from 3 to 8 km AGL; they are based on the combination between laser scanning and direct geo referencing systems (GNSS): the former, composed of scanner, survey unit and control elaboration unity, registers data to which the GNSS attaches position and orientation data with a temporal tag. The combination of the information, performed by the elaboration software, results in the point cloud (Teodoro, 2021). Even high-quality laser signals are propagated as a cone, with divergences comprised between 0,3 and 0,4 mrad: therefore, the pulse may be reflected by multiple elements. Multiple reflections of the same ray have different times and intensities, therefore already in the registration phase it is possible to distinguish and classify the so-called returns (Lunardi, 2011). The classification of the returns is fundamental because it allows us to distinguish between higher and lower surfaces: the first return contains the higher information (such as trees and roofs), the intermediate returns the lower elements (such as small bushes), the last return the ground surface (Teodoro, 2021). Most laser scanners can distinguish the first and last return, while the intermediate number varies: the highest quality sensors can register up to five returns. This decomposition of returns is helpful in the determination of the DEMs (see paragraph 2.1.2).

Image 2.6



Airborne Laser Scanning
Source: researchgate.net

Laser is not the only technology which is used for active sensors: Synthetic Aperture Radars acquire monochromatic images defining the irregularities on the analysed surface. A special SAR application, IFSAR, analyses the phase difference between two or more high-resolution SAR images, acquired in different spatial positions (Teodoro, 2021).

Once the elevation data have been acquired, there are multiple ways of representing them: use the traditional elements (height points and contour lines), mathematical solids, Triangulated Irregular Networks and height grids (Amadio, 2012).

The TIN structure is an evolution of the vectorial structure: it consists of a «connected series of contiguous, non-overlapping triangles» (Cronenborg et al., 2015); such triangles have height points as vertices, so they are unevenly distributed. The triangulation requires algorithms, such as the Delaunay one, which starts from a first triangle and defines the others accordingly (preferably equilateral); therefore, triangulation is not unique, but changes in relation to the starting one. The storage is particularly critical: both triangle coordinates and specifics are needed to model the same TIN. The vertices are not interpolated, but calculated; the TIN is particularly used for areas with a high number of break lines because, as explained in the following paragraph, regular grids cannot restitute them properly (Amadio, 2012).

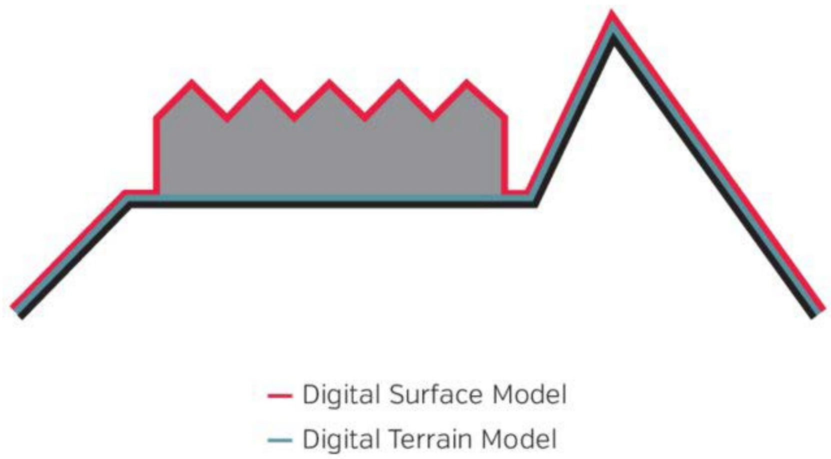
Regular grids are raster altimetric terrain models, with each grid containing the average quota of its portion of land (Biallo, 2005).

2.1.2 Regular grids

The regular grids can be defined as a representation of average or punctual values inside square tiles of the same dimension (Amadio, 2012). They are realised with not only 3D point clouds but integrating them with break lines, chorographic elements and interpolation of dead zones (where the elevation cannot be defined). Regular grids describe morphologies, including or not some elements depending on the type of model. The first definition and the IT-mathematical formula defining these grids were elaborated in the Fifties by Miller; from the Seventies, it was possible to acquire data with a given periodicity, but only 1990s photogrammetric innovations allowed a boom of this way of representing elevation (Teodoro, 2021). Such models are:

- Digital Elevation Model/Digital Terrain Model: they describe the elevation of the bare earth, not including any extrusion, be it vegetation or anthropic structure; some scholars (Croneborg et al., 2015) differentiate them based on the level of detail, with the DTM being a more complete representation than the DEM, while others (Amadio, 2012) include in the DEM the anthropic elements only.
- Digital Surface Model: it represents the surface of objects from the real world in addition to the exposed terrain (nFrames, n.d.).
- Canopy Height Model and Building Height Model: they can be defined as the difference between the DSM and DTM; the former determines the vegetation structure and height and the latter focuses on anthropic structures (Cronenborg, 2015).

Image 2.7



Difference between DTM and DSM
Source: researchgate.net

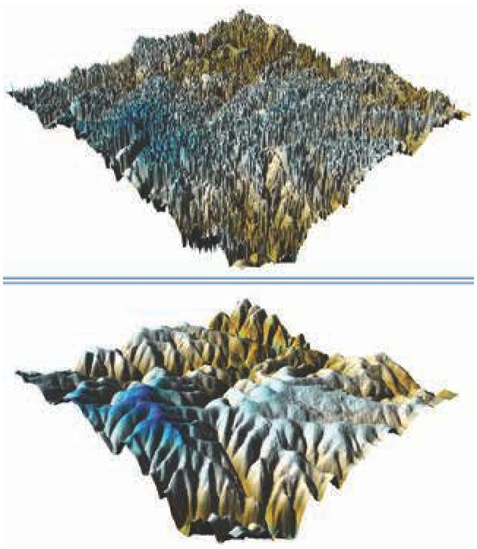
Considering that they are made of a numerical matrix, they can be defined as statistical surfaces: they represent the distribution in an area defined by a pair of coordinates of the phenomenon "elevation", which can be both measured or calculated (Teodoro, 2021). The inclusion of the third dimension in a bi-dimensional representation creates an intermediate situation so that such representations are defined as 2.5D.

The problems of the regular grids are related to their regularity, so to the raster format. First and second, it is impossible to intensify or rarefy the grid where needed and the quotas of the tiles are average: thus the representation of break lines and abrupt morphological changes is limited, peaks cannot be seen and the precise location of points gets lost. Third, it is not a topological structure: other information cannot be attached to the elevation value (Biallo, 2005).

The creation of DTMs, DEMs and DSMs strongly depends on the available resources: indeed, costs are directly proportional to the resolution, which can vary from a few centimetres to 50 metres according to the type of survey, and the vertical accuracy; they are both defined based on the scope of analysis and the needs of the end-users (Teodoro, 2021). Vertical accuracy is the principal quality parameter for DEMs; on the other hand, higher resolution is needed for areas with abrupt changes (remember that it is impossible to change the resolution following this necessity). Photogrammetry and LiDAR systems are the most suitable for both high accuracy and spatial resolution: it is generally defined as very highly accurate a DEM on the order of <50 cm, while high spatial resolution is on the order of <1 m. Other important parameters are the study area (size, location and characteristics) and the time allowed for delivery. The dimensions of the area influence the costs for aircraft collections mainly due to the fuel usage: costs are quoted on the area basis (€/km^2) (Cronenborg et al., 2015).

DEMs and similar products can be represented in several ways, considering their 2.5D nature. First, it is possible to directly represent them flat, classifying the cells and giving to each class a colour depending on the elevation or with more graphically refined representations, such as hatching. Moreover, some software allows 3D modelling based on the grids: it is the case of triangle meshes, with the density locally adapted to the geometry (nFrames, n.d.). However, regular grids are often used as input for other elaborations, as shown hereinafter.

Image 2.8



DEM and DSM of a forested area
Source: researchgate.net

2.1.3 Orthophotos

One of the applications of the DEMs and DSMs is the realisation of orthophotos. It was previously mentioned that the pictures, even if they were properly corrected, can have deformations deriving from the ground morphology: that is why during AT the DEM is located (if it was registered through LiDAR) or calculated for the realisation of orthophotos. By doing so, also the scale is made uniform: especially in hilly or mountain areas, with the scale determined for the valley floor, without such correction some major errors can emerge.

An orthophoto can be defined as a union of photographs, taken by the air (drone, plane or satellite), corrected to have a metrical correspondence. Differently from maps, they are not classified, but still need photo interpretation; however, they are 5, 10 or even 20 times quicker and therefore cheaper to realise than maps (Amadio, 2012). They can be used as both the final product or the input for the production of maps, tracing the needed elements and producing a vector dataset.

A problem of orthophotos is the building representation: it is not their actual footprint that is shown, but a perspective view. To remove the perspective distortion of the aerial images, an accurate DSM (costlier) can be applied: this is the main feature that sets a true orthophoto apart from the classical one, previously described (nFrames, n.d.).

Image 2.9

5 cm true orthophoto of Turin municipality (detail of a football field)
Source: Own elaboration on TerraItalyTM Metro HD data

2.2 3D models

Increasingly, also thanks to technological advancement, 2D data are substituted by 3D information, which represents explicitly the elevation of every point, without requiring interpolation (as it happens with break lines and height points). At first 3D models were used for visualisation only, but now their potential for geoprocessing has been unlocked (Vitalis et al., 2020). 3D models, however, can be enriched with further information: semantic 3D city models include the ontological structure. It is the semantic enrichment which allows 3D models to become profitable, expanding the user base: thematic classes, attributes and interrelationships enable simulations and applicability in different fields (Kolbe, 2009). Complex modelling also leaves space for attaching real-time information (see paragraph 2.2.2) (Schrotter & Hürzeler, 2020).

All bodies, to ensure that their GIS systems function properly, are required to implement Spatial Data Infrastructures: they are a set of policies, pacts, technologies, data and people gathered to allow the sharing and efficient use of geographical information. This applies to every data, but in particular to 3D models: indeed, they are made of various interrelated elements, which are required to be inserted in a defined schema. To ensure consistency and compatibility, it is necessary to have references; these should be safe, stable and shared, so provided by authoritative sources, and inclusive of three perspectives: technical, normative (as for the INSPIRE directive) and concerning standardisation (with the production coming from bodies such as ISO and OGC) (Amadio, 2012). Standards are required to be at the same time flexible, for wider applicability, and rigid, to uniform the necessary data (see paragraph 2.2.2.3).

However, requirements change according to the application field: while computer graphics aims at the best possible representation of the model, 3D GIS is about gathering information for large areas on multiple scales and engineering disciplines aim to detail more the single elements in terms of processes and materials. Nevertheless, all four key aspects of a tridimensional model are required for its workability: geometry, topology, semantics and graphical appearance (Kolbe et al., 2008). An accurate, consistent, rich in information and good-looking model can be adapted to a wide set of disciplines.

2.2.1. City Model

To realise a Digital Twin, it is necessary a City Model: it is defined as the set of appropriate digital data enabling the modelling of the relevant physical and social aspects (SGI, 2020) or, more simply, as a «collection of 3D spatial data» (Schrotter & Hürzeler, 2020). Being a collection, City Models are a snapshot of a given time; nevertheless, they restitute the complexity of the urban area at that time (Vitalis et al., 2019b). The adequate gathering of 3D spatial data results in representation and modelling but, with complexity levels as the ones of a city, an SDI is required to ensure the workability of the model: SDIs, enforced mainly after the publication of INSPIRE Directive (2007/2/EC) grant the possibility for querying, visualising and sharing data (SGI, 2020).

It was previously explained that 3D data can have ontological information too, creating interrelationships: from this, it derives the formation of hierarchies, at both the semantic and geometrical levels. It is possible to take advantage of these hierarchies to query or perform analyses on the model; still, consistency should be granted, ensuring correspondence between geometrical and semantical hierarchies (Kolbe et al., 2008).

2.2.1.1 CityGML

In 2008, the Special Interest Group 3D of the initiative Geodata Infrastructure North-Rhine Westphalia (Germany) published the first version of CityGML; the Special Interest Group was composed of a heterogeneous set of scholars, public administrations and people working in the industry (Kolbe, 2009). CityGML, adopted by the Open Geospatial Consortium for the visualisation and sharing of 3D data (Gröger & Plümer, 2012), aims to define univocally the basic elements of tridimensional models (Kolbe, 2009).

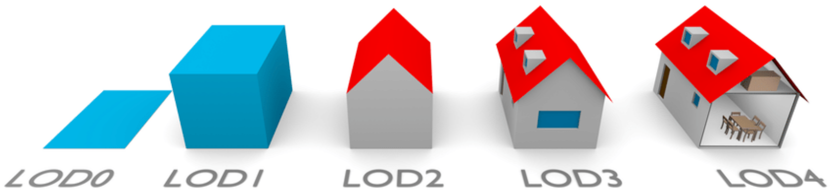
CityGML is a profile of Geography Markup Language 3: it organises the storage and access of «an interoperable, multi-functional, multi-scale and semantic 3D city model» (Kolbe et al., 2005). As for vector applications, entities are represented through geometric-topological primitives: node or point for zero-dimensional objects, edge or line for one-dimensional objects, face or surface for two-dimensional objects and solid for tridimensional objects (Kolbe et al., 2005). In the case of 3D entities, however, problems could arise for the realisation of volumes; these are solved through:

- multi surfaces representation, alternative representation by surfaces which do not complete the solid (Gröger & Plümer, 2012) and therefore do not allow the volume computation;
- closure surfaces, used for volume computation of objects open by definition, such as aeroplane hangars or tunnels; the advantage of such surfaces is that they can be used for calculations but made invisible when visualising the object.

Solid modelling of CityGML requires that objects do not overlap nor penetrate each other: in case of common boundaries (as in the case of a garage close to a house), it is necessary to store it separately from the rest of the surfaces, with a primitive of lower dimension (Kolbe et al., 2005).

The quality of a CityGML-based dataset can be expressed through Levels of Detail (LoDs). The LoDs express the scale, semantic enrichment and accuracy of the represented entity; they are five, described by Kolbe et al. (2005) and Kolbe (2009):

Image 2.10



CityGML LoDs
Source: researchgate.net

1. LoD0 is the coarsest level, a 2.5D representation with, eventually, maps or aerial images attached.
2. LoD1 corresponds to the blocks model: roofs are not represented. Its maximum accuracy is 5 m, elements with at least a 6 m x 6 m footprint should be included, so big vegetation objects are visible at this LoD.
3. LoD2, with a positional accuracy of 2 m and a height accuracy of 1 m, includes all objects with a footprint of 4 m x 4 m or bigger; roof structures and large elements (external staircases, balconies...).
4. LoD3 corresponds to an architectural model: it requires accuracies (both positional and height) of 50 cm for the representation of elements with a minimal footprint of 2 m x 2 m.
5. LoD4 is the most accurate (20 cm) and complete model: it includes interior structures, too.

CityGML is organised in thematic modules, classes that group entities with common elements. From the description of the LoDs, it is evident that the data model was based on the building module, but in total the modules are ten. The core module is the basic one, grouping entities with common attributes (as the creation date) and making all these entities inherit the information. The transportation module includes all the elements which are relevant to support route planning; the tunnel module has a link with it: it represents underground passages for people and cars, not caves, geology, mines or utility networks. Also the water body module is connected to transportation: water bodies can be either barriers or infrastructures for it. Water has a key role in CityGML: being important for human recreation but also a source of danger, its inclusion is crucial for allowing simulations on the model. Further elements are included in the vegetation and city furniture modules: while these elements require higher detail, they are fundamental for complete visualisation or precision simulations. The land use module provides semantic information, but it can be used as a base layer too: on big scales, it provides a tiling which restitutes a coarse representation. The bridge module, which at high LoDs represents also bridge parts and construction elements, was developed analogously to the building module: the aggregation structure, the relations, the attributes and the definition of the LoDs are comparable among the two (Gröger & Plümer, 2012). Finally, the relief module foresees the possibility of including several terrain representations: regular grid, TIN (either as triangulation or implicitly as a set of 3D points), break lines (discontinuity lines), skeleton lines (ridges or valley, represented through contour lines) or 3D point cloud (Kolbe et. al, 2005). All representations can have any LoD: the extent of validity (2D polygon of arbitrary shape), eventually with holes, defines the zone in which the terrain representation is valid, thus allowing the integration of multiple representations in a single data set (Gröger & Plümer, 2012).

All elements should be integrated into the model: to avoid problems of buildings floating or sinking into the terrain (common when using buildings and terrain with different LoDs) the terrain intersection curve is introduced. This curve, specific for each building and represented through a closed ring (two rings in the case of a courtyard, one for each sequence of walls touching the terrain), indicates the position where the building intersects the terrain (Kolbe et. al, 2005).

An interesting property of CityGML-based models is appearance, reporting the «observable properties of the surface as they appear to specific sensors» (Kolbe, 2009). It is a way to enrich the model with further information, traditionally provided as rasters, such as visual data (in any acquisition band) or themes (emissions, structural stress…). This information can be used for visualisation but also as an input for analyses (Kolbe, 2009).

To ensure consistency over time, the CityGML data structure introduced the possibility of referencing a 3D entity to its corresponding object in an external dataset. This grants an automatic update of the shape or the ontological attributes attached (Kolbe et. al, 2005).

2.2.1.2 CityJSON

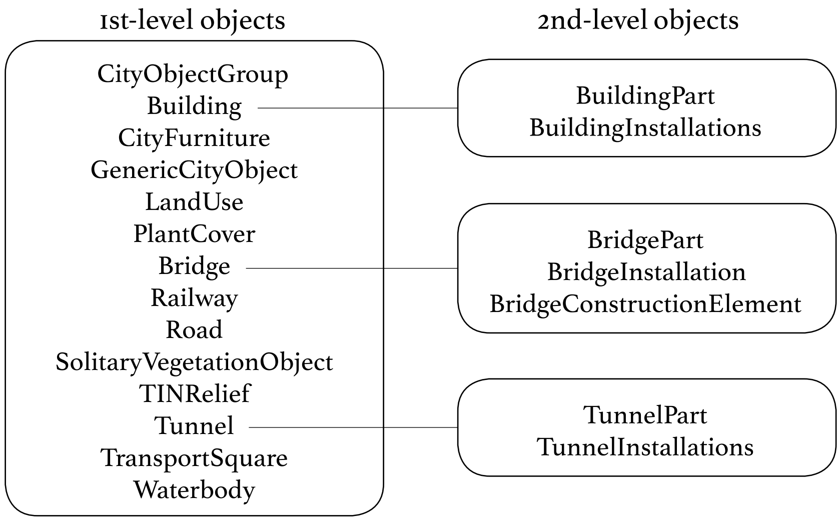
CityJSON can be defined by comparing it with CityGML, the starting point from which it was implemented: indeed, CityJSON tried to overcome the main limitations of CityGML. The latter, despite having been standardised almost fifteen years ago, is supported by a limited number of GIS software, mostly proprietary (Vitalis et al., 2020): CityJSON is intended to be more open, so readable and editable in open software too.

First, CityJSON is a data format (not a data model), using the JavaScript Object Notation encoding (Vitalis et al., 2019a), more usable and simple to use compared to the XML-based CityGML. Ledoux et al. (2019) claim that in the implementation of CityGML the usability of the exchange format was not considered properly, thus requiring a simplification for developers. Indeed, XML language is complex (there are more than twenty different ways to perform a single task, the realisation of a square) and difficultly editable; moreover, up to the 2.0 version CityGML did not support versioning. This resulted in the presence of static datasets, not updated due to these difficulties (Vitalis et al., 2019b). Finally, CityJSON is up to 6 times more compact than CityGML: this derives from a flatter data structure, limiting the hierarchies, but it can be compressed by a further 10% when storing coordinates as integers (Ledoux et al., 2019).

As mentioned, the CityGML data model was the reference for the implementation of CityJSON: all modules have been included in the latter; the parts which were not mapped were considered unnecessarily complex or not used. JSON data format supports boolean values, numbers, strings, arrays (lists of elements enclosed with square brackets and separated by commas) and dictionaries (objects consisting of key-value pairs enclosed with curly brackets);

the last two are crucial for the translation of CityGML data model into CityJSON.

Image 2.11



CityJSON City Objects
Source: own elaboration on Ledoux et al., 2019

CityJSON files have dictionaries where keys are the IDs of the city object (Ledoux et al., 2019). Compared to CityGML, CityJSON flattens the list of city objects: the hierarchy can be defined by looking at the attributes (Vitalis et al., 2019a): city objects can be of the first or second level, but they are all stored in the same dictionary. For example, a bridge (first-level object) will be stored in the same dictionary of its parts and construction elements (second-level objects). In this case, there will be "parents" and "children" properties, but they are not a key requirement (Ledoux et al., 2019).

There are pre-defined types for geometry objects: MultiPoint (0D), MultiLineString (1D), MultiSurface, CompositeSurface (2D), Solid, MultiSolid and CompositeSolid (3D). Both 2D and 3D types, however, describe the tridimensional shape of an object: 2D types do not have a volumetric interior, while Solid geometry is considered as a bounded volume. Such polygons can be further enriched semantically: surfaces can have an attribute which, for example, classifies them as walls or roofs. (Vitalis et al., 2020). The vertices of geometry objects are stored separately from the geometry: the latter indicates the position of its vertices in a dedicated array. This brings some advantages: it allows more compression (common vertices coordinates are not repeated), fosters topological relations (stored explicitly) and makes it easy the conversion from vertices array to coordinates. Like CityGML, CityJSON allows the storage of objects (and their geometries) in different LoDs. Another similarity lies in the possibility of using templates (in CityGML they are called Implicit Geometries): objects with identical geometries are stored in a single location and then reused where needed, with adequate scale and rotation factors.

The geometry key is the only required with the ID of each object. When needed, further attributes can be inserted: they are to be stored in the "attributes" key (Ledoux et al., 2019). Moreover, CityJSON, conforming to ISO 19115, supports metadata fully; this is an improvement compared to CityGML, which requires an application domain extension for their storage (Vitalis et al., 2019).

Other CityGML features not supported by CityJSON were listed by Ledoux et al. (2019):

- LoD4, due to its scarce use and the complexity it adds to the database;
- arbitrary coordinate reference systems (only EPSG codes can be adopted);
- coexistence of objects with different coordinate reference systems;
- ID allocation to most objects (only city objects and semantic surfaces have IDs).

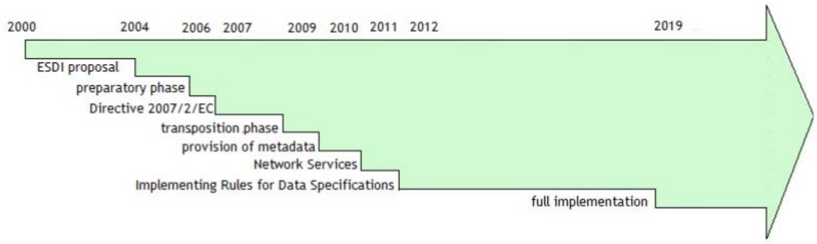
2.2.1.3 INSPIRE

INSPIRE (INfrastructure for SPatial InfoRmation in Europe) Directive (2007/2/EC) provided a legal, technological and organisational framework for European spatial data. Based on the SDIs which had already been implemented and are operated by Member States, it aimed at the harmonisation of geographical data relevant to environmental policies (Minghini et al., 2019). The resulting European SDI would be hierarchical, with National SDIs working both as nodes of the transnational and references for the regionals (Lunardi, 2011).

It is based on five main principles: to collect data only once and store them where it is more efficient, to allow the combination of information from different sources, to enable vertical sharing of information (to be detailed or generalised based on the change of scale), readiness and transparency of geographical information, easy query (EC, n.d.). These are consistent with one of the fundamental European principles, subsidiarity, claiming that all policy tasks should be carried on at the lowest level possible, generally the most efficient and transparent.

According to these principles, INSPIRE has five components, but there is no bi-univocal correspondence between principles and components. First, data sets and services should be interoperable: 34 topics (called themes) are to be made available and harmonised in the final SDI. Metadata ensure the possibility to search and evaluate INSPIRE datasets; network services (mainly geoportals) should be intended for both visualisation and download of spatial information, together with the implementation of e-commerce services. Apart from geoportals, data access and sharing should be allowed both among public authorities and third parties, widening the access to geographical information. Finally, there should be coordination measures for INSPIRE SDI realisation, monitoring and managing the whole process. These components are to be implemented in subsequent moments, organised according to a roadmap; the full implementation was to be achieved by 2019 (Bartha & Kocsis, 2011), but it has been delayed.

Image 2.12



INSPIRE roadmap
Source: Bartha & Kocsis, 2011

The approach adopted for INSPIRE was mainly top-down: Implementing Rules are adopted by the Commission (they can be issued as Decisions or Regulations) and are legally binding for all Member States. Nevertheless, the Commission was flanked by representatives of Member States (EC, n.d.) and experts from the stakeholder community. Moreover, the community is involved in the governance and the Community Forum allows discussion. Therefore, it can be considered a participatory initiative.

As mentioned, INSPIRE is oriented towards policies concerning the environment and the activities which may have impacts on it. Object types are classified into 34 themes, defined in the three Annexes of the Directive; such data standardisation is relevant for sharing: each theme is precisely defined with dedicated Technical Guidelines. The themes, pertaining to specific spatial domains, could not include general and non-environmental datasets; however, these can be deduced starting from the existing ones (Minghini et al., 2019). Every annex has its own set of milestones for the implementation of metadata, data and network services.

Annexes divide data themes with a principle similar to the one of Level of Detail: Annex I includes the basic elements for the creation of a generic dataset (coordinate reference system, geographical grid system, toponyms, administrative units) and the principal items for environmental planning (protected sites, hydrography, transport networks). Annex II introduces elevation and ways to classify the land (land cover, geology, orthoimagery). Finally, Annex III is the most complete (and therefore most difficult to be implemented) and completes the dataset with all relevant aspects, working on a precise scale e.g. land use specifies land cover.

The technical base is provided by the ISO 19100 series: it is comprehensive of rules concerning infrastructure, data models, management, services and encoding (Bartha & Kocsis, 2011), which are basically all the aspects tackled in the Directive.

The conceptual models (see paragraph 2.3.1) are to be defined in the UML, while the GML is used for encoding: respectively, ISO 19118 and ISO/TS 19139 describe the rule for encoding (Bartha & Kocsis, 2011). This framework is the result of consultations with the Open Geospatial Consortium, too: therefore, INSPIRE has some points in common with CityGML. Nevertheless, the INSPIRE Maintenance and Implementation Group proposed an alternative encoding, departing from the same UML conceptual models but based on the CityJSON standard (Minghini et al., 2019). Metadata are crucial since they store details about the geographical information for its tracking and use (like the owner, quality, validity...) (Bartha & Kocsis, 2011); that is why they were the first step of the roadmap defined drafting the Directive.

2.2.2 Digital Twin

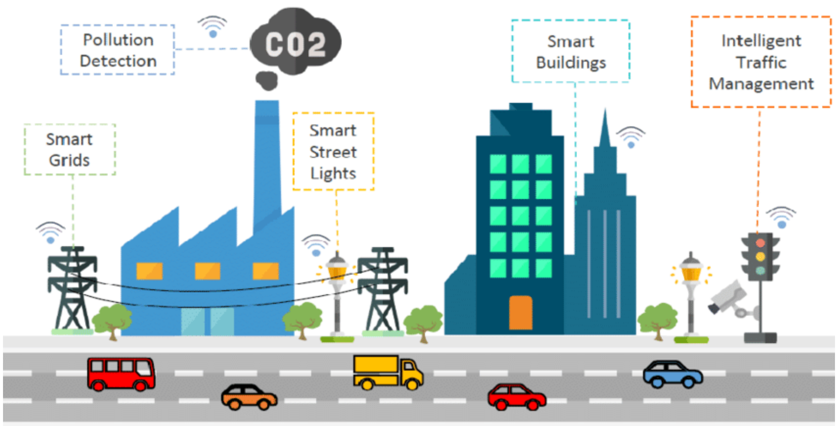
A DT is created starting from the 3D city model, implementing applications and services on it to help the management of the smart city (SGI, 2020). Therefore, it is necessary a step back, define the smart city and how the DT helps its functioning.

A prevailing concept in the definition of the smart city is integration. Ivanov et al. (2020) wrote about the integration of urban infrastructure to unlock synergies, D’Amanzo & Feijoo Rivas (2021) explained the smart city as the union of the two concepts of smart growth and intelligent city. New technologies are implemented to address several challenges connected to efficiency in the city, making it more flexible and also inclusive. Smart cities have three main components: instruments (sensors which control given aspects and enable their modelling), analysis (algorithms) and operators (digitally controlled instruments). So, it is a matter of data fluxes: the DT synthesise all these aspects in a single entry; once having recognised its complexity and defined the correct parameters for the continuous data flux on which the smart city depends (and which it generates), the DT becomes a very effective management tool.

The traditional association of the DT with the smart city concept derives from the capabilities of continuous monitoring, programmability, big data analysis, services and applications. DTs generally are elaborated for limited areas (such as smart neighbourhoods) and then scaled up, widening the services provided and increasing inter-sectorial connections simultaneously.

Applications are multiple: traffic management and energetic challenges are aspects which are traditionally tackled by DTs for smart cities. Interconnections among vehicles and between vehicles and the infrastructure can be used to make the traffic more fluent and increase safety. Sustainability in the energetic field can be improved especially through 2.5D and 3D data, which enable complex analyses based on sun maps (for production) and volumes (for consumption). Nevertheless, as it will be explained, there are relevant barriers to DT implementation: it requires a strong financial, technical and political base, being costly, complex and because it needs a wide time range to be implemented (D'Amanzo & Feijoo Rivas, 2021).

Image 2.13



Smart city applications
Source: researchgate.net

2.2.2.1 Definition

In 2003, Michael Grieves introduced the concept of Digital Twin as the virtual and digital equivalent of a physical product (Monteforte, 2021). More in general, it can be described as a comprehensive software representation of a physical object, be it a component, a system or a system of systems. It simulates the object and its behaviour alone and in its environment, for its whole lifecycle (Minerva et al., 2020). It is a useful tool for supporting decision-making and planning because it makes prediction possible, simulating alternative scenarios and understanding the current state of the physical object (WGIC, 2022). Other authors introduced the concept of DT as a system of systems: they defined it as «an integrated multi-physical, multi-scale probabilistic simulation of a complex object» (Ivanov et al., 2020).

The definition of the DT of a city is more debated, especially concerning the fidelity of the model to reality. Ivanov et al. (2020) claim that only certain aspects of the urban environment are tackled by connecting several thematic DTs, Dembski et al. (2020) define it as a «sophisticated abstraction»; by contrast, SGI (2020) describes the DT of a smart city as its exact copy in the real world, D'Amanzo & Feijoo Rivas (2021) as a digital representation, WGIC (2022) uses the term «holistic». The last goes further, claiming that DTs can cover even the globe. To support their thesis, the authors cite the Destination Earth project by the EU, which aims to build a DT for the whole world with a 1 km resolution; intended to shape climate policies, it should model both environmental changes (predicting potential catastrophes) and human behaviour. Another wide-scale example is the UK National DT Programme (2018); it is not a single DT, but an ecosystem of interconnected local DTs for improving efficiency (D'Amanzo & Feijoo Rivas, 2021).

Image 2.14

DestinE by the European Commission
Source: esa.int

The realisation of a DT is very expensive so it should be justified by a clear assessment of the effects it would have, starting from a business problem or organisational need. This implies a cost-benefit analysis which should give positive outcomes (benefits outweighing costs), a business model defining the relevant elements for the implementation and an evaluation of the appropriateness of this tool over others. Nevertheless, DTs generate strong revenues: in 2021, the associated revenues amounted to $ 12,7 billion (WGIC, 2022). Minerva et al. (2020) highlighted the three main value clusters for DT implementation.

1. System value. As mentioned, the creation of a DT allows us to understand the physical object not only by itself but also in its context. This systemic approach permits us to get how interactions unfold, forecasting the possible benefits and impacts on the affected components; obviously, the DT simulations can be run with several parameters, thus allowing a comprehensive understanding of how the objects' behaviour changes in different conditions.
2. Interoperability value. The main mean for granting interoperability is standardisation: this push comes mainly from the data source, that is IoT sensors. However, the IIoT Consortium aims to standardise even the DTs. This demonstrates that interoperability is possible on several scales, from the sensor up to the semantic level, providing standardised data structures. Often innovations are introduced without considering the readiness of all the stakeholders involved in the process, making interoperable applications fail; WGIC (2022) highlighted four approaches to mitigate such risk: pilot programmes testing before adopting on a wider scale the innovation, use of a platform ensuring compatibility within the environment, clarification of requirements and specifications, application of these approaches not only to the DT itself but also to data exchange, preserving information.
3. Business value. As mentioned, there is an important cash flow dependent on DTs. This comes from an improved customer satisfaction, deriving from the possibility of tailoring the product or service according to the needs and requirements of the final user. In general, it can be said that adopting a DT results in a higher control and management ability. The business value can be further analysed from the perspective of the enterprise and of the value chain. The enterprise values the possibility not only to monitor the functioning of the products but also to be more connected

to its customer base; moreover, DTs enable process optimisation from design to delivery. The value chain makes the individuation of four points of value aggregation possible: the physical objects (sold or leased to the customer), the virtualisation platform (the DT complex, composed of data and functions), the user interface (which can be implemented to meet the requirements) and the actual applications of the DT (Minerva et al., 2020)

A further value element is the recent development of the metaverse concept. Using augmented and virtual reality applications, it would be possible to join a representation of the real world properly scaled and located, enriched by more details too (WGIC, 2022).

These values depend on the possibility of supporting three relevant functions of human knowledge, which are conceptualisation, comparison and collaboration. DTs eliminate the need for conversions between conceptual and visual information, synthesising all the relevant data of a physical object into a virtual product. DTs also facilitate cross contaminations and learning from best practices: the virtualisation of the solution makes it immediately available across the globe, calling off the time necessary for communications and training. In short, DT capabilities free us «from the physical realm where humans operate relatively inefficiently» (Grieves, 2014).

Nevertheless, being the DT a relatively new technology, some organisations still are not ready for it, as demonstrated by four main problems. First, DT is often confused with the 3D model; in other cases, it is impossible to realise a DT due to the data unavailability or inappropriateness or due to lack of knowledge on how to implement (from design to realisation and maintenance) the model; finally, some still have not understood the potential clients and benefits of such technology.

Two needs thus emerge, education and adequate policies. DT functions are constantly expanding and the modelling phase improving: therefore, it is crucial to have a continuous uplifting of skills; this is declined not only in academia, with new graduates being ready to tackle the emerging challenges, but also in the industry, with adequate refresher courses. As for policy, some policies have to be established and some modified to improve the DT. Innovation policies and agenda should be introduced, understanding the evolutional character of the DT but framing it in a standardised framework, while challenges and gaps to tackle are the mentioned data unavailability for some topics and the narrow scope of existing policies (WGIC, 2022).

2.2.2.2 Properties

The first relevant property is representativeness: adopting the view proposed by Ivanov et al. (2020) and Dembski et al. (2020) and seeing, therefore, the DT as an abstraction, still, the DT should be as close as possible to its physical counterpart. The logical object should be simple and efficient, representing at the same time a piece of information sufficient to describe completely (according to the scope) the object. Three major parameters express how representative a virtual replica is:

- similarity: it determines to which point a DT reproduces the physical object;
- randomness: the probability that an incoherence between the logical and physical objects is found;
- contextualisation: the previous two elements applied to the surrounding environment.

Image 2.15

Urban Digital Twin
Source: WGIC, 2022

Reflection (or mirroring) quantifies how much a logical object can be used to take measures on the physical one, with respect to the application. In this light, the logical object is seen as a set of numerical values related to geometry, behaviour and attributes.

Replication refers to the possibility of multiplying the representations of the same physical object in a virtual environment. However, it is likewise possible that multiple replicas, relative to different applications, are organised in a hierarchical structure, with on top the physical object itself or a master logical object. Different replicas can contribute to a single simulation, too, sharing information quickly and efficiently. In the case of multiple replicas, it is crucial the concept of identity: both the physical and the logical object have their own identity, but in the case of several representations there is not a bijective correspondence between the two. The DT identity is therefore complex: it should include the identifier of the physical object, together with the identifiers of all the representations, spatially and temporally located; the complexity lies also in the different nature of the information since both physical and virtual objects are included.

Entanglement refers to the communication between the physical and logical objects. It is articulated in:

- connectivity: the presence of a medium of communication;
- promptness: timeliness of the communication, to make the time when there is a difference between physical and logical objects negligible according to needs and usage, with the average time of change of status being the updating threshold;
- association: typology (uni or bi-directional) of the communication; generally, it is carried on between the physical and logical object.

It is debated whether a key characteristic of a DT is that it is evolving through IoT sensors automatically or if the update can be just ensured manually through regular maintenance.

Once having ensured that different objects, both physical and logical, can be realised and communicate with each other, a further relevant characteristic is composability, the ability to assort them into a single entry. Especially when elaborating on a city DT, we refer to a system of systems: the integration of multiple components is crucial. Composability is strongly related to abstraction: in the case of complex interactions, these should be simplified, focusing on the key relations. Different levels of composability lead to a multi-scale and multi-disciplinary DT, with the various DTs providing the appropriate level of detail.

The listed ones are the foundational bases for the realisation of a DT, ensuring the correspondence between physical and logical objects in the operational context. Nevertheless, quality can be improved by adding some more elements, such as memorisation, persistency, accountability, augmentation, servitisation, ownership and predictability.

Memorisation is the potential to keep records of historical data which can be relevant for finding patterns and elaborating future scenarios. It is needed to find a proper balance between the amount of stored data and the space occupied in the memory to preserve the system's efficiency; it is still advisable to have redundancy, so that it is always possible to keep track of the different phases of the logical object and that raw data can be used as input of future elaborations, too. Memorisation does not imply that the model has to be stored as it is: DBs enable to keep track of the modifications only, thus reconstructing the historical versions accordingly.

Persistency is about the need to have continuous availability and serviceability of the DT; especially in the case of bi-directional communication, with the DT providing information to the physical counterpart, it is crucial. The key factor is the logical object used for the DT implementation, which should be reliable.

Accountability (or manageability) refers to the proper management of the DT. It is strongly related to persistency, regarding the possibility for the logical object to "break". This case should be averted, making the DT enter a recovery state. Multi-user access should be granted, too.

Augmentation is about improving the DT functions over time; it is crucial for adapting to changing needs of policymakers and citizens, extending the range of action and including a more holistic modelling of the city. Servitisation is connected to augmentation, in the way it augments the services available for the logical object. Its extreme consequence is a pay-per-usage philosophy, in which the objects are not owned anymore, but just used when needed.

By definition, the system is a pattern of elements, whose property is not the same. The DTs ownership is often ignored, but crucial; it is conjugated in the ownership of the raw data and the logical object. It is to be noticed that not necessarily the owner of the physical and logical objects coincide.

Finally, predictability concerns the possibility of simulating future scenarios through the DT: it models the objects alone and in their environment, to predict how elements interact and evolve.

2.2.2.3 Enablers

It was previously analysed how digitalisation contributed to the evolution of cartography and in particular photogrammetry; on the contrary, the DT concept could not exist without this recent innovation, as the name itself suggests. ICT is the base layer for any virtual application, but also other elements should be introduced: it is the case of cloud computing which ensures multi-user access and modification, Big Data that have to be faced when modelling a wide and complex object as a city and the Internet of Things (IoT) for effective communications between the physical and logical objects. All these aspects were tackled in the research by D'Amanzo & Feijoo (2021).

Information and Communication Technology (ICT) is the set of methods and techniques used for the transmission, reception and elaboration of data. It is interdisciplinary, conjugating IT with other disciplines such as social sciences and economics. It constitutes the digital infrastructure of a smart city: just like the physical ones, it should be properly designed and organised. ICT architecture can be seen as organised on four levels: survey (acquisition of the required data), communication, data (it is the intelligence level, ensuring that data are organised systematically) and services.

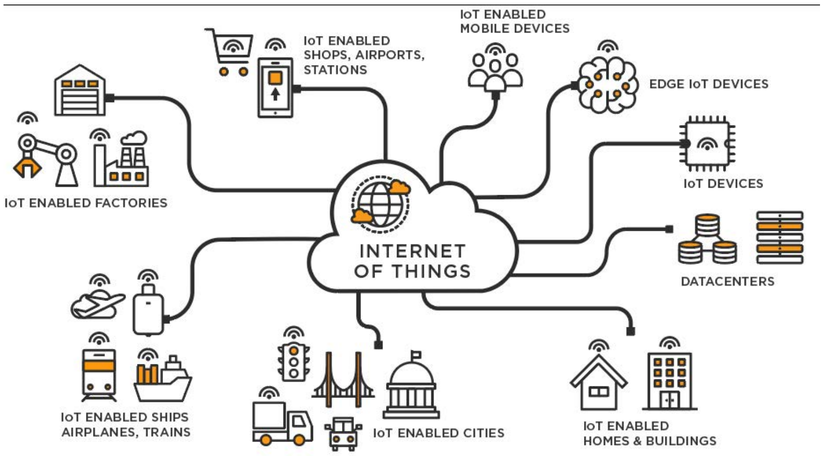
Respect for some major requirements is needed to make the ICT platform effective, not constraining daily activities but rather carrying on tasks to improve life. First, it should be affordable: economics is one of the three dimensions of sustainability, so the cost should be related to the gains the technology brings. It needs to be durable and reliable, too, in terms of both functioning and security: a management platform for a whole city is a sensitive technology so protection should be maximum and malfunctioning prevented. Finally, it was already explained how important is interoperability, considering the need to integrate the technology in such a complex system as a city.

Cloud services enable online archiving and data access: such service makes the information accessible and usable by multiple parties simultaneously. When referring to a smart city, data interoperability is fundamental in this case, too: there should be a defined DB structure, integrating data produced by several departments. The system is therefore organised in cloud infrastructure, platform cloud and application (or software) cloud. The infrastructure is the base providing the physical resource, fundamental for the sharing of information. The platform organises and integrates data, managing regional resources. Finally, the highest level is the application cloud, which enables the sharing of information. Cloud computing development has been crucial in improving the possibility of providing services through the internet.

The DT, considering its need to be updated constantly, relies on the possibility to receive data collected automatically (Ivanov et al., 2020). Given the number of elements included in such a complex model as the one of a smart city, it would be necessary to create a network of connected physical objects able to communicate directly with the model (D'Amanzo & Feijoo, 2021). This technology is already present: it is the Internet of Things (IoT), fundamental for the reduction of implementation costs and widening of the DT applications (SGI, 2020). Still, at its current state, it needs to be perfected: in particular, it is affected by the limitations of 4G (scarce support for simultaneous connections, high costs and energetic consumption), with the 5G probably unlocking its whole potential (D'Amanzo & Feijoo, 2021).

It was previously analysed that several ways of communicating between the physical and logical objects are possible: they can be distinguished both in terms of frequency (real-time, permanent or occasional) and direction (from the physical to the logical object, vice-versa or both). Therefore, even if IoT technology was applied mainly to sensors, it may be implemented on devices for calibration, too, fixing the physical object based on the simulations provided by the logical one. For such applications, virtualisation becomes crucial in the IoT context: it is the possibility for abstracting a whole ecosystem in a cloud, running functionalities on a model and providing nearly-instant feedback to the physical object (Minerva et al, 2020).

Image 2.16



IoT network
Source: tibco.com

IoT, because of the number of elements (especially after the digital miniaturisation) and the registered information, produces a wide number of data; these are archived, queried and shared for the proper functioning of the DT. Big data is a term for addressing a large dataset requiring a DBMS to be queried due to its complexity and constant update (and therefore widening) (D'Amanzo & Feijoo, 2021). Big data have to be managed adequately: this is «the first and core theme of the city digital twin» (Shahat et al., 2021). Indeed, a proper analysis, conducted in real-time, speeds up decision-making (especially in emergencies) and improves its quality (Ivanov et al., 2020).

When dealing with big data, some requirements are a direct consequence of their characteristic: the definition of efficient elaboration platforms and intelligent network infrastructures, the calculation of advanced algorithms and the definition of clear roles for citizens and government, to grant security and privacy while effectively using the data (D'Amanzo & Feijoo, 2021). A major challenge, however, is the integration of heterogeneous data which need to be channelled into the same data structure to be processed and used as input for software and applications (Shahat et al., 2021). According to WGIC (2022), standardisation of technologies, processes and workflows «is critical for collaboration, connectivity and communication» among systems, stakeholders and users.

Standards have to be elaborated aiming to be at the same time both flexible and rigid: flexibility ensures applicability, rigidity effectiveness. Two main paths can be followed for establishing an effective standard:

- structured approach following some steps, that are meaning definition, use-cases identification, frameworks establishment and standard definition;
- collaborative user-demand approach, normalising practices already in use.

It is also to be considered that standards in some moments limit the potential to grow, so the firms would be forced to create alternative working frameworks to unlock their potential.

2.3 GeoDataBases

In the previous paragraphs, the focus was on cartographic products and their potential; in particular, talking about the DT, it was evident the complexity of the data structure. A computer cannot work like our brains, instead, there should be a translation process between the organisation we have in mind and the data structure read by GIS. The design of a GIS consists of modelling which allows the description of the real world in mathematical algorithms; this process has to be carried on focusing on the characteristics needed for understanding a given phenomenon (Biallo, 2005).

The final output of this abstraction process is a GDB, which is an organised collection of data concerning the position and attributes of geographical objects (natural or artificial elements not further divisible) on a 1:1 scale. A GDB is a container, whose dimensions are constrained by the hardware only (so in theory it could be unlimited). Differently from traditional maps, it can be queried: the geographical information is stored as accurately as possible (potentially turning off some of the entities), so data quality depends on the survey only (Amadio, 2012).

However, GDBs are just one of the possibilities to store geographical data. Once, they were kept separately from their metadata and joined when needed. Then a new approach, the file system, emerged, emerged: it was marked especially by the invention of the shapefile, by ESRI. The shapefile is now the dominant standard in the GIS framework: it allows the description of different geometries and the extension of geometrical features. It is a vector file, to which complementary files should necessarily be attached. However, using a GDB is convenient because it allows an extension of the capabilities of a DataBase Management System: in this case, the user works on the entities rather than on the objects themselves or records and files. DBMS have some characteristics that make them particularly suitable for the implementation of complex spatial projects like DTs:

- good performances, necessary when dealing with Big Data coming from smart city management;
- availability of tools for controlling data integrity
- possibility of storing and querying historical data through solid frameworks for data management;
- multi-user environment: DBMS allow the simultaneous access

of multiple users, even when they are editing, with versioning ensuring consistency.

There is a standard language for querying the DBMS: it is the Structured Query Language (SQL). It can be used by all the professionals involved in a GIS project: the GDB designer creates the structures, administrators can manage accesses and the users use it for manipulating data. Nonetheless, given the complexity of such language, some GIS programmes employ user-friendly interfaces simplifying the translation between commands and SQL language.

2.3.1 GDB realisation

The abstraction can be defined as the process of individuation and isolation of objects and phenomena to explain the geographical reality into a model. Its scope is not only to find an adequate IT form but also to make it useful for the users (Amadio, 2012). The modelling needs a preparatory phase and three abstraction levels: the elaboration of the external model precedes the definition of the conceptual, the logical and the physical models; from a simple selection of the objects to represent as entities, there is a gradual conversion to the final model (Biallo, 2005).

Every model is expressed in a schema or diagram, which are communication and documentation tools that, using proper language, explicit the findings of each phase. Models individuate:

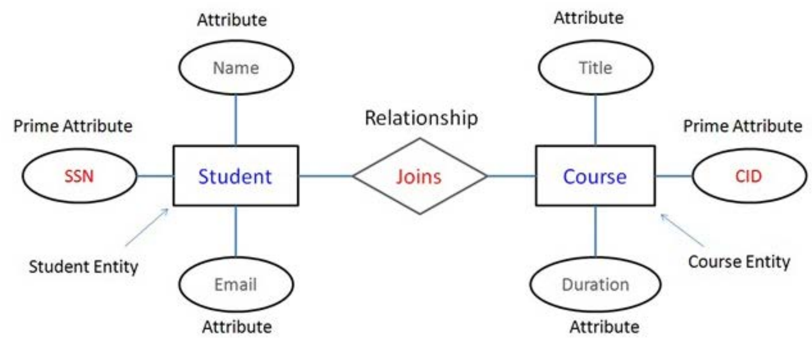
- classes: groups of objects which will have homogeneous characteristics in the GDB;
- attributes: characteristics of each entity, describing its properties;
- relations: they identify correlations among the objects;
    - associations: structural relations among classes, which are classification (common properties), aggregation (new concepts derive from existing ones), generalisation (new classes emerge);
- constraints: limitations on objects or relations, ensuring consistency in the model;
- operations: set of actions that an object can carry on, shaping its behaviour.

The preparatory phase, leading towards the definition of an external model, is required to select the necessary functionalities, data and structures to have; it consists of a selection and simplification of the reality. This phase unfolds on the base of the requirements provided by the final user, considering the services to provide, but it is equally important to leave room for potential new needs emerging in a second moment (Amadio, 2012). The name of the output is misleading: the external model is just a text or list, written in everyday language, and it has not a diagrammatic representation.

The first level of abstraction is the semantic-conceptual model, defining the entities and their characteristics. Entities are catalogued thoroughly, indicating all the elements which will be fundamental for the GDB realisation: to do so, it uses the Entity Relationship (ER) language.

ER, introduced in 1976 by Peter Chen to standardise the panorama of relational models, schematises a phenomenon to represent, as the name suggests, using entities (with their attributes) and the relationships among them; relationships occur among classes by rule of the attributes, so spatial relationships cannot be indicated. In the ER, generally, entities are represented as blocks with the name in capital letters and a list of attributes underneath; the attribute which gives the univocal identification of the entity is underlined. Relationships are represented with lines and a term (generally a verb) to express the nature of the correlation. For each relation (in each direction) the cardinality is reported: it indicates the minimum and maximum times that the relationship can occur among the two entities.

Image 2.17



ER diagram
Source: learncomputerscienceonline.com

The second phase output is the logical model: it specifies the conceptual model in a way oriented towards the implementation of the system. It is drawn up after having decided what software (or DBMS) to use, considering its limitations and data structures, but independently from the hardware (Biallo, 2005). The resulting data structure can be easily converted in the computer input, the main core of the third phase: indeed, the logical modelling can be synthesised as the translation of the conceptual schema in the DBMS data model. There are various ways to realise the logical model: the hierarchical, reticular and relational models (generally described as record oriented) and the object-oriented approach.

The hierarchical model defines a tree-shaped structure based on father-child relations; the principal record (or father node) is at the top of the structure and all the other classes depend on it. The tree shape constrains the cardinalities: each child can have just one father, while fathers can have multiple children (1:N cardinality). Because of this constraint, it cannot be considered suitable for a GIS, where queries should be free.

The reticular model was born as an evolution of the hierarchical, removing the 1:N cardinality. Formalised in the 1971 Conference on Data System Language, by eliminating redundancy it facilitated queries and editing.

The relational model was elaborated in 1970 by an IBM specialist, Edgard Frank Codd. The relation, a mathematical term to indicate a two-dimensional table, expresses at the same time both the entities (on the lines) and the attributes (in the columns), thus reporting the relationships too. It is a rigorous but flexible model, suitable for GIS because it enables the definition of a data structure, easy editing and the possibility of querying the model (Amadio, 2012). A relation is defined by name, attribute list, identifiers and potentially a text description.

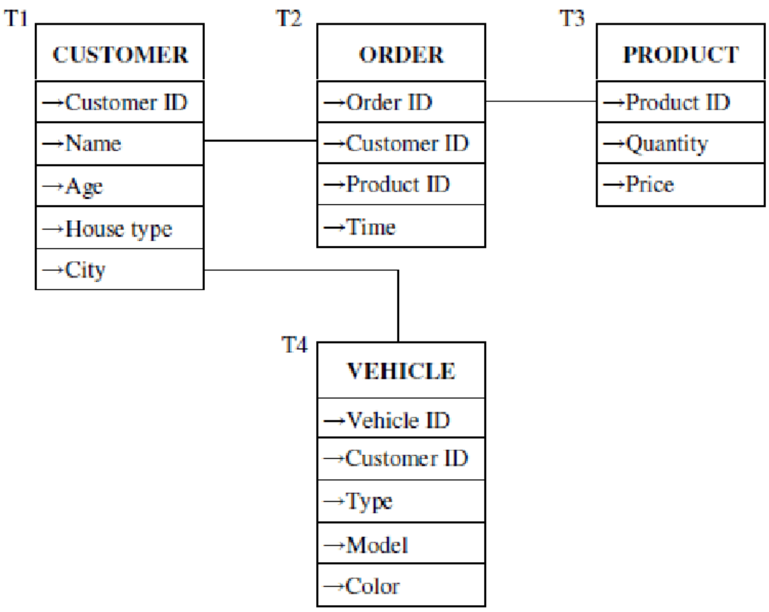


Image 2.18

Codd relational model
Source: researchgate.net

The techniques foreseeing sequential routines inside a principal programme through messages are called object-oriented. The object-oriented approach creates a direct correspondence between objects and their corresponding entity. Classes, objects and operations follow the inheritance principle, with sub-classes inheriting all the attributes of the superclass. There are no standardised data models, a common theoretical base and a standard interrogation language (such as SQL for relational DBs): this is the main problem.

The object-relational model conjugates the relational model and object-oriented approach, overcoming the limitations of the former: it has no fixed data types, substituted by personalised data types (Abstract Data Types).

Finally, an internal (or physical) model is produced. It represents the translation into machine language (file, numbers, strings, bytes and bits) and it is generally carried on by the DBMS. In a GIS, it is the phase in which the topology of the geometrical attributes is verified (Biallo, 2005). It is a critical phase, involving the choice of the proper hardware too: performances have to be ensured according to the scope. Indeed, a DBMS relies also on physical components, e.g. for storage: the primary memory of the computer is often not sufficient, but the reading time should be minimised.

This process takes time and resources, also human. Indeed, three kinds of professionals have key roles in the GDB design and implementation:

1. final users compile the external model, operating the selection from the real world and defining the requirements;
2. IT technical figures are involved in the process since the second phase: in the choice of the DBMS for the logical model the software developers are contacted;
3. and technology providers provide consultation for the choice of the most appropriate hardware during the definition of the physical model.

3

Energy transition

The concept of energetic transition derives from the paradigm of sustainable development, defined in the Brundtland report (1987) following serious energetic and environmental events in the Seventies and Eighties, such as the oil crisis and the Chernobyl disaster. Sustainable development is a «development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs» (WCED, 1987).

This framework was put into reality by the UN Rio de Janeiro Conference (1992) and by Kyoto Protocol (1997). In Japan, 180 countries on a global scale defined clear goals and timings for the reduction of polluting emissions caused by human activities: the concept of decarbonisation appeared. The final target was a 5% pollutant reduction compared to 1990 to be achieved by 2012, with further national specifications: Italy signed for a 6,5% reduction.

The Programme 20-20-20 (Directive 2009/29/EC) went further with such targeting policy, stating (compared to 1990): a 20% reduction in GreenHouse Gas (GHG) emissions, 20% increase in energy coming from renewable sources, 20% increase in energy efficiency. Further cuts were foreseen in 2020 in the European Climate Target Plan for 2030: the Commission targeted a 55% reduction compared to 1990 (EC, 2020).

Image 3.1

The 17 SDGs
Source: un.org/sustainabledevelopment

Another global framework was defined by the United Nations in 2015: the Agenda 2030 defined 17 Sustainable Development Goals (SDGs) for making development sustainable in fifteen years. This chapter touches on the topics of SDG 7 “Affordable and Clean Energy” and SDG 11 “Sustainable Cities and Communities”: nevertheless, being the goals interconnected, several others will be included. An example is goal 13 “Take urgent action to combat climate change and its impacts”: in particular, indicator 13.2.2 puts the accent on GHG emissions, stressing the importance of their reduction and creating a link with decarbonisation.

The challenge of decarbonisation was a key aspect of the last report by the Italian Ministry of Infrastructures and Sustainable Mobility (2022). It stressed the centrality of cities in this process, first providing some data: cities occupy only 4% of the EU surface, but host 75% of the citizens and are the main responsible for energy consumption (40%) and GHG emissions (36%) (MIMS, 2022). Moreover, the annual rate of energetic renovation is very low: at the current pace (1%), the process for the total elimination of carbon emissions would take centuries. The initiative Renovation Wave for Europe aims at doubling the refurbishment rate and favours profound renovations (ENEA, 2021).

Cities, but also buildings (which can be considered as their smallest unity) are complex elements: therefore, it is necessary to adopt a systemic approach, organised on three principal levels.

1. Modification of the structure of the city to make it compact and efficient, thus reducing energy consumption.
2. Shift towards Renewable Energy Sources (RES) for meeting the residual energy demand.
3. Improvement in carbon absorption and storage.

It is evident from these action axes that the focus is not on the creation of sustainable districts, but rather on the modification of the existing structure. Indeed, according to a classification by IPCC, most European and Italian cities can be considered as mature: soil sealing has to be limited, on the contrary, it is possible to improve adaptation, resilience, social inclusion and development drivers with existing solutions (MIMS, 2022). The Climate Target Plan stresses the importance of the residential sector: compared to 2015, the energy demand for heating and cooling should decrease at a rate comprised between 19% and 23%; there should be a concurrent increase of both the RESs (38-42%) and in the rate of substitution of heating systems (the goal is 4%/year) (ENEA, 2021). Such measures can be organised hierarchically. The base of the pyramid is constituted by a reduction in the energy demand: casing and ventilation technologies have the highest potential. Once achieved this reduction, it is then appropriate to improve the energy efficiency of the systems serving the building. Finally, RESs can be used for meeting the remaining energy demand.

The first step towards decarbonisation should be taken by policymakers; in particular, at the level of the European Union, some measures are required. First, to increase the renovation rate an incentivisation programme should be launched together with minimum energy requirements, setting standards for the communitarian building stock (both existing and newly built) to meet the zero emissions target by 2050; at the same time, any incentive on fossil fuels-powered heating system should be removed, redistributing those funds for RESs. Wide-scale plans for the enhancement of energetic efficiency should be drafted, introducing some requirements too, e.g. to insulate the roof when installing solar panels.

3.1 Improving energy efficiency

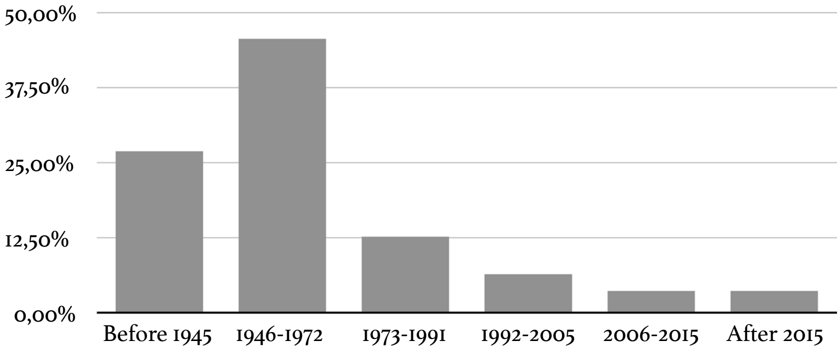
The principal conclusion of the previous paragraph is that it is necessary to work starting from the building, minimum unity of the city. In Italy, the first standards for building design, installation and maintenance of thermal systems and for energy insulation were set by Law 373/1976. It introduced the unit of measurement of the Heat Degrees (defined as the sum for all days of the year of the difference between inner and outer temperature) and, based on it, the definition of six climatic zones. Moreover, the surface-to-volume ratio was to be used in defining the energy performance of a building.

Still, the presence of such standards is not sufficient: the data explained previously show that the building sector is the main responsible for energy consumption and pollutant emissions. The following paragraph is aimed at describing the current situation, searching for the reasons for such unsatisfying performances.

3.1.1 State of the art

It was previously indicated a milestone, 1976: a first relevant analysis is therefore on the average age of the building stock. ISTAT, in the 2011 census, reported the average age of the Turin residential buildings to be 36,8 (so precedent to 1976) (8milaCensus, n.d.). Considering the buildings with a certificate of energy performance in the Metropolitan City of Turin (88,8% of them are residential), 72,81% were realised before 1973 (SIAPE, n.d.).

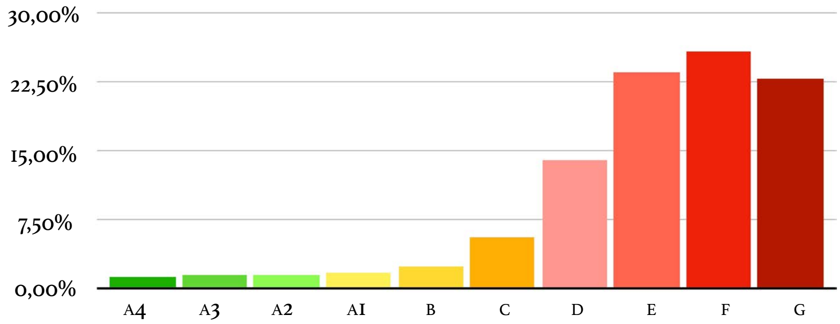
Graph 3.1



Share of buildings with APE divided by age in Turin Metropolitan area
Source: SIAPE, n.d.

Therefore, a wide share of the existing building stock in the local panorama was not realised in compliance with law 373; considering the low renovation rate on the European scale, it is not surprising to observe low energetic performances. Only 6,8% of the buildings fall in the A class, while more than 50% are comprised in the two less-performing classes (F and G) (SIAPE, n.d.).

Graph 3.2



Share of buildings with APE divided by class in Turin Metropolitan area
Source: SIAPE, n.d.

Given that the average CO_2 emissions for A class buildings are 23,5 kg/m2/year, approximately 1/4 of the emissions for G class buildings, this data should exemplify the urgency for interventions on the building stock.

Such urgency was also recognised by the European Commission, which in December 2021 proposed a revision to the Energy Performance of Buildings Directive (Directive 2010/31/EU, modified by Directive 2018/844/EU). Indeed, the main goal defined in this proposal concerns renovations, increasing the rate and profoundness. Member States would draft their National Long-Term Refurbishment Strategies to specify how such goals would be met; the guidelines by the Commission propose the introduction of standards on energy performance, the regular revision of the certificates of energetic performance, the introduction of a Building Refurbishment Passport and a univocal definition of profound refurbishment.

Italy has already drafted the STREPIN (Italian Strategy for the Energetic Refurbishment of the National Building Stock): it is based on technical, fiscal and normative actions to improve both the number and the effectiveness of the renovations (ENEA, 2021).

3.1.2 Energetic renovations

The energetic renovations comprise all the interventions carried out on public or private buildings to improve energy efficiency, by optimising the ratio between energy demand and emission levels (Teodoro, 2021). Based on the payback time, the use of components for regulation and control (such as thermostatic valves) is preferred to the improvement of the building energy efficiency with thermal insulation from outside or substitution of window fixtures. Such installations, aimed at reducing the thermal and cooling demand, precede the provision of high-efficiency systemic solutions and RES production systems. Finally, automation and digitalisation can be implemented for high-efficiency buildings (MIMS, 2022).

In this research, which is oriented towards the use of solar energy for satisfying the energy demand, it is particularly interesting the model of Passive Solar House: it involves the research for optimal building orientation, efficient windows and boilers and shading systems. The Passive Solar House stores the heat within the building structure and releases it when needed, using at the same time shading (with both artificial structures and vegetation) to mitigate overheating. It improves indoor comfort through the exploitation of daylight conditions, decreasing heating costs. However, this model is cost-effective and flexible for new constructions, while it needs proper integration with other technologies in renovations.

A more comprehensive model, compared to the Passive Solar House, is the Nearly Zero Energy Building, introduced by the mentioned Energy Performance of Buildings Directive (2010), whose requirements should apply as of 2027 for public buildings and 2030 for all new buildings. It was defined as «a building that has a very high energy performance» with the energy demand «covered to a very significant extent by energy from renewable sources» (EU, 2010). So, this model aims to integrate technologies for the reduction of energy demand and the efficient use of renewable energy. It represents a step forward from all the previous initiatives because it integrates the three relevant aspects of sustainable buildings: demand reduction, system efficiency and use of renewable sources; moreover, it recognises the complexity of the buildings and analyses qualitatively such aspects. A systemic approach to this concept would lead to the definition of a Nearly Zero Energy District, shifting to the neighbourhood scale. This would add a further element of complexity, scaling up the model to a PED or energy community (see paragraph 3.3).

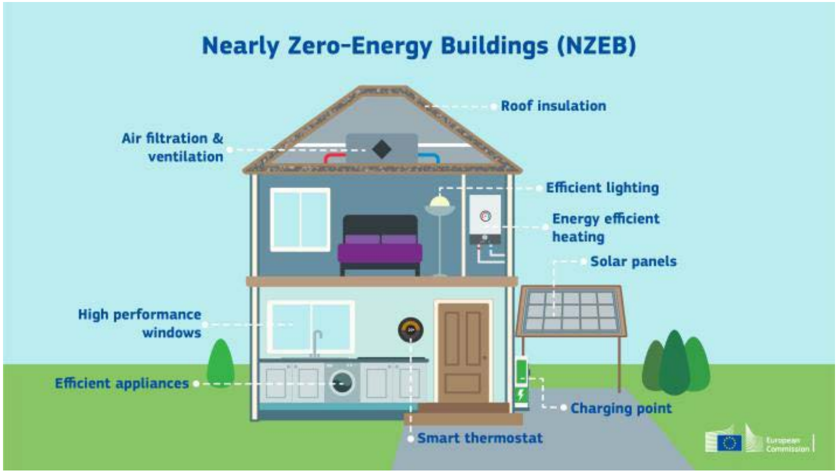


Image 3.2

NZEB
Source: energy.ec.europa.eu

At this point, a clear distinction should be made between new constructions and renovations: while a realisation from scratch allows the adoption of a pre-defined model, renovations have to cope with what is already existing. In particular, working on a historical building stock often the workers face masonry works or concrete structures. In this case, further attention should be given to the material selection, to ensure durability, compatibility, distinguishability and reversibility (making an intervention similar to a restoration). Indeed, a major challenge is to keep the artistic-historical value in such interventions, using for instance insulating materials for the interior, intelligent casing and highly-integrated photovoltaic panels.

In its 2021 yearly report, ENEA provided data about the energy retrofit in Italy for the period 2014-2020. This list is useful for a brief explanation of the different possibilities for the improvement of the energy efficiency of existing buildings. Nevertheless, the challenge is to consider not only the working energy demand but rather the global one: solutions have to be sustainable since their design and realisation and the construction industry should be decarbonised too (MIMS, 2022).

Table 3.1

	Interventions [n]	Investments [M€]	Savings [GWh/year]
Vertical walls	9.369	265,4	108,4
Horizontal and oblique walls	11.929	417	187,5
Doors and windows	188.773	1.466,3	552,4
Shields	54.367	112,7	13
Condensation boilers	77.828	649,3	281,6
Heating pumps	9.727	87,3	27,4
Building automation	770	10,7	4
Biomass systems	3.237	32,6	11,6
Thermal solar	7.523	51,8	34
Other	2.073	22	6,7
Total	365.866	3.095	1.227

Energetic renovations in Italy (2014-2020)
Source: ENEA

Walls, roofs and floors are the main ones responsible for thermal insulation: the evaluation of their "endurance" in such a sense was introduced by Law 10/1991, acknowledging their key role in keeping the temperature of the spaces. In the mentioned period, the savings per year amounted to 0,4 kWh/€ and a total of 295,9 GWh is to be saved every year thanks to such interventions (ENEA, 2021). Thermal insulation interventions on the casing realised using the incentives of the Superbonus 110% in 2021 concerned walls in 67% of the cases, roofs and slabs in 26% (MIMS, 2022).

Window fixtures, when efficient, cancel the airflows and therefore improve the insulation. PVC fixtures are particularly effective. The saving achieved with an investment of a single euro is slightly lower than the casing one, but in the analysed time frame window substitution was the most relevant intervention in terms of the number, investments and therefore savings, totalling 552,4 GWh saved yearly.

Solar shields are intended to freshen the air by preventing the Sun rays from directly striking inside the spaces. As mentioned, they are particularly effective on new buildings, while the savings are very limited: only 0,1 kWh/year is saved with an investment of €1. For this reason, it was scarcely adopted, with low investments and therefore savings.

Moving up the energy efficiency enhancement pyramid, the systems serving the building have to be improved. Condensation boilers and heating pumps allow high energy savings: in particular the former contributed to a yearly consumption reduction of 281,6 GWh. The MIMS report (2022) stressed the increasing rigidity of the requirements, resulting in an equally increasing attention to the cooling systems and sanitary hot water demand. This led to a general diffusion of systems based on heating pumps. Heat recovery devices reach efficiencies higher than 75%: despite their energy consumption for granting air movement, they are used for high energetic classes (from A1 to A4).

Building automation was little applied: only 0,18% of the interventions concerned such technologies. Nevertheless, it grants higher savings than a heating pump compared to the investment (0,374 KWh/year/euro). This technology is particularly interesting from a future perspective, considering the progress of artificial intelligence in recent years.

Finally, among the renewable energies used for meeting the thermal energy demand, biomass systems and solar thermal panels can be used. Generally, biomass systems are centralised and the resulting energy is distributed through heat distribution systems (in the case of a single building) or district heating; energy derives from the pyrolysis (or gasification) process. It is rarely adopted singularly: combined heating and power systems conjugate biomass systems with other sources. Solar thermal technologies produce heat from solar energy through a collector (conductive plate absorbing the incident radiation and transforming it into heat). Traditional collectors can be glazed or unglazed: the latter, less efficient, is generally used for seasonal water heating (e.g. for pools); the main innovation in the field is the vacuum collector, which reduces the heat convection losses through the elimination of the air inside the device.

To evaluate the actual effects of the Ecobonus for energetic renovations in Italy it is interesting to provide a segmentation of such technologies on the market, based on the total investments. It is not surprising that considering the general prevalence of such technology, the highest investments were for window fixtures: in particular, buildings realised between 1961 and 1970 were the most affected, with a total expenditure of €49 M. Looking at the distribution of investments according to the age of the building, the effects of law 373 are evident: more than 50% of the expenses were taken for buildings realised until 1970. It is the 1961-1970 range the most affected by energetic renovation (ENEA, 2021): it can be assumed that such constructions were realised with poor quality to solve the problem of overcrowding which followed the intense northwards migration of the economic boom; therefore, it is that the building stock with the highest urgency for renovation (ENEA, 2021).

Table 3.2

	Investment [M€]	Percentage [%]
< 1919	48,7	12,17
1919 - 1945	34,1	8,52
1946 - 1960	71,6	17,89
1961 - 1970	96,1	24,01
1971 - 1980	67,1	16,77
1981 - 1990	31,3	7,82
1991 - 2000	25,2	6,30
2001 - 2005	11,6	2,90
> 2006	14,5	3,62
Total	400	100

Investments [M€] with Ecobonus in Italy (2020)
Source: ENEA

Even if mature cities, such as Turin, are interested mainly in the possibilities for energy renovation, it is also important to briefly tackle the topic of new constructions. The construction sector, nowadays, is not sustainable: 7% of the total world emissions derive from concrete alone. The reduction of the environmental impacts should be a main goal for the whole realisation process, since the design: in this phase, the need for raw materials should be minimised, reducing negative externalities depending on transport by preferring local materials. Moreover, materials have to be chosen not only for their aesthetic or structural value but after a careful evaluation of properties such as insulation, pollutants absorption and reflectance (reducing the urban heat island effect) properties (MIMS, 2022).

3.2 Photovoltaic technologies

Solar technologies are the most diffused among the RESs, which are inexhaustible sources. They use the energy coming from the Sun: the fusion on the Sun surface, which reaches temperatures of approximately 6˙000 K, causes the emission of high quantities of energy in the form of electromagnetic radiation and particles flux (the so-called solar wind); this energy arrives on Earth as radiation. Irradiation depends on the geographical position (it is maximum on the Equator, minimum at the Poles) and on the atmospheric layers: any obstacle (elevations, vapour, smog...) absorbs part of it.

Two main technologies are present: photovoltaic, producing electricity, and solar thermal (see the previous paragraph). The photovoltaic effect, discovered by William G. Adams and Richard Evans in 1876, consists of a semi-conductor generating electricity when stroked by the Sun: the two scientists noted it on the telegraph cables, at the time made in silicon, the material which is now used for producing most photovoltaic panels. Charles Fritt, in 1879, created the first prototype with a selenium cell covered by a semi-transparent golden film; it was only 75 years later, in 1954, when Pearson, Chapin and Fuller created the first silicon solar cell in the Bell Laboratories.

The photovoltaic panels (distinguished based on their basic component, silicon or thin film) have to be properly oriented and inclined to maximise the incident radiation and therefore the production; however, many panels (approximately 50%) are integrated into the building roofs, so being constrained to a given layout. Nevertheless, from the perspective of independent energy production, photovoltaic technologies grant partial or total independence from the electrical network: it is an added quality for the buildings on which it is installed, increasing the economical value (Teodoro, 2021).

In Italy, in 2014, 650˙000 active systems produced 22,3 TWh. Nonetheless, their vast majority is installed in the countryside: among nine Italian cities included in the Horizon Europe mission "Climate-neutral and smart cities", aiming to reach climate neutrality by 2030, forms of energy auto-production are negligible currently (MIMS, 2022)

3.2.1 Legislative framework

Despite the gains ensured by the photovoltaic technology, the high initial costs have slowed its development, especially in the initial phase. This is why several incentivisation policies have been launched since 2000.

The programme *tetti fotovoltaici* (photovoltaic roofs), instituted by Ministerial Decree in 2001, aimed at the installation of integrated photovoltaic panels with power comprised between 1 and 50 kWp. It was divided into two parts: one for the public sector and the other for privates, to which funds were to be given through regions and autonomous provinces. The incentive consisted of a contribution to the capital bill for 75% of the total installation investment (RSE, 2016). The parallel programme "photovoltaic at high architectural vale" funded the realisation of modules on valuable buildings, to be realised by public administrations (Teodoro, 2021).

Two years later, Legislative Decree 387/2003 introduced the *certificati verdi* (green certificates): each negotiable certificate, to be released by GSE (the authority for energetic services) demonstrated the production of 1 MWh from RESs. This mechanism was based on the requirement by law for energy producers using non-renewable sources to introduce in the national network a minimum share of electricity produced through RESs.

The same Legislative Decree, recognising the Directive 2001/77/EC, introduced also the *Conto energia* (energy bill), which rewarded photovoltaic energy with 20-year incentives (RSE, 2016). The GSE had a key role in the implementation, considering that it was designated as the operator for the energy policies, responsible for the promotion, incentivisation and development of RESs (Teodoro, 2021). Five energy bills were launched by Ministerial Decrees (compiled jointly by the Ministry of Economic Development and the Ministry of Environment) over time.

1. The MDs of 28 July 2005 and 6 February 2006 specified the rules for obtaining the incentives of the first *Conto Energia*: photovoltaic systems producing with peaks comprised between 1 and 20 kW were financeable in the case of immediate consumption or on-site exchange. Systems producing energy inserted in the network could be financed from 20 kWp to 1 MWp.

2. The second energy bill was launched by the MD 19 February 2007: it extended the applicability of the incentives for all produced energy, removing the threshold of 20 kWp; it also introduced rates based on the architectonic integration and dimensioning of the system, introducing a prize for virtuous systems conjugating

photovoltaic modules and efficient energy uses.

3. MD 6 August 2010, in drafting the third energy bill, set the target of 8 GW to be produced by photovoltaic technologies by 2020. One week later, Law 129 postponed the end of the second *Conto Energia* to 30 June 2011; installations boomed and the target set by the MD was overtaken shortly: 2,3 GW and 9,3 GW were produced in 2010 and 2011, respectively.
4. Considering the ongoing boom, the MD 5 May 2011 defined new mandatory documents to be submitted for systems installed after 20 June 2012.
5. MD 5 July 2012 changed once more the procedure for obtaining the incentives: it activated a system based on all-encompassing rates for the energy introduced in the network and prizes for auto-consumption.

The Legislative Decree 28/2011 moved up the pyramid compared to Law 373: once having ensured that a minimum efficiency is granted, it made mandatory for new constructions and profound renovations to foresee the coverage, at least partial, of the energy demand through RESs; the minimum power to be installed was calculated based on the ground-floor surface, increasing it by 10% in the case of public buildings, with the exceeding share to be incentivised. This provided a major boost to photovoltaic, considering that it is the RES par excellence to be installed on buildings (RSE, 2016): the possibility of integrating it into the roof makes it little invasive, the presence of pitches generally allows at least one of them to be in a favourable orientation.

In 2020, the Ministry of Economic Development published the PNIEC (National Integrated Plan for Energy and Climate); in accordance with the United Nations and European frameworks, it fostered multi-user configurations for auto-production and consumption, but it also set a new threshold for the energy production to be covered by RESs, 30% of the total.

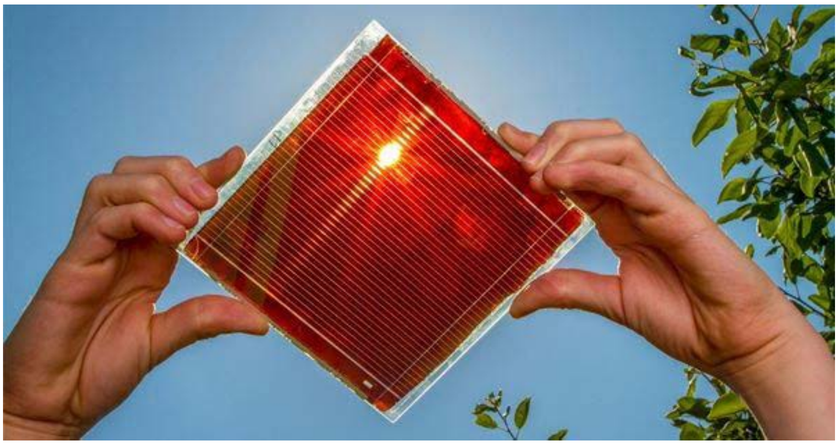
Finally, the ecobonus 110%, introduced by Law 77/2020, introduced a tax detraction of 110% of the costs sustained for the installation of photovoltaic systems and storage batteries; as previously mentioned, it is important that in such interventions the thermal insulation is taken into account, too: the law introduced a requirement for opaque surfaces insulation to access the incentives (Teodoro, 2021).

3.2.2 Characteristics and typologies

As mentioned, photovoltaic panels take advantage of the properties of semiconductors to generate electricity from their modules. The photovoltaic (or photoelectric) effect causes the material to absorb light photons and release electrons; their flow is granted by the overlapping of two overlapping silicon layers, doped with boron and phosphorous.

The prevalent material for the production of photovoltaic cells is silicon, mono or polycrystalline; monocrystalline panels have round or square cells and they are more costly and efficient compared to the polycrystalline: the latter has high-density square cells. Amorphous layers are the base for thin film modules: they are the cheapest and least performing technologies, despite minor efficiency differences between various base materials (CdTe or amorphous silicon). On the contrary, the most advanced solar technologies are the third-generation systems; they incorporate several technologies to maximise the cost-efficiency ratio: indeed, their cost is lower both in terms of the purchase price and the environmental impact (thanks to the lower amount of energy required for their production). Perovskite solar cells, in particular, are certified with efficiencies higher than 20%, compared to the 12% efficiency of a traditional monocrystalline panel; for this reason, they are the most concrete alternative to silicon-based cells (Sanson & Giuffrida, 2017). Efficiency is quantified as the percentage of incident solar energy which is converted into electrical energy; it is inversely proportional to temperature.

Image 3.3

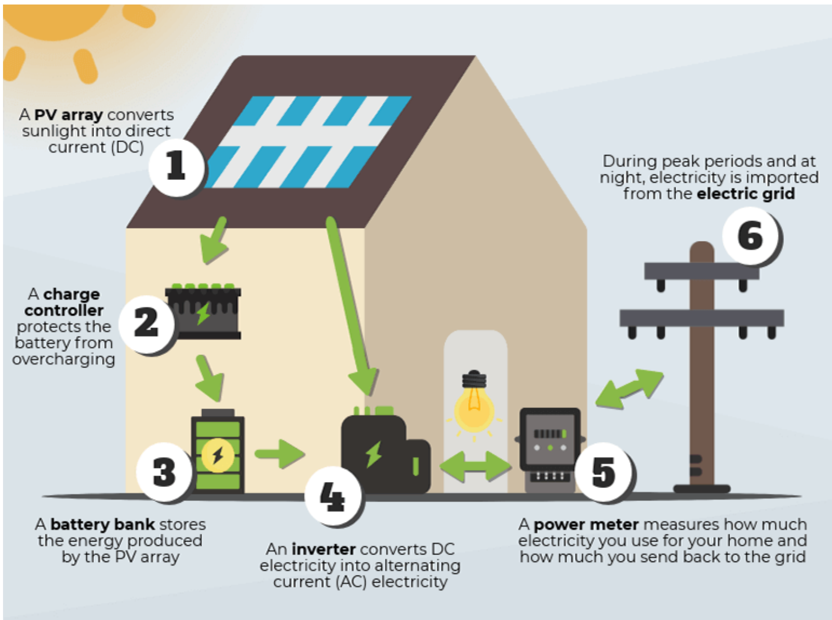


Perovskite solar cell
Source: solarmagazine.com

When installing a photovoltaic system, efficiency is not the only parameter to consider: instead, it was previously explained that geographical position and orientation are key factors for a productive system. Nevertheless, it has to be highlighted that such production is characterised by variability and limited forecasting, with the generated power depending on the period of the year, the time and meteorological conditions (RSE, 2016). Another element to take into account is the available surface: for each kWp of installed power, approximately 6, 8 or 12 m^2 are necessary for installing monocrystalline, polycrystalline and thin film modules, respectively.

Then, the performance and reliability of the supporting system should be evaluated, too. The power conditioner is made of a charge controller (to control input and output), a rectifier and an inverter, transforming AC into DC. Then there should be adequate storage systems: when the solar correlation (both seasonal and daily) is negative, there is a time offset between electricity production and consumption; it is critical because batteries require a lot of space and they are very costly. Finally, if the system is not connected to the national grid, it could be necessary to have other generators (from fossil or renewable sources) to meet the energy demand when photovoltaic production is not sufficient.

Image 3.4



PV system
Source: linkedin.com

At the end of such evaluation, the producible energy can be esteemed; however, not all the energy which can be produced in theory is actually produced: the Performance Ratio evaluates the share between the produced and theoretically producible energy. Typical values of this indicator constantly increased over time from 50-75% in the Eighties; empirical research has demonstrated that, nowadays, systems properly functioning and oriented have a Performance Ratio of about 80-85%. This derives not only from R&D innovations but also from the availability of a skilled workforce, abler to install the panels properly. The Performance Ratio strongly depends on degradation: the reliability and the ability to keep the initial performances over time are key aspects for obtaining the foreseen payback time and, consequently, for the commercial success of this technology. Different studies have been conducted on the topic due to its relevance for all the stakeholders involved, finding out the main factors for degradation:

- firstly, major problems derive from manufacturing, transport and installation, during which there should be problems and damages that lead to a consistent degradation since the first months of exposition;
- Light Induce Degradation is a rapid decrease in the performances that happens once the module (especially for thin film-based technology) is exposed to light, with performances stabilising after some months on the values of nominal power defined ex-ante by manufacturers;
- problems in electrical connectivity, among cells (sometimes deriving from breaks) or caused by diodes malfunctioning;
- de-lamination, which is a phenomenon by which parts of the module tend to detach from the glass casing.

In standard conditions, it was demonstrated that the average decrease in the power output of monocrystalline panels is 0,5%/year; it is slightly higher for polycrystalline (0,8%/year) and up to four times higher for thin films (1-2%/year).

The photovoltaic technology's main advantage is the limited environmental footprint. An RSE study on the Life Cycle Assessment of such systems (realised following the ISO 14040 rule) highlighted the environmental compatibility of photovoltaic for all the analysed impacts, especially compared to fossil fuels. In particular, the raw material consumption is limited mainly to silicon: it would be tolerable not only keeping the same installation rate as today but even increasing it. No water is required for the working of the technology nor CO_2 or pollutants are emitted. More critical is the waste: while it is limited in the production phase, it has to be disposed of accordingly to Directive 2012/19/UE and, in Italy, to the Legislative Decree 49/2014 (which recognised the directive). Indeed, photovoltaic panels are classified as Waste Electrical and Electronic Equipment. Another problem, only in the case of installations on land, is the high land take: wide surfaces are required.

Another positive aspect is the competitiveness in terms of costs, especially in the geographical areas where solar radiation is good. This is mainly due to the reliability of the system, limiting the necessary maintenance: there are no moving mechanical parts, nor combustion or need for filters (to reduce pollutants or noise) (Sanson & Giuffrida, 2017). However, also the purchase cost is decreasing: the diffusion of the technology resulted in economies of scale and for auto-consumption of the whole production the photovoltaic is competitive also without the incentives.

This virtuous cycle of cost decrease and installations increase would proceed but analysts do not agree upon the rate: the principal factor influencing the debate is the presence of regulatory barriers (RSE, 2016). A first debated problem is the possibility of installing photovoltaic panels in urban centres: while restrictions on the city centres are generally accepted and believed to be reasonable, they are discussed when extended to the bordering zones. In particular, it seems contradictory the presence of similarly, when not more, impacting technologies, such as antennas or external parts of air conditioning systems (MIMS, 2022). Especially after the reform of the Constitution Title V, the administrative fragmentation led to the drafting of different rules, resulting in strong heterogeneity throughout the peninsula. Legislative Decree 28/2011 (recognising Directive 28/2009/EU) levelled out the legislation. The regulative framework, as seen, ensured several incentives over time: price variations provoked disorientation and uncertainty for the investors, thus limiting the development of such technologies (RSE, 2016). A final legislative problem is given by the constraints on land take: public programming and careful analysis of the soil already sealed can help to overcome it (Sanson & Giuffrida, 2017).

Constraints, however, are not only legislative but also physical. Only in recent years, the national electrical network has improved; before, several lines were marked as critical: they could not sustain further capacity (RSE, 2016).

Finally, some conclusions can be drafted based on ISTAT data on the Turin Metropolitan City. Table 3.3 shows that photovoltaic systems are located mainly outside the administrative centre: only 5% of the systems are in Turin. Nevertheless, the average power of the systems is similar, approximately 20 kW. It is possible to interpret such information claiming that photovoltaic is more suitable for rural areas, thanks to the lesser presence of obstacles; still, in pre-defined areas, it is possible to install effective modules able to meet, at least partially, the energy demand.

Table 3.3

	Number of systems [n]	Installed power [kW]
Metropolitan area	23.694	458.830
Turin	1.200	24.668
% in Turin	5,06 %	5,38 %

Installed photovoltaic systems in Turin Metropolitan City
Source: ISTAT, elaboration on GSE data

3.3 Energy communities

Citizens and governments, in approaching the challenge of the energy transition, have to acknowledge the moment of crisis we are currently living. Structural factors, together with current circumstances, led to an energetic crisis: the sanctions which followed the Russian invasion of Ukraine led to a strong increase in gas prices. Italy, like many European countries, strongly relied on natural gas as the main fuel for its power plants: therefore, the price of electricity increased, too. This resulted in a social crisis: energetic poverty levels are strongly increasing. Finally, environmental movements have widely demonstrated the urgency of taking actions to face Climate Change: the third aspect of the crisis is ecological; from this derives the need to speed up the path for emissions reduction. The solution for tackling these three problems together is the creation of energy communities (MIMS, 2022). They can be defined as a «collective cooperation of an energy related activity around specific ownership, governance and a non-commercial purpose» (Roberts et al., 2019).

European Directives have defined two kinds of energy communities: Directive 2019/944/EU (Electricity Market Directive) introduced the Citizen Energy Community (CEC), Directive 2018/2001/EU (Renewable Energy Directive) the Renewable Energy Community (REC).

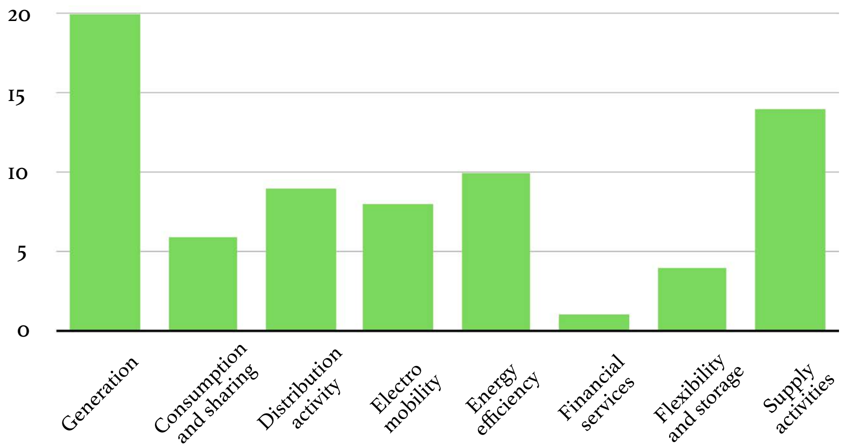
Their legal structures can be multiple (cooperative, partnership, trust...), both laws just require them to be legal entities. However, the organisational form is not the only common element. Both norms claimed openness and voluntary title for participation. The Electricity Market Directive went further, by affirming that there must not be barriers both for entering and leaving the community: access to the network cannot be forbidden to any local subject. Ownership is shared: citizens, local authorities and small businesses (with the clause not to have the energy sector as primary economic activity) directly own the community infrastructures. Finally, also the purpose is similar: to provide the members or the area with social, economic and environmental benefits, overlooking (at least at the first moment) the profits. CECs and RECs are non-commercial actors redistributing profit for improving the local community through services and benefits.

Nevertheless, some differences can be stressed, too, connected to further specifications added by a normative or the other. First, the

RECs are required to be tied to the proximity between production and consumption places and among the members; on the contrary, the Electricity Market directive does not specify it. The 2018 Directive is more restrictive even for the membership, while CECs can be joined by every actor who does not have energy as the main business. On the contrary, CECs are more limiting about effective control: they exclude medium and large enterprises from the community not to let them take control. Finally, RECs have to keep their autonomy from any of their stakeholders, while there are no such specifications for CECs (Caramizaru & Uihlein, 2020). Registering these differences, it can be claimed that RECs are a specific category of CECs (Roberts et al., 2019).

The activities which can be carried out by the energy communities are several: JRC scholars, in a study published in 2020, studied the activities carried on by 24 energy communities throughout Europe. The results are summarised in graph 3.3.

Graph 3.3



Activities carried on by energy communities (sample: 24 case studies)
Source: JRC, 2019

Generation is the first key aspect: the vast majority of the analysed energy communities produce energy by using or owning production plants. Despite, commonly, such plants are powered through RESs (mostly solar, wind or hydro sources), Directive 2019/944/EU is technology-neutral, not making mandatory the use of renewable sources; it just claims that CECs deal with electricity. Consumption and sharing are not very present (Caramizaru & Uihlein, 2020); when this activity takes place, the members of the community become prosumers: such denomination, introduced by Directive 2018/2001/EU, indicates a person who is both producer and consumer. The prosumer is defined as a subject authorised to produce energy for auto-consumption, storage and sale of the exceeding energy; its sales should be granted by trade agreements and not limited by any other actor. Systems foreseeing auto-production can be configured in an island mode, not being connected to the national grid, or grid-connected, able to take electricity when the production is not sufficient to meet the whole energy demand (Vecchi, 2020). The community can provide for the distribution itself: electricity grids, gas or district heating networks can be owned (or just managed) by local cooperatives; when large communities are established, it could be necessary to provide the community with storage systems, which grant flexibility. Moreover, in the case in which the energy is not totally consumed on site, agreements can be stipulated with other customers to supply them with the exceeding energy. The presence of distribution infrastructures allows also other forms of service to the community: it is the case of electro-mobility, activated in various forms (charging columns, car-sharing...). Finally, energy communities can become knowledge centres, able to provide consultation to their customers. Services can be provided about energy efficiency and savings, assessing the possibility of installing RES-based systems or renovating the properties, but they can concern even the financial sphere; especially when local authorities are involved, tailored incentivisation policies can be issued (Caramizaru & Uihlein, 2020).

Apart from the social and environmental benefits deriving from positive externalities on the community as a whole, energy communities are also profitable: according to MIMS (2022) bills can decrease up to 30%, with the savings to be summed to the governmental prizes for auto-consumption and the profits from the sale of the exceeding energy. Energy communities' birth is favoured by mainly three forms of incentivisation: the National Resiliency Plan has allocated € 2,2 B, hyper-amortisation of the initial investments is granted to businesses and complementary initiatives (such as the enhancement of energy efficiency) are eligible for 110% measures. Nevertheless, some conditions have to be ensured to increment the rate of creation of energy communities. First, the economic benefits have to be safeguarded (in the case of the prize for auto-consumptions) and extended (including also the share of electricity stored and used in a second moment). Then, adequate infrastructures should be provided: the ecological transition will likely result in the electrification of many technologies, causing an increase in the traffic on the grids. Despite autonomous local grids and auto-consumption can limit the energy demand on the high-voltage network, its adaptation can reduce the risks of congestion and overload.

The European Green Deal introduced the Positive Energy Districts: they are small urban areas (even a group of buildings or a block) energetically efficient and flexible, producing more renewable energy (with zero emissions) than what they consume. They can be designed singularly, considering three key parameters: the potential production from RESs, the feasibility of renovations for maximising energy efficiency and the capacity to work in synergy with the energetic system in which they are inserted (MIMS, 2022). Therefore, they are more easily applicable than the energy communities and more suitable for the urban context: PEDs can be experimented both by themselves and as the first nucleus for a future energetic community.

4

Application

This research learns its moves from a need of the Turin municipality: to improve from an energetic point of view the city, working in close collaboration with IREN Energia, the main energy company operating in the city. Pilot projects for the energetic renovations in the city should start from the most downgraded zones, that are the outskirts. After the progressive de-industrialisation of the Nineties, the municipal councils put big efforts into the refurbishment of the city centre, to transform Turin into a touristic city; however, this resulted in a progressive abandonment of the outskirts, where the most fragile part of the population lives.

4.1 Case study

Considering the interest for the municipality to work on the outskirts, the Northern edge was immediately indicated as suitable for such a study. In particular, District 6 was chosen for its heterogeneity. Indeed, it is an interesting case study thanks to the presence of a variegated set of human activities, from highly populated areas to the principal Turin dump and wide industrial areas. The district is divided by the Stura river: in the part closer to the city centre, known as *Barriera di Milano*, there is a compact settlement structure, while the other is characterised by a residential area, a big infrastructural node, the mentioned dump and a social housing district built in the Fifties, *Falchera*.

The mentioned differences are evident when looking at the population density, with most citizens gathered Southern to the river. In particular, the areas close to the avenues Vercelli and Giulio Cesare are the most populated.

However, such population is often at the margins: out of the 300 sections of *Barriera di Milano*, 158 have a percentage of foreigners higher than the Turin average (14,9%). These people have generally low education rates, with only one out of four people who has completed high school, and 1,5% of illiterates. The final indicators for demonstrating the marginality of the district compared to the rest of Turin are the income per capita, the average price of houses and the number of public houses. As shown in the maps, for the first two District 6 shows the worst values, while social housing is widespread, following a pressing need.

Image 4.1

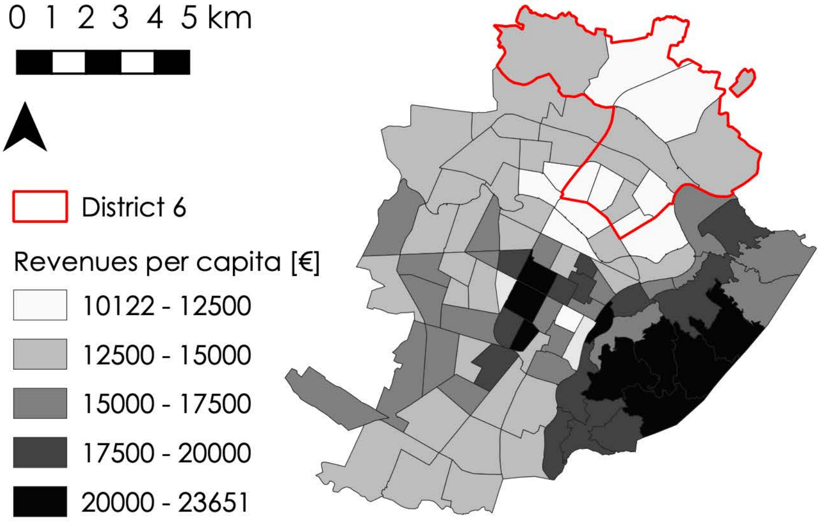


Image 4.2

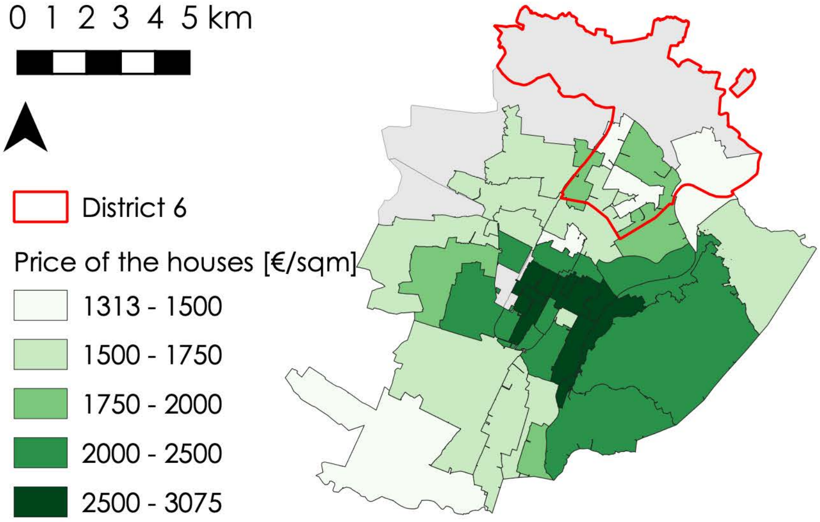
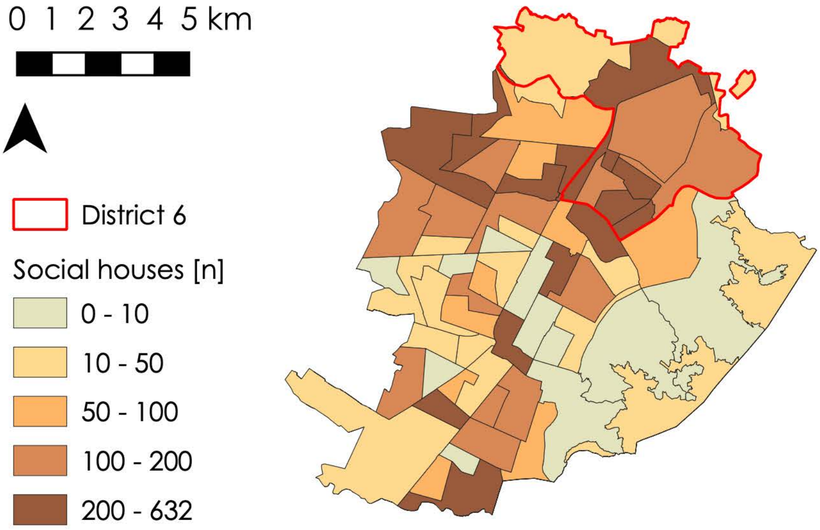


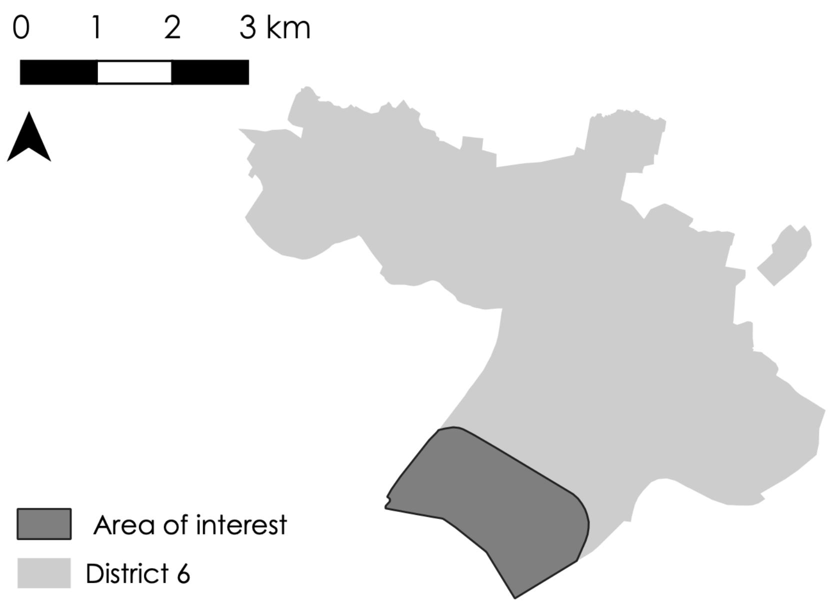
Image 4.3



Income per capita, average price of the houses and number of social housing
Source: own elaboration on Rapporto Rota data

To minimise the elaboration time and provide an analysis as accurate as possible, it was decided to reduce the study area to the denser part of the District. As the Northern border, it was chosen the so-called *Trincerone*, the trench hosting a former railway line abandoned in the Nineties, while the other three sides correspond to the limits of District 6. Such area is the core of *Barriera di Milano* and it is interesting for the presence of a varied building stock: from West to East there are a residential area, some industrial buildings and a brownfield to be reconverted.

Image 4.4



Area of interest
Source: own elaboration

The history of the district is connected to its industrial past: the neighbouring *Aurora* area (South-West to *Barriera*) was characterised by a number of plants, some of which were relevant on a national scale (such as the FIAT plant producing engines for ships). After World War II, the substantial increase in employees led to a pressing housing demand: districts at the margins of the city, known as *Barriere* for their location in proximity of toll stations, were considered suitable for meeting such demand. Nearly half of the volumetric units were realised in the post-war period: saturation was reached in the 1970s, with few constructions dating back to the Eighties. However, the North-West border of the area of interest is close to the so-called backbone, renovated following the masterplan by Gregotti and Cagnardi (1995); that intervention was realised in the 2000s. In the same period, also the area of Bologna street (South-East part) was renovated, realising new structures. Other exceptions, in the opposite way, are industrial buildings which were realised outside the toll barrier (not to pay taxes on both inputs and outputs) before the war and survived the bombing. They are located at the opposite borders of the area of interest: on the West there are the Docks Dora (warehouses) and a plant producing biscuits, on the East a woollen mill and a military warehouse.

The period of construction has, among its many outcomes, the height of the building: this can be quantified according to the number of floors or the absolute height (in metres). Height is particularly important in this research: tall buildings generate longer shadows, preventing a wider area to be exploited with photovoltaic installations, and, when detached from the others, present higher surfaces dissipating heat (when not properly insulated). Constructions are between 3 and 5 floors tall, with higher values along the principal avenues, in particular Giulio Cesare avenue. The highest buildings are the ones realised recently: due to urbanisation standards, however, they are inserted in wide open spaces, thus preventing the shadowing of other buildings. The tallest constructions, in the area of Peccei park (West), overcome a height of 40 m, while most buildings are between 10 and 20 m tall.

Finally, looking at the surfaces of the volumetric units, most of them have a surface comprised between 100 and 500 m^2. Extremes are present in both senses: on the one hand, minor buildings have often a limited surface (lower than 20 m^2) by definition, on the other historical plants occupy wide surfaces, together with the newly-realised supermarkets.

It emerged, as made explicit from the beginning of the paragraph, a heterogeneous building stock, but still, with many common elements. The presence of homogeneous areas could turn out to be a positive element, especially concerning photovoltaic production, with few obstruction elements.

4.2 Starting problem

One of the most urgent problems of 2022 is the energy crisis: the Russian invasion of Ukraine led to a dramatic increase in energy prices, but also to the need to reduce energy consumption not to finish the gas reserves. Ordinances by the Mayor prevented the citizens to turn on their heating systems before the 1st of November, taking advantage of the mild climate. However, this was just a provisional measure: structural changes are required to reduce energy consumption significantly, mitigating the economic pressure on families and the environmental impacts.

This research aims to assess the impacts of a wide-scale energy retrofit based on an analysis of the current state: the comparison of different scenarios aims to orient policy-making by providing concrete data on the savings, in terms of both cash and environmental indicators. Once having obtained the energy demand in kWh, it would be possible to evaluate also the advantages of electrification, shifting from natural gas-powered heating systems to auto-production through RESs.

Turin Municipality, through its Finanziaria Città di Torino Holding S.p.A, owns 13,8% of the IREN Group, multi-utility active in the sectors of gas, thermal energy, water systems and environmental technologies (Gruppo IREN, n.d.). The same group, through its company IREN Energia S.p.A., will provide the area of *Barriera di Milano* (together with most of the areas comprised between the rivers Dora and Stura) with district heating, using energy provided by the Leinì co-generation plant. So, the Municipality is both a shareholder and a customer of the group: its interest is to have lower expenses as a client but, at the same time, higher revenues as a shareholder; this optimum can be achieved by improving the energy system.

Moreover, the Municipality acts also as a real estate agent: apart from the public buildings, it owns real estates which are rented. An improvement in the energy efficiency of such assets would also increase their economic value.

4.3 Available data

In GIS software, the form and position of the objects are represented with two main spatial data structures: field-based (raster) and object-based (vector). Such types are complementary and it is appropriate to use one data structure or the other according to the phenomenon to be represented and its spatial diffusion. Raster and vector have some elements in common: they both have geometrical (describing the form and position of the objects with pre-determined accuracy) and relational (reporting the relationships among objects) components and some attributes (which describe the characteristics of the object) (Amadio, 2012).

Multiple data sources can be used: as seen in chapter 2, maps can be produced mainly following direct surveying or photo interpretation. However, in everyday work it is common to use data digitalised by other specialists: according to the scope of the analysis, the data source can vary. First, in the Italian context, many data are available online: the geoportals are repositories of geographical information, stored mainly in shapefile or WMS/WFS. Mostly, the use of such files is open, with limits for commercial uses only. However, in some cases, authoritative information does not exist or it is not accessible: Volunteered Geographic Information solves this problem. VGI is defined as the harnessing of tools to create, assemble and disseminate geographic data provided voluntarily by individuals; it is less reliable compared to government data due to the lack of controls on data quality as accuracy, for both planimetric and elevation measures. It is complementary to authoritative data and plays an important role in emergencies: for instance, there was massive use of VGI after the Haiti earthquake. The most used VGI service is OpenStreetMap, an initiative launched in 2004 which aims to create a free, editable map of the whole world; OpenStreetMap data, when used non-commercially, can be queried and downloaded for free.

4.3.1 Vector data

The vector data structure uses the geometrical primitives (point, line and polygon) to describe the geometrical component of the entities: it is an implicit representation, showing just the shape of the objects. Graphical primitives can be used to indicate the name or similar attributes. Vectors can store 2D, 2.5D and 3D information. In the case of 3D data, it is generally preferred to use surfaces rather than volumes, more complex to be handled (Amadio, 2012).

One of the main advantages of vector data is the use of the topological structure: it creates a relationship between geographical and descriptive data, but (in some cases) also among geographical objects themselves. In this way it ensures geometrical consistency, thus enabling spatial analyses. The possibility to carry out geometrical analyses, or geoprocessing (unions, intersections, clipping, buffering...), differentiates the vector from the raster (Biallo, 2005).

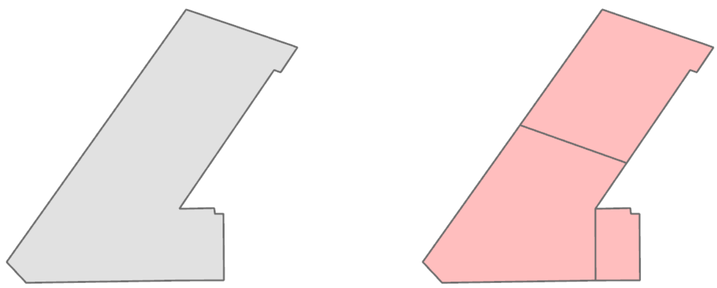
In this research, vector data were used mainly as input for spatial analyses and geoprocessing tools. They were produced by mainly two different bodies.

- Turin Municipality, which uses the Monte Mario/Italy Zone 1 (EPSG: 3003) reference system: the datum is Roma 40, with a Gauss-Boaga projection.
- ISTAT, using the ED50/UTM zone 32N (EPSG: 23032) reference system: the datum is the European Datum 50, with a Universal Transverse Mercator projection.

As previously mentioned, the macro area of interest was District 6. To individuate its boundaries, the *Carta delle Circoscrizioni* (Districts Map) produced on a 1:5˙000 scale was used; it was lastly updated on 30 June 2016.

The other shapefiles from Turin Municipality which were used are included in the technical map updated on 30 September 2020. They are grouped in category 02 "real estates and anthropisations" and subcategory 01 "building stock": their univocal codes are 01 for the volumetric units (defined in paragraph 2.1.1), 02 for buildings and 06 for minor buildings.

Image 4.5



Comparison between building and volumetric unit (Via Cigna, 118)
Source: own elaboration on Turin Municipality data

The volumetric unit was used as the smallest unity of analysis during the application phase, while the other two were used for semantic enrichment. The volumetric units shapefile describes the volumes of both buildings and minor buildings, reporting in the attributes a unique identifier, the surface, the type of the support base (ground, porches or underpass), the elevation on the ground and of the eaves, the height and the number of floors (reporting attics separately). However, it does not provide any information on its year of realisation: that is why it was necessary to perform a spatial join with buildings and minor buildings. Indeed, the year of construction is reported for such objects: it is classified in time ranges until 2012, while for the successive period the precise year of realisation is reported. Still, some data are missing.

ISTAT information filled the holes about the years of realisation: for every census section, it reports how many buildings fall inside a given class. Fields from E8 to E16 stand, respectively, for buildings realised before 1919, in the time frames 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2005 and after 2006. For every census section, it was calculated the modal value and all the buildings inside it were assigned to that time frame.

4.3.2 Raster data

In the case of extremely variable phenomena, the raster data structure has to be preferred: it represents surfaces as tiled regularly and continuously, with a theme at a time (Amadio, 2012). The mesh is defined accordingly to the variability of the phenomenon: the more abrupt the changes are, the smaller the pixel dimension is. Thanks to their regularity, rasters are generally more easily manageable than vectors; by contrast, they are also less accurate, being a discrete representation of a continuous phenomenon. The constraint of using a grid representation brings some problems: elements lose their identity, the presence of an object is assigned to the whole cell and if an object is located precisely on the edge between two cells it should necessarily be assigned to one or the other (Biallo, 2005). However, the continuity of pixel representation makes it explicit: the object is shown in the same shape we perceive it; the pixel represents both position and value of the portion of the object, but its value is independent of one of the neighbouring cells. To further improve the manageability of rasters, different solutions can be considered: they can be split into smaller tiles, arranged in a pyramid (with downsampled levels shown according to the scale) or organised into a mosaic (which creates a single entity with multiple overlapping information).

Rasters with several themes were generated and used during the applicative process, as will be explained in the following chapters. However, the imagery was used as input, too.

First, thermal data were extracted from aerial images by DigiSky S.r.l. taken in January 2022. These images were acquired by recording the Thermal Infrared band (7-15 µm) through passive sensors and cover limited portions of the area of interest. They were not acquired following a pre-defined flight path and they were not oriented: it was necessary to geo-reference them. This operation was carried out in ArcGIS Pro.

The starting input for tridimensional elaborations was a DSM with a 5 cm resolution derived from LiDAR data taken during the TerraItaly™ Metro HD process. It was referenced in ETRS89 / UTM zone 32N system (EPSG: 25832): it uses the European Terrestrial Reference System 1989 and the Universal Transverse Mercator projection.

4.3.2.1 TerraItaly™ Metro HD

The specifications about the project come from the company which realised them, Compagnia Generale Ripresearee S.p.A. (CGR). The final aim was to realise a precision orthophoto on 1:1000 scale, with a Ground Sample Distance (spatial resolution) of 5 cm.

CGR used the CityMapper-2 digital sensor, produced by Leica Geosystem: it has both passive and active sensors. In particular, it can take advantage of two nadir (registering RGB and NIR) and four oblique (with a 45° inclination) cameras; all six have a resolution of 150 MP and a lens system ensuring low distortion. The LiDAR unity emits up to 2 MHz and manages 15 return pulses. The whole CityMapper-2 is checked and calibrated yearly by Leica, but further adjustments are carried out through calibration polygons once the sensor has been installed on the plane.

CGR uses a Piper PA31 from 1975, registered I-BGFE. As explained in paragraph 2.1, the flight plan is influenced by the required scale and resolution: in this case, it is necessary to fly at a maximum speed of 160 Kts and a calibrated altitude of 1489 m AGL. The in-strip overlap should be 80%, cross-strip 60%. From these parameters, determined by the photogrammetric camera, the LiDAR resolution derives: 20 points/m^2. The flight over Turin was carried out on 29 January 2022: while the absence of leaved trees was avoided, some photograms show shadowing problems.

Image 4.6

Image 4.7

Leica CityMapper-2 sensor and its configuration on the plane
Sources: leica-geosystems.com, geo-matching.com, apei.fr, twitter.com

Image 4.8

Piper PA31 (I-BGFE)
Source: raciweb.altervista.org

Image 4.9

LEICA CITYMAPPER-2 POD

Consists of	
Nadir RGB camera	1 x Leica MFC150
Nadir NIR camera	1 x Leica MFC150-NIR, monochrome
Oblique RGB camera	4 x Leica MFC150, viewing angle 45°
LiDAR Unit	1 x Leica Hyperion2+
GNSS/IMU	Integrated NovAtel SPAN
System Controller Module	Integrated
Height / diameter	745 mm / 408 mm (lower diameter) / 435 (upper diameter)
Weight	57.5 kg
Max. system frame rate	0.9 sec
Designed for installation in Leica PAV200 with Leica Pod Lifter Heavy Load	

LEICA CITYMAPPER-2 VERSIONS

Leica CityMapper-2L	
Nadir lenses	
RGB	Leica D69.70/4.0 with 71 mm focal length 41.2° FOV across track 31.5° FOV along track
NIR	Leica D69.70/4.0-NIR with 71 mm focal length 41.2° FOV across track 31.5° FOV along track
Oblique RGB lenses	
Left/Right	Leica D69.112/4.0 with 112 mm focal length 45° ±10.1° FOV across track 26.8° FOV along track
Forward/Backward	26.8° FOV across track 45° ±10.1° FOV along track
RGB : NIR resolution	1 : 1.0
Nadir : Oblique focal length ratio	1 : 1.6
Flying height examples	380 m AGL @ 2cm GSD 945 m AGL @ 5cm GSD 1890 m AGL @ 10cm GSD 3780 m AGL @ 20cm GSD
Leica CityMapper-2S	
Nadir lenses	
RGB	Leica D69.112/4.0 with 112 mm focal length 26.8° FOV across track 20.3° FOV along track
NIR	Leica D69.70/4.0-NIR with 71 mm focal length 41.2° FOV across track 31.5° FOV along track
Oblique RGB lenses	
Left/Right	Leica D69.146/4.8 with 146 mm focal length 45° ±7.8° FOV across track 20.7° FOV along track
Forward/Backward	20.7° FOV across track 45° ±7.8° FOV along track
RGB : NIR resolution	1 : 1.6
Nadir : Oblique focal length ratio	1 : 1.3
Flying height examples	600 m AGL @ 2cm GSD 1490 m AGL @ 5cm GSD 2980 m AGL @ 10cm GSD 5960 m AGL @ 20cm GSD
Leica CityMapper-2H	
Nadir Lenses	
RGB	Leica D69.146/4.8 with 146 mm focal length 20.7° FOV across track 15.6° FOV along track
NIR	Leica D69.70/4.0-NIR with 71 mm focal length 41.2° FOV across track 31.5° FOV along track
Oblique RGB lenses	
Left/Right	Leica D69.189/5.6 with 189 mm focal length 45° ±6.0° FOV across track 16.1° FOV along track
Forward/Backward	16.1° FOV across track 45° ±6.1° FOV along track
RGB : NIR resolution	1 : 2.1
Nadir : Oblique focal length ratio	1:1.3
Flying height examples	780 m AGL @ 2cm GSD 1940 m AGL @ 5cm GSD 3880 m AGL @ 10cm GSD 7760 m AGL @ 20cm GSD

LEICA MFC150 / LEICA MFC150-NIR CAMERA HEAD

Sensor size (150MP)	14,192 x 10,640 pixels
Pixel size & type	3.76 um, BSI CMOS
Dynamic range	83 dB
Resolution A/D converter	14-bit
Data channel	14-bit proprietary compression
Motion compensation	Mechanical FMC
Spectral bands	
Leica MFC150 (Bayer pattern)	R (580 - 660 nm) G (480 - 590 nm) B (420 - 510 nm)
Leica MFC150-NIR	NIR (720 - 850 nm, monochrome)
Shutter	Max. speed 1/1000 sec Mechanical central shutter with up to 500,000 cycles Field exchangeable
Aperture	Automatically controlled aperture 7 half f-stop steps
Lens mount	Exchangeable lenses, positive mechanical connection

LEICA HYPERION2+ LIDAR UNIT [6]

Laser wavelength	1,064 nm
Laser divergence	0.23 mrad (1/e²) nominal
Pulse repetition frequency	Up to 2 MHz (height dependent)
Return pulses	• Programmable up to 15 returns, including intensity • Full waveform recording option at down-sampled rates • Real-time waveform analysis and pulse extraction • Multiple-Pulses-in-the-Air (MPiA): Up to 35 MPiA zones simultaneously • Ambiguity resolution for targets in multiple simultaneous MPiA zones • Gateless MPiA
Intensity digitisation	14 bits
Operation altitude[1]	300 - 5,500 m AGL
Scanner pattern	Oblique scanning with options for constant point density or constant pulse rate
Scan speed	Programmable, 60-150 Hz (120-300 scans per second)
Field of view	20 - 40°
Min. vertical separation	0.5 m
Vertical accuracy [2, 3, 4]	< 5 cm 1 σ
Horizontal accuracy [2, 3, 4]	< 13 cm 1 σ

INTEGRATED SYSTEM CONTROLLER MODULE

System controller module	Controls all Camera Heads, LiDAR Unit and gyro-stabilised sensor mount Includes deeply coupled GNSS/IMU solution
Processor	64-bit WIN10, 16 GB RAM, 64 GB SSD, USB 3.0, SATA 3
Mass memory	Leica MM30 solid state drive 7,680 GB each CityMapper-2 holds 2 MM30s
Mass memory weight	0.4 kg each, 2 required, removable and portable
Mass memory capacity[5]	Joint volume 15.36 TB, ≥ 8.0 h of data collection

INTEGRATED GNSS/IMU SYSTEM

IMU	SPAN CNUS5-H, Class 5, 500 Hz, FOG no export license required US ECCN 7A994
GNSS	NovAtel SPAN OEM7, 555 channel multi constellation receiver with 10 Hz GNSS data rate
Additional features	Real-time deeply coupled solution for position and attitude at highest accuracies, fully integrated and embedded solution, no interfaces to 3rd party needed
Position RMS DGNSS	Post-processed (specification): X,Y ≤ 3-5 cm, Z ≤ 5-7 cm Post processed (typical): X,Y ≤ 2-3 cm, Z ≤ 3-5 cm
Attitude RMS	Post-processed (specification): R,P ≤ 0.005°, H ≤ 0.008° Post-processed (experienced): R,P ≤ 0.003°, H ≤ 0.004°

PERIPHERALS

Sensor mount	Leica PAV200 gyro-stabilised sensor mount for high-performance data acquisition 36.0 kg
Pod lifter (optional)	Leica Pod Lifter Heavy Load, to retract entire CityMapper-2 pod for takeoff and landing 19.6 kg
Operator console	Leica OC61 12.1" screen with 1024 x 768 resolution 3.9 kg
Pilot display	Leica PD61 6.3" screen with 1024 x 768 resolution, designed for cockpit mounting 1.0 kg
Display stand	IS40-LW stand for Leica OC61 Operator Display 3.2 kg

ENVIRONMENTAL

Pressure	Non-pressurised cabin up to ICAO 15,000 ft
Humidity	0% to 95% RH according to ISO7137 (non-condensing)
Operating temperature	-10°C to 35°C (-10°C after warm-up period)
Storage temperature	-40°C to 70°C

ELECTRICAL

Max. avg. power consumption of complete system	811 W / 28 VDC
Max. peak power consumption of complete system	1,031 W (<60s) / 28 VDC
Fuse on aircraft power outlet	1 x 50 A recommended

SYSTEM WEIGHT

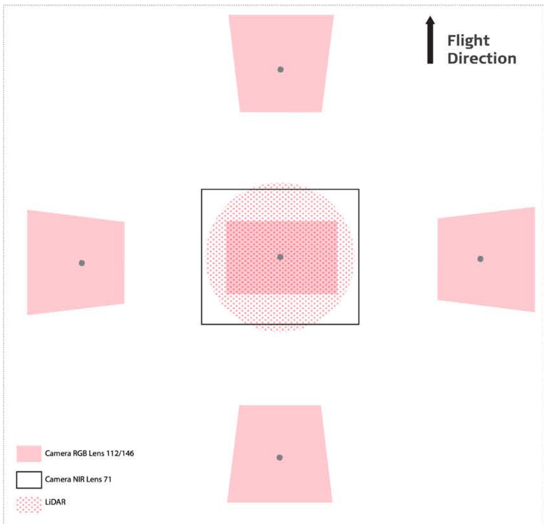
System installation without Pod Lifter	<108kg
System installation with Pod Lifter	<128 kg

SOFTWARE

Mission planning	Leica MissionPro
Flight navigation & sensor operation	Leica FlightPro
GNSS/INS trajectory processing	NovAtel Inertial Explorer
Point cloud/image processing	Leica HxMap

STANDARDS

RTCA DO-160G, EUROCAE-14G, USA FCC Part 15, ISO7137, EN/IEC 60825-1:2014



Exampel of the CityMapper-2S foot print

[1] Maximum operating altitude is specified for 90% detection at ≥10% reflectivity (e.g., dry asphalt) and 100% laser output.
[2] Accuracy and point density stated is acquired @1,000 m AGL, 60 m/s aircraft speed.
[3] The 1σ value represents the 68% confidence interval. Typically, the RMSE value is equal to 1 standard deviation.
[4] Stated vertical and horizontal accuracies after calibration and registration using Leica HxMap workflow and with an assumed GNSS position error of 4 cm
[5] Data collection is based on typical project data rate.
[6] Invisible laser radiation, avoid eye or skin exposure to direct or scattered radiation. Class 4 laser product in accordance with EN/IEC 60825-1:2014.

Leica CityMapper-2 product specifications
Source: leica-geosstems.com

The processing starts with the download: it is not secondary, considering the volume of data produced. Differential GNSS data are processed through ground reference stations and fused with IMU data. Once having defined the correct flight path and corrected the pictures radiometrically to ensure homogeneity, orientation took place. Finally, in the production of the true orthophoto, the DSM realised with LiDAR data was used; only in critical cases the DSM was corrected with data originated by the correlation activity of the photogrammetric process.

The outputs of the projects are multiple. Apart from the mentioned precision orthophoto, the LiDAR point cloud (in .las format) was provided with the resulting elevation regular grids. The DTM elaboration process followed the progressive classification theory by Axelsson (1999): it starts with a triangle of points which are for sure on the ground, then it progressively joins other points and tests their actual belonging to the terrain; a manual quality control follows for the final definition of the DTM, which uses break lines too. However, further products can be realised based on the outputs: using both the LiDAR point cloud and the internally-oriented pictures, software such as SURE can realise a precise TIN and even a coloured 3D mesh.

4.3.3 GDB realisation

ArcGIS Pro (n.d.) defines its database as «a collection of geographic datasets of various types held in a common file system folder»; ESRI implemented its own GDB data structure, whose specifications were not published. The GDB is the data format for which ArcGIS Pro is designed to work; nevertheless, also shapefiles and other geographical data structures can be read and processed by the software.

ESRI GDB is of an object-relational type, using multi-tier architecture. Data are managed in user-defined tables, while system tables store the metadata necessary for the proper functioning of the GDB. As for data types, the GDB can contain features (the GDB equivalent for vector files), rasters and tables. The whole information of feature datasets is contained in the table: the field "shape" includes coordinates and geometry to define the entities.

The GDB in this application will be used as the main container for both inputs and outputs of the different phases. Considering the limited number of inputs and the relationships mainly at the spatial level, overall the project is not complex: therefore, only an external model was produced, not proceeding with the conceptual and physical models.

Based on the aim to model the behaviour of buildings in relation to their volume, it was necessary to include in the GDB mainly two elements: the surface model, expressing the orientation and inclination of building structures, and the building footprints, contained into a vector file.

The original files, both vectorial and raster, are inserted in the GDB through the “Feature Class to Feature Class” (for vectors) and “Raster to Geodatabase” commands in ArcGIS Pro. An intermediate step is the unification of the reference systems: it was chosen to work in ETRS89/ UTM zone 32N, to keep as much as possible the integrity of the data provided by CGR S.p.A.. Considering that several intermediate products will be used, specific GDBs will be created for storing them.

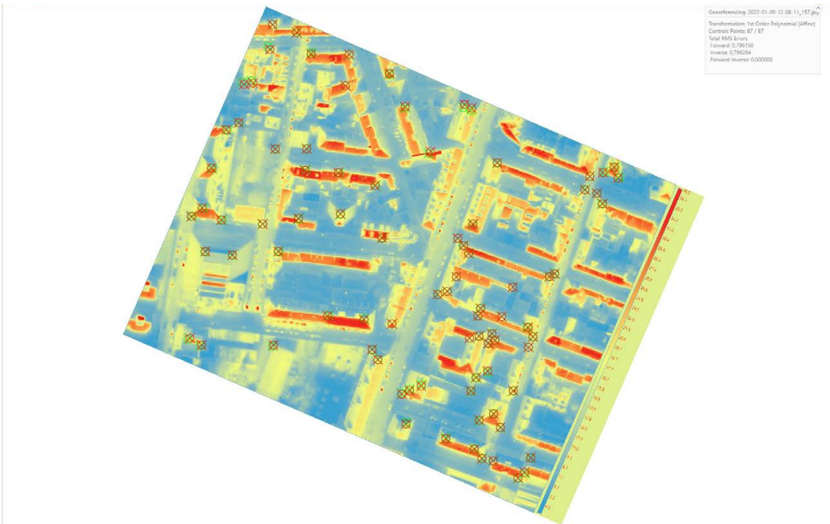
4.4 Evaluation of the energy demand

Once having prepared the dataset, the first step consisted of the analysis of the energy demand of the buildings in the analysed zone. In this step, the inputs were mainly two: the volumetric units and the thermal images coming from DigiSky S.r.l.; the former were used for the surface and the number of floors, considering that energy consumption is quantified in kWh/m^2, the latter restituted the thermal dispersion of the building.

4.4.1 Definition of the energetic classes

To classify the volumetric units in classes, the five images from DigiSky were used. Through the Thermal Infrared Band, they quantify the heat on the visible surfaces: they are nadir images oriented with photogrammetry, so the surfaces at issue are roofs. The flight took place in January 2022 during the day: therefore, the temperature of the roofs is influenced by solar radiation, with the shadowed parts colder than the sunny ones.

Image 4.11

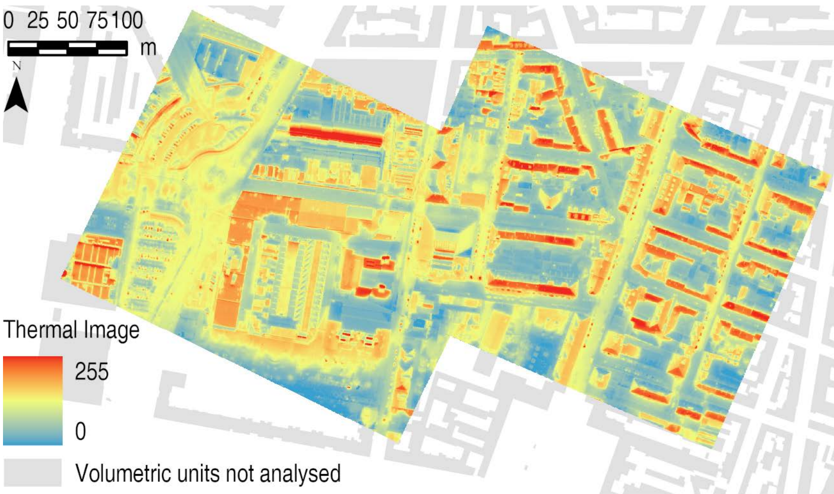


Georeferencing in ArcGIS Pro
Source: screenshot from own elaboration

The first preparatory step consisted of the georeferencing of the images; using ArcGIS Pro, the image was provided with a reference system (ETRS89 / UTM zone 32N), opportunely scaled and rotated for a first fit. Then, GCPs were determined based on the precision orthophoto produced by CGR S.p.A.; on average, forty points were individuated for each image, with a peak of 87 for the picture including the highest number of buildings (image 4.11). The images were corrected according to the final need: the northernmost picture shows only a small number of units included in the area of interest, resulting in a lower number of GCPs; moreover, the following phase was manual, so minor errors in georeferencing were corrected later. ArcGIS Pro calculates the root-mean-square deviation in two main ways: the forward residual error shows the deviation in the same units as the data frame spatial reference, the inverse in the pixel units. The forward error was 0,941 on average and the inverse was 1,412.

The images include an area of approximately 0,35 km², in three clusters. The two northernmost images show the area of the former Gondrand plant, between Venezia avenue and Cigna street. Moving southwards along Venezia avenue, the only image with no overlaps shows the Southern part of the Docks Dora. Finally, the areas of Cigna street and Vercelli avenue are included in the third cluster. Even if less than 1/10 of the surface of the area of interest is covered by such pictures, these are extremely representative of its heterogeneity. Both industrial and residential, dense and open urban fabric, old and modern buildings are represented.

Image 4.12



Cluster of Cigna street and Vercelli avenue
Source: own elaboration on DigiSky S.r.l. data

Then, for every building, its thermal dispersion was calculated. Such analysis was carried out by observing the pixel value for each roof, in its shadowed part. However, the raster data structure implies extreme variability, so taking a single point would have led to errors and misallocation. The followed procedure consisted in:

1. definition of a shadowed area for each volumetric unit, taking the largest part possible;
2. clip of the original raster with each defined area, singularly;

3. calculation of the statistics and attribution of the average pixel value to each volumetric unit.

The process had to be performed manually, intersecting, calculating and transcribing the values singularly: it obviously proved to be inefficient, especially due to the processing time; on average, it took slightly less than one minute for each volumetric unit. In total 430 units were analysed: these include all the units of buildings (268) and the ones constituting the most significant (in terms of space) minor buildings. The analysed units are totally comprised inside the footprint of the images.

Table 4.1

Energy class	Whole range			Observed values		
	Pixel threshold [n]	Temperature threshold [°C]	Count [n]	Pixel threshold [n]	Temperature threshold [°C]	Count [n]
B	42,5	8,33	143	25,5	6,2	69
C	85	13,67	192	51	9,4	106
D	127,5	19	95	76,5	12,6	130
E	170	24,33	7	102	15,8	83
F	212,5	29,67	0	127,5	19	42
G	255	35	0	153	22,2	7

Possible classifications of thermal data
Source: own elaboration

The observed values range from 0,428 to 151,205, corresponding to temperatures ranging from 3°C to 22°C (approximately). Sunny pitches were generally hotter, with values reaching a maximum of 35°C. The classification could have considered the whole range or just the observed values. Table 4.1 shows the thresholds to be set according to the two classification methods and the count of the volumetric units to be included in the different classes when choosing one method or the other. In the case of considering the whole range for the classification, from 3°C to 35°C, most buildings would be classified as highly performing (76% as B or C class): this does not correspond to reality, as it would be shown after (see paragraph 4.4.2), so the second classification was preferred. A single class includes volumetric units in a range of 3,2°C. The prevailing class is the D, with roughly 30% of the units included; 40% of buildings is included in the two most performing classes and the remaining 30% is in the least performing. Moreover, the average surface of the units included in each class constantly increases from B (120 m^2) to E (274 m^2) but is significantly smaller for F (123 m^2) and G (72 m^2): the least performing classes constitute only 6% of the total footprints.

Considering the spatial arrangement of the buildings classified as similarly consuming, it is difficult to observe a pattern. Indeed, all classes are evenly distributed. Still, there are some exceptions. The complex of the former Gondrand plant is composed of constructions with high dispersion: the main warehouse falls in class E, other buildings in classes F and G. On the contrary, the westernmost area, comprised between Venezia avenue and Cigna street, is characterised by high-performing buildings: most of them are classified as B or C. The densest area is also the most heterogeneous: constructions of all classes are gathered around Vercelli avenue. This heterogeneity is surprising, in a way: it could be expected that the minor buildings realised inside the courtyards are the most dispersive ones, while all the classes can be observed for both buildings and minor buildings.

4.4.2 Calculation of the average consumption

Energy efficiency is a parameter introduced by Directive 2002/91/EC to sensitise real estate operators and final users on energetic and environmental problems. The energetic class is defined based on the global index of non-renewable energy performance, expressed in kWh/m^2: it is calculated by summing the energy performance index for winter air conditioning and domestic hot water production. The *Attestato di Prestazione Energetica* (APE, Certificate of Energy Performance), drafted according to the Legislative Decree 192/2005, uses specific indicators to describe the energy performance of a building (or building unit) and suggests possible improvements (ANIT, 2019).

The APEs are gathered on a national scale by the *Sistema Informativo sugli Attestati di Prestazione Energetica* (IT System on APEs), a web portal by the National Agency for New Technologies, Energy and Sustainable Economic Development. In Piedmont, the *Sistema Informativo per la Prestazione Energetica degli Edifici* (IT System for the Buildings Energy Performance) is a web service by the Region gathering local certificates. The latter was queried to define the average Global Energy Performance Index of the six classes, from B to G.

The first step was to define which certificates were to be searched: for having the most site-specific data possible, it was chosen to download certificates from the area of interest. All certificates are connected to an address, so the list of streets and avenues was defined: as for the dispersion analysis, it was chosen to work only on the units which are entirely comprised in the thermal pictures. Most certificates were issued for building units rather than for the whole construction: it was chosen to take one certificate per address, the most recent one. In a few cases, only expired certificates were available (they last 10 years): these were not included.

In total, 63 certificates were considered for the analysis. However, considering the lack of units in class B, further three buildings in Turin, but not in the analysed area, were considered: the Museum Ettore Fico (via Cigna, 114), *The Number 6* (via Alfieri, 6) and the former Tobler plant now converted into lofts (via Aosta, 8). The results are shown in table 4.2.

Differently from the classification adopted in paragraph 4.4.2, there is a clear tendency towards less performing buildings, with more than half of the units comprised in classes E and F.

The aim of this data gathering was to define a reference value for the GEPI of each class, expressed in kWh/m². It is necessary to specify that the energy class is not defined according to the GEPI only, but considering a reference building (or unit) and comparing the energetic performances: that is why it is possible that, for example, the GEPI of a building in class B is higher than the one of a class C-building. This justifies that, considering the average value for each class, there was an error apparently: class D buildings show higher values compared to class E ones. To remove the extremes and balance the results, it was chosen to take as reference value the median.

Table 4.2

Energy class	Count [n]	Average [kWh/m²]	Median [kWh/m²]
B	3	86,33	98,06
C	3	117,95	118,95
D	11	146,27	123,15
E	17	143,11	130,49
F	20	174,35	176,24
G	12	293,79	276,22
Average	11	160,30	153,85

Global Energy Performance Index for the energy classes
Source: own elaboration on SIPEE data

Discrepancies between classes are not constant: they are maximum for lower classes, with class G requiring approximately 100 kWh/m^2 more than class F. On the contrary, they are quite limited for the central classes, with less than 15 kWh/m^2 dividing classes C and E.

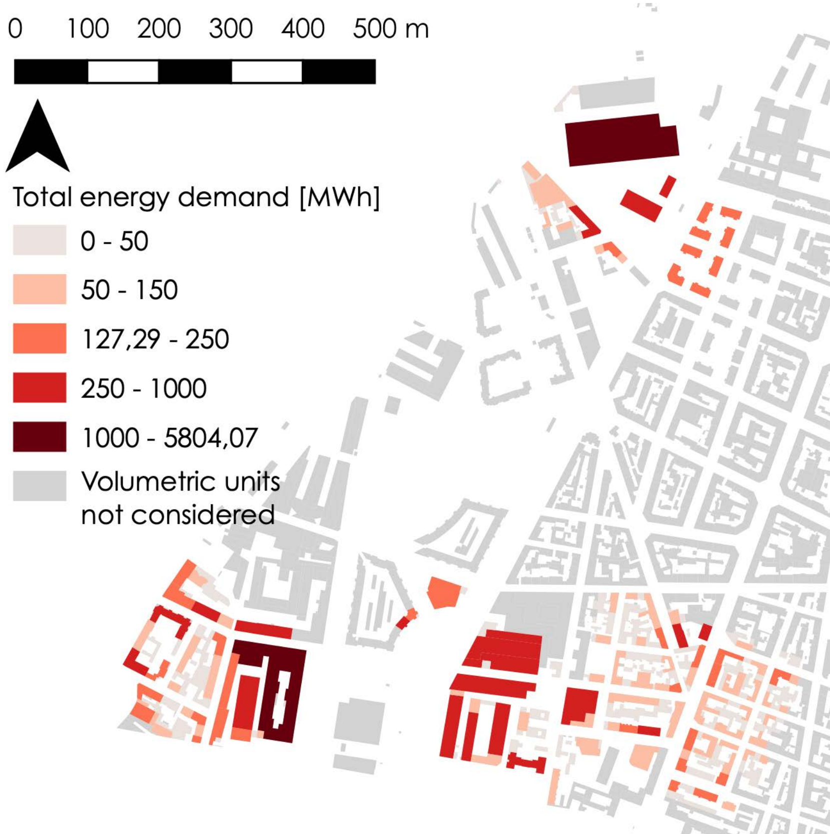
It is to be pointed out that Piedmont Region, in the implementation rules which followed the Regional Law 13/2007, indicates GEPI reference thresholds for each class. The proposed classification is very restrictive for non-residential buildings, while it allows low performances for residential ones. The proposed reference values, therefore, can be considered a balanced GEPI, taking into account both residential and non-residential constructions.

4.4.3 Calculation of the total energy demand

The GEPI is quantified in kWh/m^2: to calculate the total energy demand it is necessary to multiply the GEPI by the gross floor surface. The latter has to be calculated, too: to do so, the necessary data are the footprint and the number of floors. While the former is reported by the Turin Municipality (which produced the information) and also easily calculated with GIS tools, for the latter the coverage is not total and has to be corrected. First, some entities have "non-applicable" or "unknown" values: these were corrected by dividing the height by 3 (the average height of a storey) and rounding off the result for obtaining an integer. Then, the "+1" and "+s", indicating a habitable or inhabitable attic respectively, were corrected by adding a floor in case of "+1" and nothing for "+s": the reason is that habitable attics only need to be heated up and therefore cause an increase in the energy demand. On average, the constructions have 2,17 floors, with this number increasing to 2,83 when excluding the minor buildings from the count. However, the footprint of the buildings is generally bigger: that is why buildings have a gross floor surface 50% higher than the one calculated considering all volumetric units. After this pre-processing phase, the total energy demand could be calculated.

Looking at the distribution of the values of total energy demand, it is immediately evident that this indicator is strongly dependent on the dimension of the building itself: indeed, considering the general height of the building stock as quite limited, the footprint is the factor which influences more the gross heated surface. The less demanding units are the smallest, generally located inside blocks, while the former industrial buildings are the most consuming: it should be noted that this research uses rough data for a wider-scale application, but such buildings have storeys generally higher than the residential ones, thus leading to an increase in the volume and resulting in even higher energy demand.

Image 4.13



Total energy demand
Source: own elaboration

To provide a general assessment of the building stock, raw data can be aggregated: on average, the total energy demand amounts to 80˙000 kWh/year, corresponding to 126 kWh/m². Therefore, it could be stated that the average building in the area of interest is a C-class. The two extremes are a minor building in a courtyard of Elvo street (140,39 kWh/year) and the former Gondrand plant, consuming more than 5˙000˙000 kWh/year. Considering that the latter is to be transformed, it would be necessary to provide it with adequate insulation to make it less energy-intensive. The most common range is the one comprised between 10˙000 and 100˙000 kWh/year, with buildings which can be observed especially in the Southern area.

4.4.4 Evaluation of retrofit measures

After having assessed the energy performance and the corresponding energy demand for each building, thus having a snapshot of the current situation, the research proposed two energy retrofitting scenarios. An optimum scenario would bring all the buildings in class B, while a limited improvement one targets to improve all buildings by two energy classes.

The benefits were analysed in terms of energy saving, prevention of CO_2 emissions and primary energy calculation. As for CO_2 and primary energy, three combinations would be taken into account, considering different energy mixes: heating provided by district heating only, gas boilers only or a mix between the two.

Values for District Heating were calculated by Rina Services S.p.A. for IREN (2021): it causes emissions of 165,2 g CO_2/kWh and has a primary energy consumption index of 0,884. It was calculated that natural gas boilers emit on average 240 g CO_2/kWh, while Ministerial Decree 26/6/2015 stated that the primary energy consumption index amounts to 1,05.

The costs of the two interventions are different: therefore, the optimum scenario should be justified by a substantial reduction in consumption compared not only to the current state but also to the less expensive scenario.

4.4.4.1 Optimum scenario

In this scenario, all buildings are brought to class B: it is considered that with traditional, relatively low-cost solutions it is possible to bring a building to such an energy performance level, while A class often requires high-tech and costly solutions.

With the whole building stock classified as B (and the GEPI being 98 kWh/m^2), the total energy demand would be reduced by 22,3% (28,7% considering buildings only), corresponding to more than 7˙000˙000 kWh saved every year. Looking at units one by one, savings range from 0 kWh/year (for the 69 buildings which were already in class B) to 1˙442˙454 kWh/year for the former Gondrand plant: it is in class E and, considering its wide surface, it is highly energy-intensive. In general, the highest improvements were observed for the buildings with a big footprint: despite they were already in classes C or D (apart from the mentioned factory), the wide gross floor area causes them to be crucial for a district energy renovation.

Image 4.14

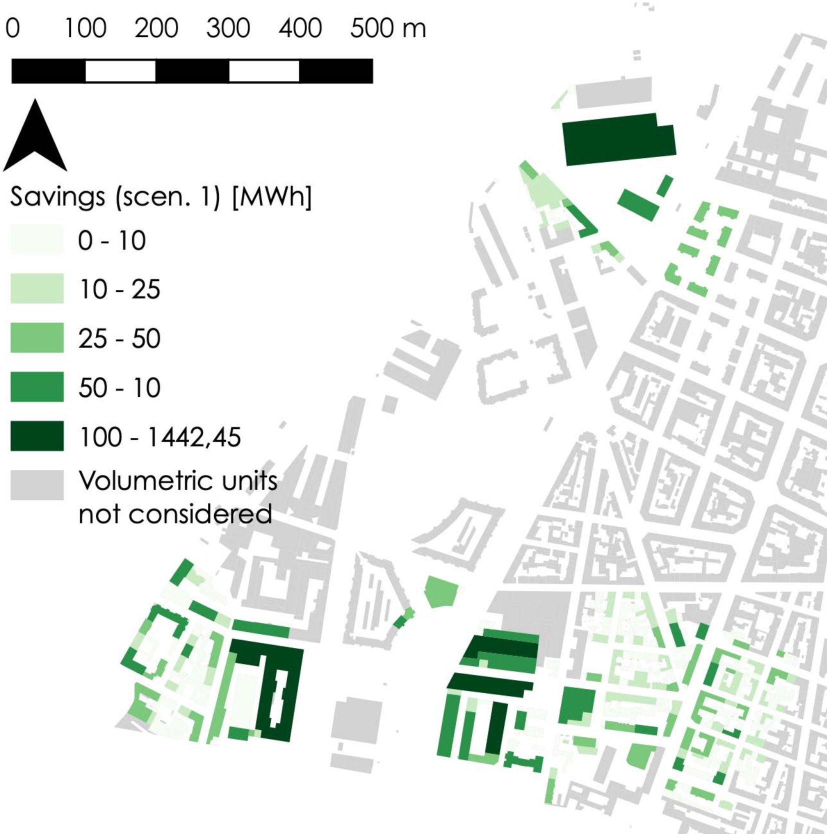
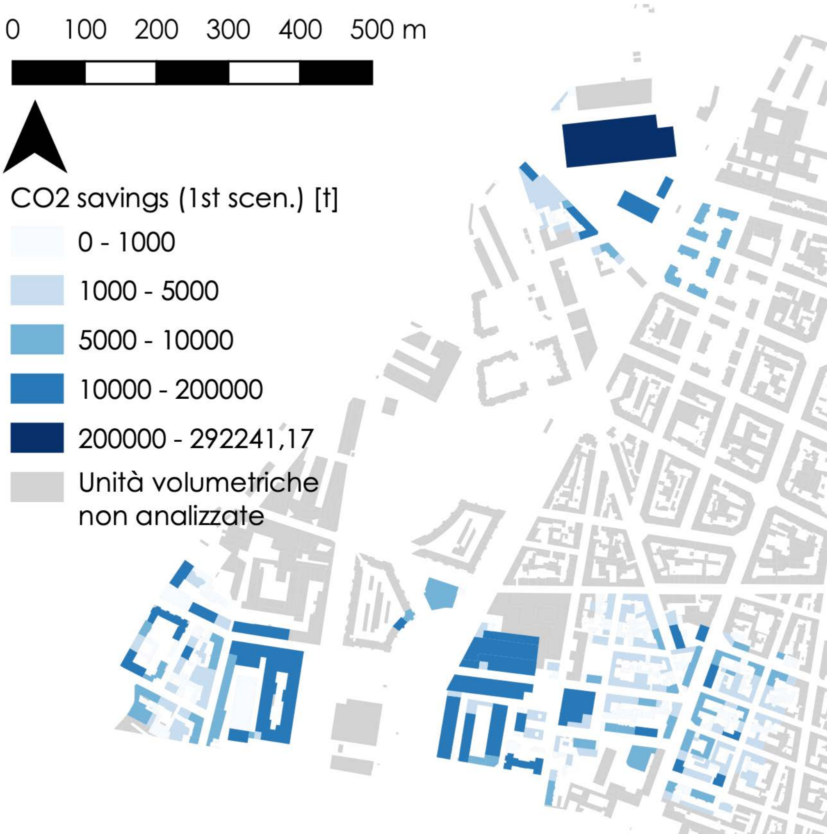


Image 4.15



Energy and CO_2 savings in the first scenario
Source: own elaboration

At least 1,3 million kg CO_2 could be saved with this renovation scenario, assuming district heating as covering the whole energy demand. However, considering that such network has not yet been extended to this area, the saving would amount to 1,8 million kg CO_2. Being the emissions dependent on the savings in kWh, the spatial distribution is similar to the one of the energy savings. In the natural gas scenario, the extreme is represented by the 346˙000 kg CO_2 of the Gondrand factory, with an average of 4˙200 kg CO_2 saved every year by each volumetric unit.

Primary energy consumption varies according to the scenario: considering that District Heating has an index $f_{P,nren}$ lower than 1 (because part of the heat is obtained through RES), the actual improvements would be less compared to the scenario in which the whole heating demand is covered by natural gas boilers. The range is relevant, with a difference of 1,3 million kWh/year: compared to a natural gas-powered scenario, the impact of renovations is lower in the case of a sustainable grid whose heat is produced through RESs, but still relevant, amounting to 6,7 million kWh/year. From this it derives an important assumption, that sustainable energy production can partially mitigate even the impacts of a dated building stock, reducing the primary energy impact.

4.4.4.2 Limited improvement scenario

To obtain the 110% superbonus from the Italian government, Legislative Decree 34/2020 stated that an improvement of at least two energy classes should be certified through an APE. Despite the superbonus going to end or at least be changed, it is likely that incentives for renovations would have similar clauses also in the future.

Analysing the values shown in table 4.1 and this improvement scenario, 54% of volumetric units would be re-classified as B after this proposed renovation campaign, bringing the total to nearly 70% of the whole building stock. The two least performing classes would be abolished, considering E as the worst possible case. The total improvement would be 19% (18,9% considering the buildings only) of the total energy demand, that are more than 5.500.000 kWh/year. After the renovation campaign, the average building would consume 106 kWh/m^2, so it would be a good-performances C-class building.

The impact on the single volumetric units is similar to the previous scenario: the former Gondrand factory would see, still, the highest improvement. However, the saving is influenced by two factors: the improvement in energy performance is not constant from class to class (e.g. passing from E to C 12 kWh/m^2 change, while from G to E 146 kWh/m^2) and C-class units improve only by one class. As a result, the smallest average savings are observed for class E (12˙352 kWh/year passing to C), the maximum for class D (17˙590 kWh/year passing to B).

In this case, prevented emissions are approximately 2/3 compared to the previous scenario, with average values ranging from 2˙000 to 3˙000 kg CO_2 saved for each volumetric unit. Still, considering that today District Heating has not yet been installed in the area of interest, 1,3 million kg CO_2 could be saved yearly.

Proportionally to the used energy saved yearly, also the primary energy saving is lower compared to the previous scenario. Nevertheless, it ranges from 4,8 to 5,7 million kWh/year. Not only the District Heating scenario shows a reduced consumption after the conversion to primary energy, but also the mixed one. Even if the reduction is more limited, 0,5 million kWh/year are saved with this configuration instead of the worst one, resulting in an average $f_{P,nren}$ of 0,967.

Image 4.16

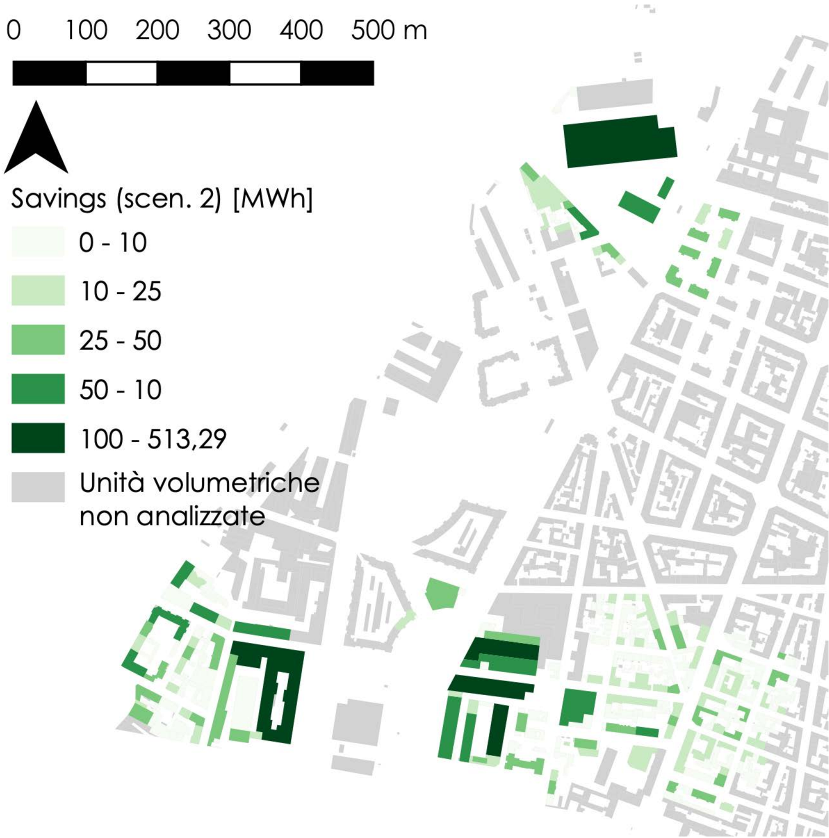
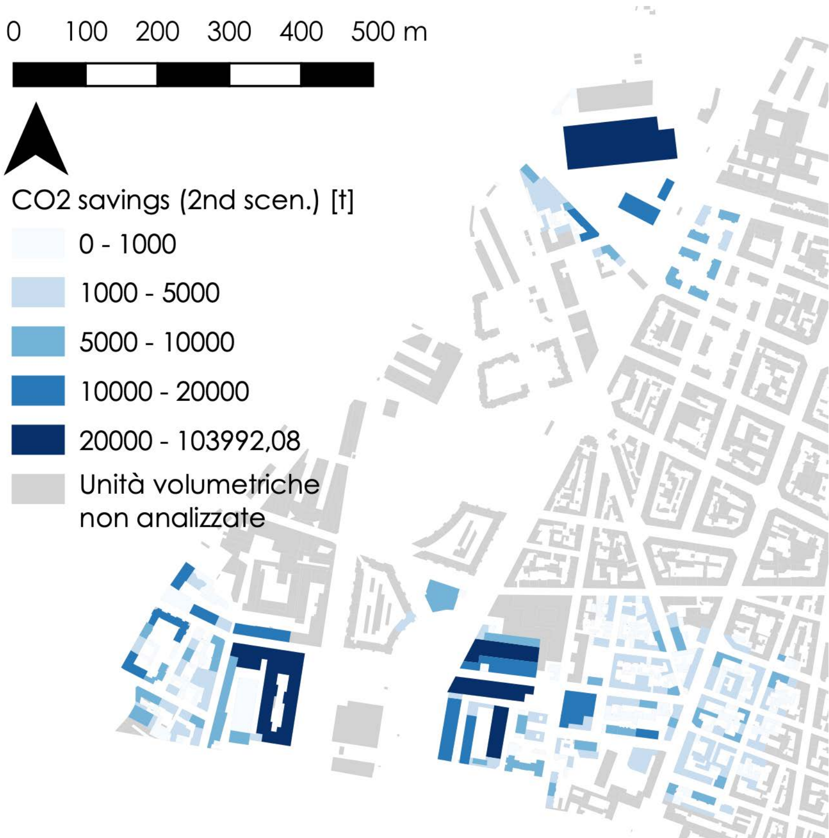


Image 4.17



Energy and CO_2 savings in the second scenario
Source: own elaboration

4.5 Evaluation of the photovoltaic potential

As explained in chapter 3, solar technologies are the most suitable for being installed on roofs. In particular, photovoltaic panels are the most efficient and their potential can be exploited in multiple ways: increasingly, the tendency is towards electrification, so electricity can be used not only for traditional uses (like powering domestic appliances or lighting up spaces) but also for heating purposes through the use of heating pumps. These aspects would be analysed more in depth in the following paragraphs.

4.5.1 Evaluation of the solar radiation

To calculate the photovoltaic potential, the first step is the computation of the solar radiation striking the roofs. Solar radiation is divided into three main components: direct, diffused and reflected; the sum of these components is defined as total or global solar radiation. Such elaboration was made possible by the tool "Area Solar Radiation" in ArcGIS Pro. The key input is a DSM for the area of analysis: it was used the DSM produced through the LiDAR points registered during the flight for the TerraItaly™ Metro HD project; when using a georeferenced file, the latitude is automatically set. The default "sky size", 200, was chosen, while for the "time configuration" it was chosen the "whole year" option, analysing 2022 with a day interval of 14 days (set by default) and an hour interval of 1 hour. Finally, the "create outputs for each interval" option was checked: the output raster will contain one band for each of the set time intervals. Further parameters are grouped in two clusters.

- Topographic parameters: the "z factor" was kept by default, 1, because planar and vertical units use the same unit of measure. The "slope and aspect input type" was calculated "from the input surface raster" (the DSM) and the "calculation directions" were reduced from the default 32 to 16 to speed up the process.
- Radiation parameters: zenith and azimuth diffusions were kept by default, 8 each, and the "diffuse model type" was changed into "standard overcast sky", with the diffuse radiation flux varying with the zenith angle.

The last two parameters, in the "radiation parameters" cluster, require a deeper analysis: they are the diffuse proportion and the transmissivity. The former was calculated through the online tool PVIGS, by the European Commission, calculating monthly data of the global horizontal radiation. The latter was calculated with the values reported in table 4.3.

Table 4.3

Energy class	Direct radiation [kWh/m²]	Diffuse ratio	Diffuse radiation [kWh/m²]	Hours of light [kWh/m²]	Direct solar irradiance [W/m²]	LINKE turbidity factor	Transmissivity
January	64,97	0,28	25,27	279	232,87	3,10	0,56
February	90,83	0,29	37,10	280	324,39	3,20	0,64
March	106,34	0,45	87,01	372	285,86	3,50	0,64
April	164,03	0,31	73,69	420	390,55	4,00	0,73
May	188,22	0,41	130,80	465	404,77	4,20	0,75
June	188,08	0,38	115,27	480	391,83	4,30	0,75
July	209,02	0,38	128,11	496	421,41	4,40	0,77
August	181,79	0,36	102,26	434	418,87	4,30	0,76
September	134,64	0,40	89,76	390	345,23	4,00	0,71
October	75,87	0,50	75,87	341	222,49	3,60	0,60
November	58,46	0,40	38,97	300	194,87	3,30	0,55
December	36,42	0,56	46,35	279	130,54	3,10	0,47
Average	124,89	0,39	79,20	370	313,64	3,75	0,66

Diffuse ratio and transmittivity (monthly data)
Sources: own elaboration on PVGIS and grass.osgeo.org

Table 4.4

Energy class	Direct radiation [kWh/m²]	Diffuse ratio	Diffuse radiation [kWh/m²]	Hours of light [kWh/m²]	Direct solar irradiance [W/m²]	LINKE turbidity factor	Transmissivity
Winter	62,67	0,38	36,92	284,50	220,67	3,18	0,56
Summer	191,78	0,38	119,11	468,75	409,22	4,30	0,76
Spring/ Autumn	120,22	0,42	81,58	380,75	311,03	3,78	0,67

Diffuse ratio and transmittivity (aggregated data)
Sources: own elaboration on PVGIS and grass.osgeo.org

The known parameters were the direct radiation, the diffuse ratio and the hours of light (calculated with PVGIS) and the LINKE turbidity factor (downloaded from the grassGIS manual). The direct solar irradiance (power incident on a unit area) was calculated as the product of direct radiation and hours of light and the transmissivity as the ratio between direct solar irradiance and the solar constant (1367), elevated to the inverse of the LINKE factor. The parameters were calculated separately for each month but then aggregated in average values for winter, summer and spring and autumn.

The process took approximately 1,5 hours for each elaboration. The output of the ArcGIS Pro tool consisted of three rasters with 12 bands each, one for each month. An apposite GDB was created to store them. The correct bands were chosen from each raster:

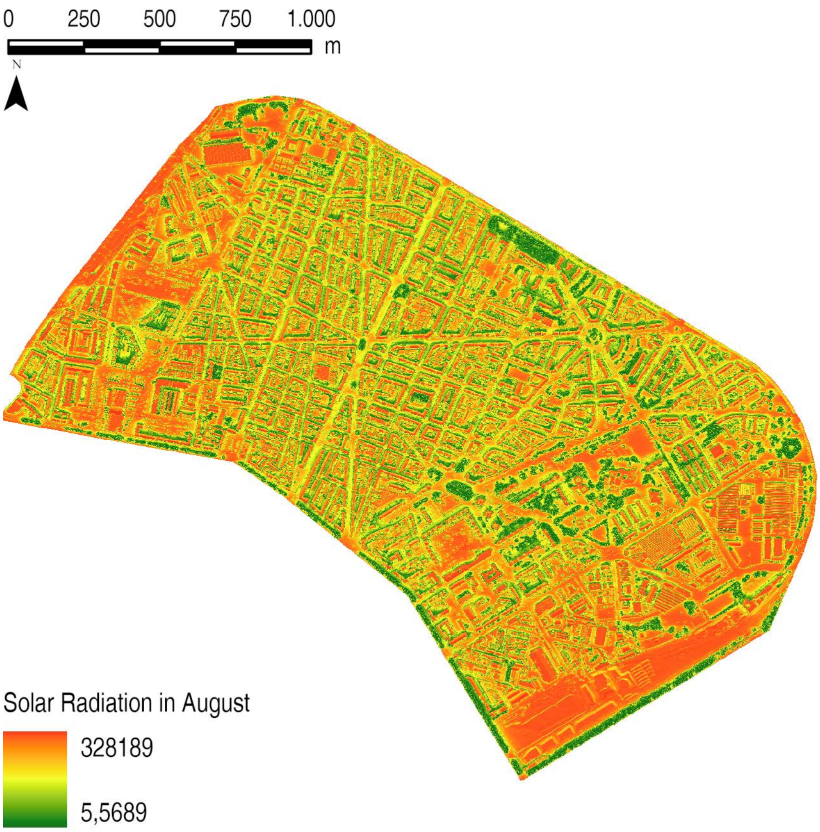
- January, February, November and December from winter;
- May, June, July and August from summer;
- March, April, September and October from spring and autumn.

The values of the solar radiation outputs change according to the month, for both minimum and maximum values, with the peaks during summer, when the hours of light are more and the radiation more intense. However, the most evident difference when comparing winter and summer outputs derives from the different solar heights: while during winter the roofs emerge as the only surfaces stroke by relevant solar radiation values, in summer also roads (at least the biggest ones) show high radiation values overall. Still, there are open spaces that have the highest values in the district during the whole year; these are mainly three: the former *scalo Vanchiglia*, the Peccei park and the central area recently subjected to urban renovation. Especially the old railway rail yard, being a huge surface without structures or vegetation, has the highest values. On the contrary, the park is characterised by vegetation: it is likely that, when it will be grown, it will prevent the sun from striking that intensely.

Each monthly-data raster was then exported to the GDB and converted into a feature class through the "raster to point" tool. Finally, a spatial join using the "match option" "completely within" was chosen to link each building to the values of solar radiation. This step is a simplification, too: it would have been more appropriate to select the significant points, link them all to the building they pertain to and calculate an average radiation value; however, this would have slowed down too much the process, thus proving to be inefficient.

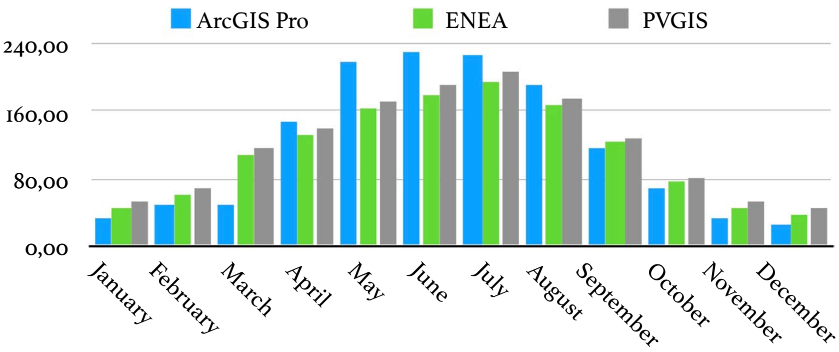
To prove the soundness of the analysis, the average calculated values were compared to the ones calculated with two online tools, PVGIS and the one provided by ENEA: the former assesses the monthly radiation only, the latter also daily data. For both daily and monthly data, the results are satisfying, with an average relative error of 3,01%. However, the differences are evidently decomposing the yearly average into months. In particular, March is the month for which values are more discrepant, on both a daily and monthly basis: it is the month in which, according to the online tools, the radiation values increase strongly, while ArcGIS Pro restitutes a more gradual increase. It is also interesting that the variation calculated by ArcGIS Pro is the highest: the calculated radiation is the lowest in winter and the highest in summer, compared to the other two.

Image 4.18



Solar radiation in August
Source: own elaboration

Graph 4.1



Average monthly radiation
Sources: own elaboration, PVGIS, ENEA

4.5.2 Calculation of the photovoltaic potential

After having assessed the solar radiation and connected the monthly values to each analysed volumetric unit, it is possible to compute the potential photovoltaic production. It was chosen to focus on monocrystalline, polycrystalline and thin films, not considering the perovskite solar cells, for two main reasons: first, their price is, still, not competitive with technologies which are widely diffused in the market and, second, their efficiency is not very higher compared to other technologies. The conversion efficiency (ratio of incident solar energy to produced energy) of the three technologies was defined according to Green et al. (2022): 24,2% for monocrystalline, 18,4% for polycrystalline and 11% for thin film. As for the performance index, restituting the efficiency of the system, it was assumed 75%.

The productivity of the panel is quantified in the kilowatt-hours which can be produced by a panel with an installed power of 1 kWp; then, considering that generally one of the two main pitches of the roof is suitable for installing panels, for the total production of a building it can be assumed the 40% of the roof surface as usable. Looking at a single volumetric unit, it is the efficiency of the panel the only variable, determining the differences between the production of the different technologies; instead, comparing the production of different buildings, also the surface availability has a strong influence on the performances: 1,67 m^2 of thin film panels, for instance, level off the production of 1 m^2 of monocrystalline and 1,32 m^2 of polycrystalline.

On average, the production per kWp for the volumetric units is 1036,59 kWh/year. However, there is a huge monthly variability, with 172,84 kWh produced only in June and just 18,01 kWh in December, due to the different amounts of solar radiation. Looking at the spatial distribution of the most productive constructions, it is evident the impact of the shadowing: tall buildings or buildings located in open areas are more productive than the ones close to tall elements. The less productive volumetric unit, 20 m tall, is located in the area of Peccei park and it is 26 m lower than the neighbouring one. By contrast, the less productive one is lower, 15,8 m, but surrounded by low fabric which makes it emerge and catch the whole of solar radiation. It was previously highlighted that the height is quite homogeneous in the different clusters, with the modern taller than the historical ones but, still, with little variations. That is why it is difficult to find a pattern in productivity, the only zone with higher values is the former industrial area in the South-Eastern part close to the rail yard because the urban

Image 4.19

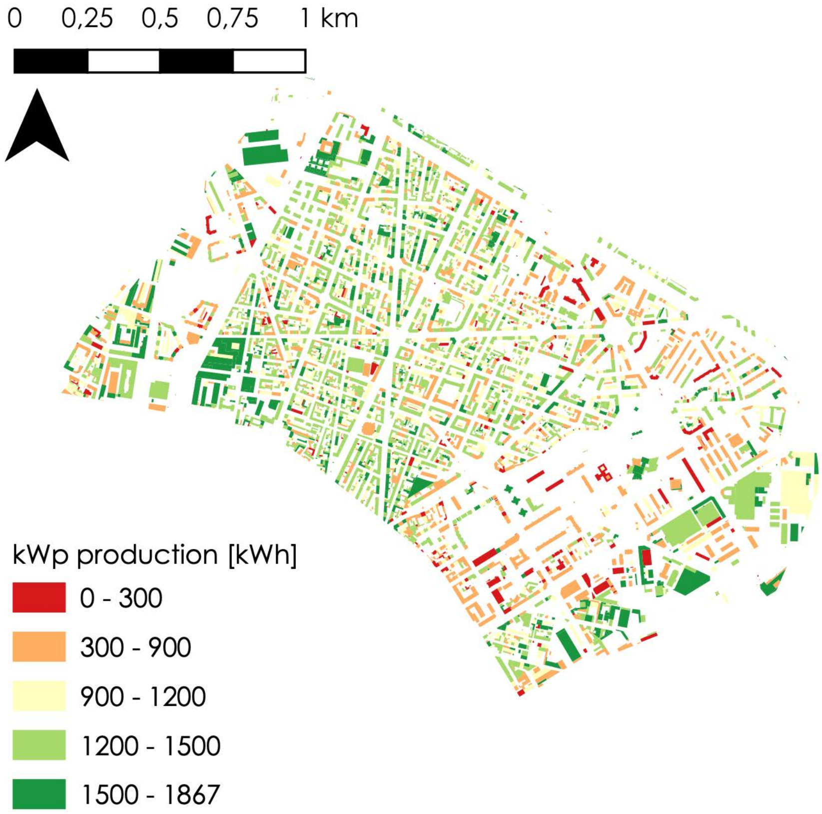
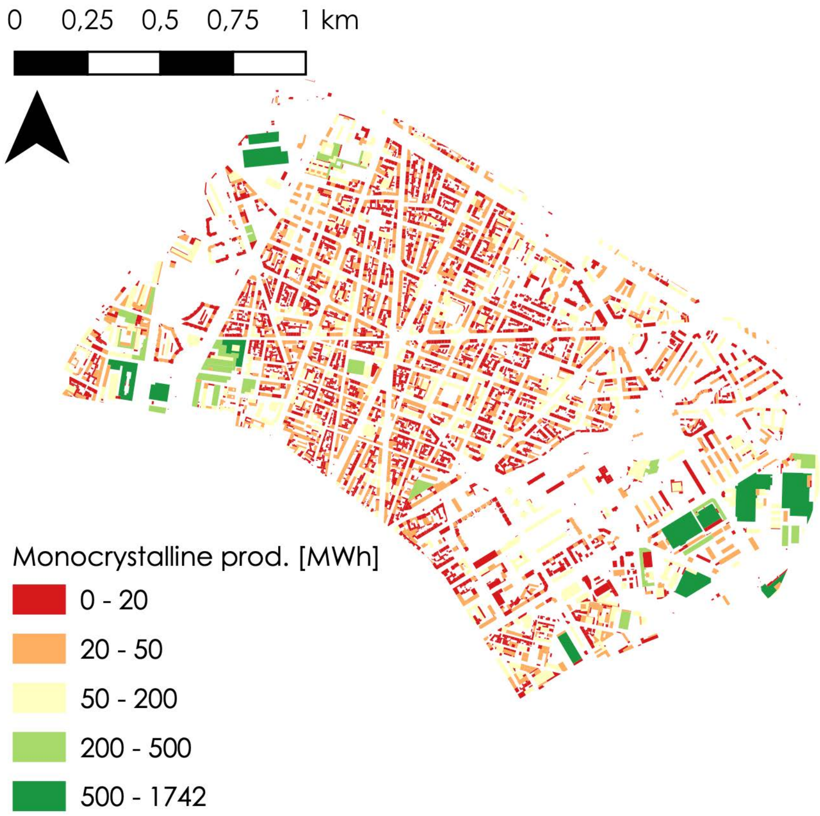


Image 4.20



Yearly productivity of a panel with 1 kWp and monocrystalline production
Source: own elaboration

fabric is rarer and has wider surfaces, preventing the shadowing of each other.

Due to the different efficiencies, the panel surface required to produce 1 kWp varies: 8 m^2 for monocrystalline, 10 m^2 for polycrystalline and 12 m^2 for thin films. To calculate the total productivity the efficiency of the panel and the working surface should be included. Considering the same roof and therefore the same usable surface there are differences between the analysed technologies.

The most productive buildings are the ones with the widest roof surfaces: they can exploit a wider area for the installation of the panels and this is reflected in the productivity: among the buildings producing more than 400˙000 kWh/year, the one with the smallest footprint is 2526 m^2 wide. Moreover, often the largest buildings are also the ones with higher productivity per kWp, as previously mentioned. A further element emerges: while looking at the productivity per kWp it could appear as suitable to locate panels on the roofs of minor buildings, their negligible surface makes them unproductive most times.

The efficiency of the panels creates differences among them: thin film production is 55% lower than monocrystalline. On average, each building could produce 18˙000 kWh/year using monocrystalline panels, 13˙600 kWh/year with polycrystalline and 8˙100 kWh/year with thin films. Still, some buildings have the potential to produce even less than 1 kWh/year, with others producing more than 1,5 million kWh/year. In total, the area of interest could produce more than 100 million kWh/year, installing monocrystalline panels on every roof, but this would imply huge costs. Therefore, a careful analysis is required.

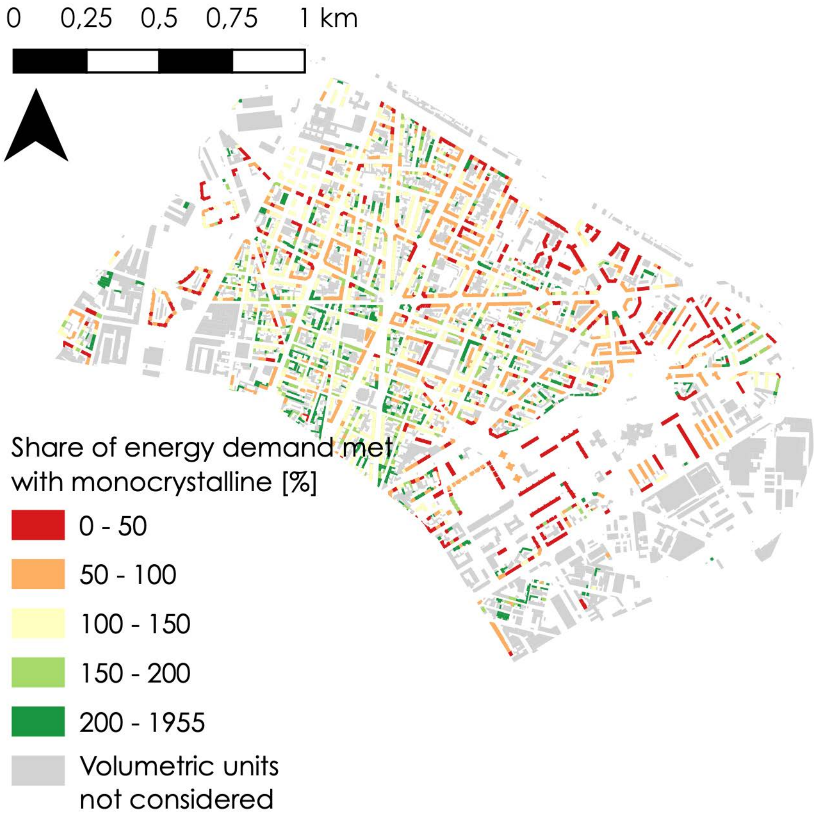
4.5.3 Share of demand met by photovoltaic

To evaluate the convenience of installing photovoltaic panels on the roofs, the electricity demand has to be calculated, then computing the share which can be covered through photovoltaic panels.

The municipality data reports the uses of the buildings, not of the single volumetric units, so a spatial join was performed to attach the necessary information to the units. Ex-ante, each building was assigned a correction factor for the volume: 0 for the non-residential buildings (including all minor buildings), 0,5 for buildings with mixed uses and 1 for residential buildings; by doing so, only residential volumes are taken into account. The electricity demand is esteemed to be 1˙000 kWh/person/year: to compute the number of residents in a building the average number of people per cubic metre was used, then multiplying the total by 1000.

The most productive technology, monocrystalline, can meet the energy demand of 62,52% of the residential buildings; considering the other technologies, this percentage decreases to 44,79% (polycrystalline) or 19,1% (thin film). Considering an average population of 21,55 people per building, the ones which cannot fulfil their energy demand through photovoltaic technology are the most populated, averaging 35,66 people per building (considering monocrystalline). On average, they are also the ones with the highest roof surface, 245 m² compared to the average 196,93 m². The area in which the share between production and consumption is generally lower is around Respighi square; on the contrary, most buildings located Eastern than Palermo avenue fulfil their energy demand.

Image 4.21



Share of electricity demand met with monocrystalline panels
Source: own elaboration

The results show a high potential of the district; however, it is to be remembered that a big part of the roof, 40%, has been considered productive: this could result in high expenses and an unsatisfactory payback time. However, it was highlighted that in 19,1% of the cases, even thin film technology can meet the demand, ensuring a good ratio between savings and initial investment. Finally, it has to be considered that only residential buildings were taken into account: there is the potential to install panels on the roofs of non-residential buildings too, considering the wide surfaces they had and the high productivity (see the previous paragraph).

The findings of this paragraph leave room for the creation of PEBs in the area of interest. There are some blocks, like the one comprised between the streets Montanaro, Sesia, Monte Rosa and Malone, which are constituted by buildings producing more than their consumption. As described in paragraph 3.3, PEBs can be the starting point for creating an energy community on a wider scale.

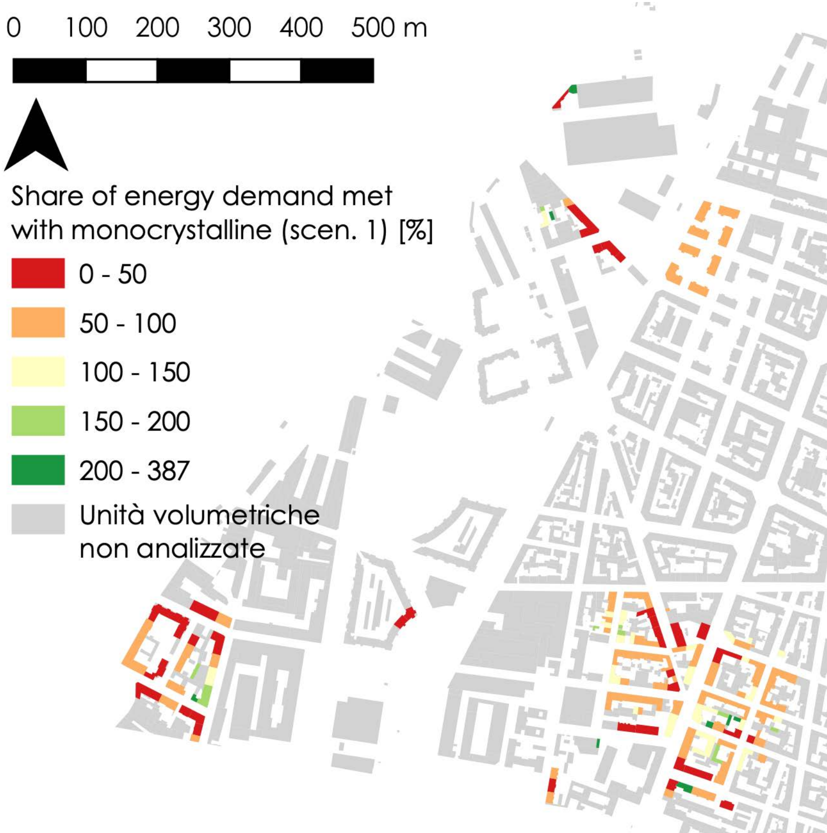
4.5.4 Proposal for electrification

An integrated scenario was also proposed, exploring the possibility to meet both thermal and electrical demand through photovoltaic panels, by installing heating pumps. Such devices, powered by electricity, use the external air to convey heat; depending on the direction of the flux (from the internal to the external air or vice-versa), they can work for both heating and cooling. Heating pumps are also used for the production of sanitary hot water.

Heating pumps are more convenient than electrical heating because, by definition, they have a CoP (Coefficient of Performance) higher than 1: it means that, consuming 1 kWh of electricity, they produce more than 1 kWh of heat. In this research, the CoP would be 4. The energy required for heating has to be summed to the electricity demand which was already calculated.

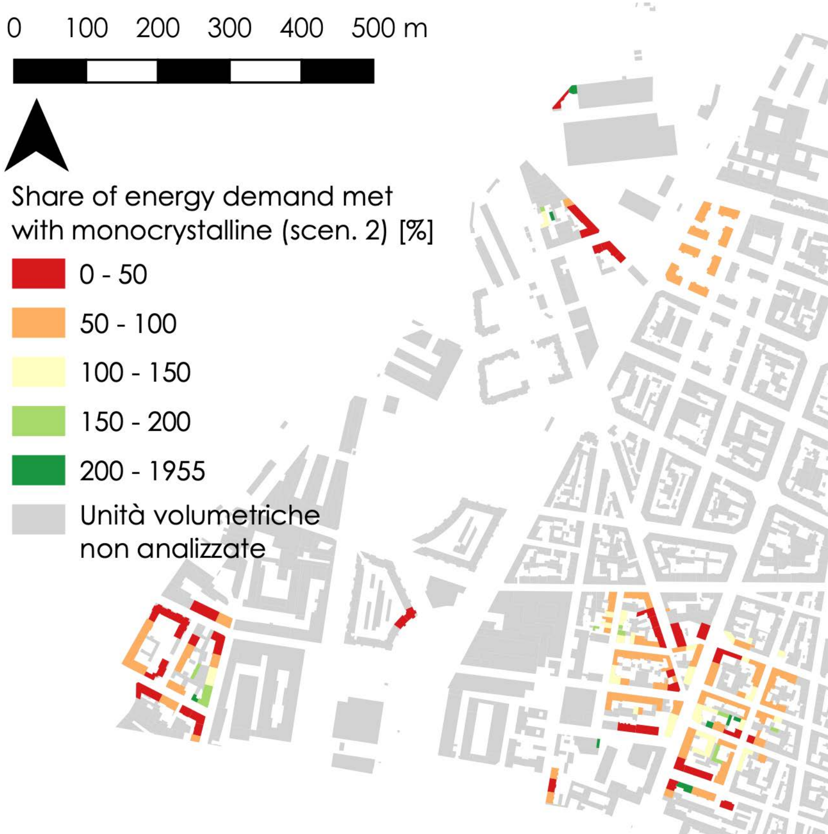
The sample is reduced to 161 volumetric units, which are the ones analysed with DigiSky data excluding non-residential and minor buildings. On average, they produced nearly double their electricity need. This average, when the heating demand has to be met with electricity, is reduced to 90,7% and 87,3%, respectively for the optimum and limited improvement scenario. 41 buildings can use monocrystalline panels to cover the whole energy demand in the limited improvement scenario. In this case, the roof surface is not an impacting parameter: they are small buildings (1/3 of the average gross surface), characterised by productivity that, despite being lower, impacts more on the total energy demand. Considering that many of them are located in the South-Eastern cluster, around Vercelli avenue, it can be deepened the analysis on the possibility of creating a PEB.

Image 4.22



Share of energy demand met with monocrystalline panels in the first scenario
Source: own elaboration

Image 4.23



Share of energy demand met with monocrystalline panels in the second scenario
Source: own elaboration

5

Conclusions

The present thesis proposed an application of data including elevation information for the energy transition. Starting from a mixed dataset, composed of data coming from a photogrammetric flight and government data (partially from Turin Municipality and partially from ISTAT), the analysis focused on the building sector and the possibilities to reduce its environmental footprint. Despite social and economical aspects were not directly addressed throughout the research, positive externalities from environmental improvements can lead to concrete benefits in both the other dimensions.

The research started with the description of the photogrammetric process, focusing then on how the elevation component can be included in digital representations and be instrumental in the realisation of orthophotos. It is in this section that the concepts of 2.5D and DSM were introduced as hybrid products, with a bi-dimensional representation and tridimensional information. The second part of the chapter analysed the dominant standards in 3D modelling, from the SDI (INSPIRE Directive) to the data structure and data model (CityGML and CityJSON). This background was fundamental to explore the digital twin as a concept and its properties before moving to the geodatabase, container of geographical data. The latter was widely used during the applicative part for storing intermediate and final products. The third chapter was pivoted around sustainability in the building sector. First, the alternatives for energy renovations were explored starting from the description of the current state; second, an introduction to the legislative and technical framework for the photovoltaic, which is the dominant RES for building-integrated energy production, was provided. This chapter aimed to provide the necessary background for the applicative part, the fourth, which was further divided into three macro sections. The first analysed the request from the City of Turin and focused on data gathering. The other two followed the same organisation as chapter three, starting from the renovation of buildings and then moving to the possibility of installing photovoltaic panels.

The main finding is that an integrated scenario, in which energy renovation is followed by the exploitation of solar radiation through photovoltaic panels, is preferable. Two alternative scenarios were proposed for energy renovation, improving the building stock to meet the requirements of class B or, alternatively, by two energy classes. On the other hand, the potential production of different photovoltaic technologies was calculated starting from the incident solar radiation: monocrystalline, polycrystalline and thin film panels were compared after having assessed the energy produced with modules having a maximum power of 1 kWp.

In both cases, the savings in terms of energy and environmental impact are relevant: in a portion covering about 1/10 of the area of interest, analysed with thermal images, more than 7,5 million kWh can be saved every year. Converted in equivalent CO_2, this saving is quantified as more than 1˙000 tonnes. On the other hand, 107 million kWh can be produced by installing monocrystalline panels on each roof: it means that the whole electricity demand can be covered through RES. However, as mentioned, the best scenario implies an integration between energy retrofitting and photovoltaic production: heat pumps with a COP equal to 4 could be installed, meeting the total energy demand with panels. Indeed, it was calculated that assuming a total electricity need of around 6 million kWh/year, monocrystalline panels can meet 60% of the total demand. Moreover, when considering the volumetric units separately, the potential can be judged as even better, with at least 1/4 of the buildings which can satisfy their energy demand by themselves.

The conclusion of this work can be seen as open: it can be presented as the starting point of more complete and precise research. In several steps, simplification was required to keep the process efficient and there is the potential for exploring more the topic to find the optimum balance between costs and benefits.

First, there is the possibility to refine the analysis on thermal dispersion. Nadir photos, showing the roofs only, were used instead of oblique pictures. These, by showing also the walls, allow a more precise definition of the surface temperature, which would be reflected in a more accurate analysis of the global energy demand. Moreover, for such an analysis also the time of the acquisition is relevant: the dataset which was used consisted of images taken during the day, with temperature values influenced by solar radiation; images acquired at night would not have this problem, further perfecting the classification. The presence of shadows resulted in the need to manually check the most appropriate portion of each roof for the thermal analysis, causing a drastic increase in the time of elaboration. The integration of the information (presuming oblique pictures acquired at night) in a tridimensional model could allow the automatisation of the process, intersecting the thermal data with the volumes of the analysed building. Once having automatised the process, thermal information can be included in the Digital Twin as one of the enabling datasets for realising analyses on the energy performance. This can activate a virtuous cycle with progressive addition and integration of data, resulting in a complete framework for energy data.

Implementing a Digital Twin is an important step towards user-friendliness and, consequently, citizen participation. Tridimensional reconstructions from high-precision photogrammetric flights allow an accurate reconstruction of the urban environment, thus not requiring the user to understand an abstract or symbolic representation. Enriching 3D models with semantic information can improve awareness, making the information easily accessible and including more citizens in decision processes.

Further possibilities come from the output format of the TerraItaly™ Metro HD project. Raw LiDAR data can be processed with a software which reads the classification, like ENVI, to create a file in which pitches are represented as separate vector entities: it can be used for identifying the pitch with the highest productivity, removing instead the surfaces which cannot be used (like windows on the roofs). Moreover, accurate DSMs can be used not only for assessing the amount of solar radiation but also to calculate the orientation and angles of the pitches (imagining an integration with 3D meshes), perfecting the solar potential analysis. In this research, buildings were considered as blocks: roofs were considered flat, while sloped surfaces are bigger; a refinement in this sense would improve the accuracy of the results.

Finally, further research concerns not only the geomatic aspect but also the energetic. First, it was mentioned that there is a chance to create Positive Energy Districts: once having recognised that the potential photovoltaic production in some cases is higher than the energy demand, areas with the possibility of having an energy surplus are to be highlighted, then defining the feasibility of energy supply to neighbouring zones. By establishing a first form of collaboration, it is possible to define a path towards the creation of an energy community, with citizen empowerment and, therefore, increased awareness about energy topics. However, before the formation of any sort of organisation, it is necessary to define as accurately as possible the possible problems. An aspect which was mentioned, but not included in the practical process, is the correlation: the possibility of storing energy and in particular electricity has to be explored, studying the moments in which the energy demand is maximum and comparing them with the production at various times of the year (with different hours of light a day). Batteries, but also solar panels, are critical waste: the analysis should imply a Life Cycle Assessment, to overcome environmental problems instead of simply moving them to another sector.

Finally, it was claimed that integration is the key to sustainability. Extreme solutions are to be analysed, foreseeing a completely electric scenario or expecting all buildings to meet the maximum energy standards, but it is equally important to consider intermediate solutions, e.g. satisfying a part of the energy needs with district heating and fulfilling the remaining with heating pumps. For doing so, economical parameters have to be taken into account more deeply, finding a cost-optimal which balances initial investments and life-long savings. Moreover, incremental scenarios can be defined, planning to improve the sustainability of building stock with subsequent interventions.

6

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