

Energy and Environmental Assessment of Urban Areas: an Integrated Approach for Urban Planning

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Abstract

The article presents a bottom-up approach for the assessment of the performance of urban areas from the energy and environmental point of view, based on the definition of virtual archetypes, defined analyzing the characteristics of the considered area. The model provides an estimation of primary energy consumption and CO₂ emissions of buildings, and the overheating risk and the potential runoff of urban areas. The method is used for the evaluation of the impact of new expansion areas by defining intervention scenarios based on the analysis of recent building stock. The province of Monza and Brianza is used as case study.

Key Innovations

- Integration of energy and environmental aspects in urban policies
- Evaluation of the impact of new expansion areas on the municipal performance
- Support tool for urban planning

Practical Implications

The article presents a support model for public authorities to assess the impact of new expansion areas from an energy and environmental point of view. The outcomes of the tool can be applied in a “rewarding” schema based on the impacts of each municipality. This allows to drive urban policies for the reduction of overall impact.

Introduction

Modelling the complex flows that characterize an urban area is a hot topic for the definition of sustainable urban policies for the reduction of energy consumption and environmental impacts and the improvement of energy efficiency and safety of the building sector. The development of Urban Building Energy Models (UBEMs) provides a response to the need to characterize the energy behavior of buildings at urban scale, facilitating the process definition of energy and urban policies including the target of reducing energy consumption and greenhouse gases emissions (Hong et al., 2020). Several authors have paved the way for the development of UBEMs defining a shared framework that identifies the characteristics of the used approaches (Reinhart and Davila, 2016 and Li et al., 2017). There are two main recognized categories for the energy model of urban areas: top-down and bottom-up (Swan and Ugursal, 2009). The former is based on aggregated input at

different scales according to the objective of the study, the latter is based on the analysis of disaggregated data, at individual building or group of buildings level, extracted to represent the energy behaviour of the built environment under investigation. Under this classification, several physics or statistics-based, deterministic or stochastic methods have been developed. Among them, the bottom-up physics-based models have revealed their suitability in simulating and analysing buildings performance at urban level, thanks to the growing of a series of detailed simulation tools (Ferrando et al., 2020). These models are based on the definition of archetypes or sample buildings that summarize the characteristics of the overall building stock under investigation. The use of archetypes makes UBEM flexible and relevant for a wide range of scales, from neighborhood (Belussi et al., 2017) up to entire nation (Lombardi et al., 2019). However, the choice of the most suitable archetypes is based on the balance between the simplification of the sample and the accuracy of the information (Monteiro et al., 2017). Even if UBEMs are worldwide applied and tools and methodologies are more and more consolidated, challenges must be still faced. One of these is the integration of UBEMs with other urban models, such as climate and outdoor comfort models (Johari et al., 2020). Sola et al. (2020) reviewed the state-of-the-art of multi-domain tools for the analysis of the dynamic behavior in districts and cities. Examples of the integration of energy and urban simulation can be seen in: Salamone et al. (2019), where the authors present a multi-level and multi-domain model based on a bottom-up approach for both building energy efficiency and outdoor comfort analysis; Tsoka et al. (2019) coupled ENVI-met model and EnergyPlus to consider the site-specific microclimatic characteristics of urban areas; Huang et al. (2020) developed a model that couples building and micro-climate simulation at neighborhood level.

According to Ang et al. (2020), UBEMs find application in four main fields: planning and design of new neighborhoods, building stock analysis, individual building recommendation and grid integration. In particular, the article focuses on the analysis of the building stock and the effect of new neighborhoods on energy consumption (heating and cooling), CO₂ emissions and urban overheating of individual municipalities. The analysis is made on new neighborhoods identified by Public Authorities. The method is based on a bottom-up approach for the planning of urban areas from an energy and environmental point of

view, based on the definition of specific virtual archetypes. Using information held by Public Authorities and statistical studies, the model provides an estimation of the current energy performance of the building stock, in terms of primary energy consumption and CO₂ emissions, and the environmental characteristics of urban fabric related to the potential overheating. The method is used to evaluate the impact of new urban neighborhood respect to the previous criteria in the province of Monza and Brianza, in northern Italy.

Objectives and methods

The goal of the research is to provide to public authorities a tool for the assessment of the quality of urban areas and assess the potential impact of new buildings to drive urban and energy policies, “rewarding” the most efficient areas. For this purpose, the tool has been applied to the Province of Monza and Brianza with the aim of evaluating the energy and environmental performance of each municipality and evaluate the impact of building expansion.

The methodology is designed according to a bottom-up approach, moving from single components (buildings and neighbourhoods) to the overall urban area. The twofold analysis is carried out by considering the available information provided by open-source database, mainly made available by the regional territorial information system, needed to characterize both building stock and surrounding from a geometrical, morphological and functional point of view.

The methodology involves the following steps:

- Classification of the building stock and urban area characterization and simulation of the archetypes;
- Identification of the key performance indicators (KPIs) for the analysis of the urban area;
- Energy and environmental analysis of current state of the territory under analysis, through KPIs (current scenario);
- Identification of the intervention scenarios for buildings in planning;
- Assessment of the future energy and environmental KPIs after the implementation of the interventions (ex-post scenario).

The results are presented with different granularity: at building, municipalities and group of municipality level.

Case study

The case study is the Province of Monza and Brianza, with a territory of 405 km², situated at NE of the city of Milan within the Lombardy region. The province is divided into 55 municipalities. It is the most urbanized province in Italy, with a land cover of 41%, that makes it a unique application case.

Despite the presence of wide green areas and parks following Lambro river and significant agricultural land use, the province is characterized by an intensive soil consumption due to the residential and industrial urbanization performed after 70s.

Lombardy region geographic portal provides, for the province territory, both vector (shapefile) and raster

(geotiff) open data. The formers are related to buildings properties, soil use classification map DUSAF 6.0 (2018) (*Destinazione d'Uso dei Suoli Agricoli e Forestali*, for the year 2018) and vegetation presence. DUSAF is the land-cover/land-use map of Lombardy Region organized in five hierarchical levels where the first three are compliant with the European Corine Land Cover (CLC) map. For the characterization of the province we used the fourth level. Besides, a sub-municipal territory subdivision shapefile is available and represents the Italian territorial census tracks (TCS), (source ISTAT, National Institute of Statistics).

The raster source refers to the maps called Regional Technical Map (CTR) and reports, among the others, the buildings' footprints at different periods of the survey.

Energy model

The energy model aims at assessing the primary energy consumption and the CO₂ emission related to buildings operation.

The classification and characterization processes identify the most suitable building archetypes following a deterministic approach. The building stock is classified considering: building typology, construction period and urban contest (adjacent, dense or isolated). This information is made available by several local Geographical Information System (GIS) data and is managed using GrassGIS software. In Table 1 the list of the features for the classification of the building stock is presented. The result of the combination of the reported features is a building matrix of virtual archetypes for the energy and environmental characterization of the province. Each column reports the list of the classification parameters. The “Typology” refers to the intended use of buildings. We consider six main features (Residential, Office, School, Commercial, Supermarket and Industry). The granularity of residential buildings, offices and schools is further enhanced, due to a more accurate characterization of the building stock. This further subdivision is represented by the bullet list in the same column.

Table 1: Building archetypes features.

Typology	Construction period	Urban contest
RESIDENTIAL	- Before 1976	- Dense (distance between buildings ≤10m)
- Single family house	- Between 1976 and 1990	- Open arrangement (distance between buildings ≤20m)
- Detached house	- Between 1991 and 2005	- Isolated (distance between buildings >20m)
- Multifamily building	- After 2005	
- Apartment block		
OFFICE		
- Small office		
- Large office		
SCHOOL		
- Small school		
- Large school		
COMMERCIAL		
SUPERMARKET		
INDUSTRY		

The residential buildings are divided into four categories respect to the Surface to Volume ratio (S/V):

- Single family house: $S/V \geq 0.72$
- Detached house: $0.57 \leq S/V < 0.72$
- Multifamily building: $0.38 \leq S/V < 0.57$
- Apartment block: $S/V < 0.38$.

The external envelope areas and the building volume are calculated using the building height attribute. When buildings are adjacent to the area of the shared façade is calculated using the buffer function of the building footprint perimeter and then a geometry intersection between buffered and non-buffered buildings layers to retrieve common perimeter properties.

Offices are divided into two categories as a function of the number of floors, as follow:

- Small offices: number of floors ≤ 2
- Large offices: number of floors > 2

An analysis of the characteristics of the Italian offices, indeed, identifies that these samples are the most diffused. The analysis of the building stock of the areas case study confirms this outcome.

Two typologies of schools are provided within the UBEM, to reflect the characteristics of the buildings in the selected areas. The classification is based on the location of the schools, in a dense or semi-dense area and in an open or sparse arrangement. The formers mainly consist of buildings integrated into the urban fabric, the latter of large isolated educational buildings.

The range of the “Construction period” is selected considering milestones in Italian legislation, that has affected the thermal and energy performance of buildings. The construction period refers to the age of the building. The building stock was analysed to verify that the characteristics of buildings within a period were similar. The age of buildings, correlated with architectural and structural features, affects energy consumption. The considered milestones are:

- Law March 30th 1976, Norme per il contenimento del consumo energetico per usi termici negli edifici;
- Law January 9th 1991, Norme per l'attuazione del Piano energetico nazionale in materia di uso nazionale dell'energia, di risparmio energetico e di sviluppo delle fonti rinnovabili di energia;
- Legislative Decree 192 August 19th 2005, Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia.

Therefore, we identify four period of construction: before 1976, 1976-1990, 1991-2005, after 2005. The aggregation of buildings per wide period of construction is common in building stock modelling, as a function of the dimension of the field of application and buildings characteristics (Oberegger et al. 2020). The reference to national law allows to apply the model to other contexts.

The “Urban context” is defined considering the average distances between buildings. In the dense and open arrangement urban context, multifamily buildings and apartment blocks are considered adjacent to other

buildings. The height of buildings of the neighborhood is calculated as the average height of building of the case study. Figure 1 shows the context for the multifamily building in the dense urban context.

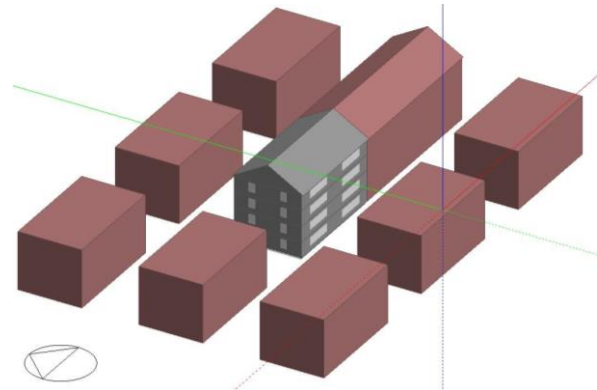


Figure 1: Multifamily building into the dense urban context

Each reference building is then characterized by the performance of the envelope, HVAC, energy carriers and occupancy profile. The main references are UNI/TR 11552 for the envelope data, UNI TS 11300-1, EN 16798-1 and UNI 10339 for the heat gains and profile and plants. Residential buildings archetypes are checked with the information provided by Tabula Project. For non-residential buildings, input data are found from ISO 18523-1 coupled with Ministerial Studies carried out in collaboration with ENEA, in which reference buildings for each category were defined based on in-field analyses. This study is used to check the consistency of non-residential building archetypes. As a result, a matrix of 92 archetypes is defined. The primary energy consumption (kWh) and the CO₂ emissions (kgCO₂) of the archetypes are calculated using the simulation tool EnergyPlus and its interface DesignBuilder®. The calculation of the KPIs is performed including the energy services as a function of the typology of the buildings (Table 2). This is the result of the analysis of the characteristic of the Italian building stock and the values are expressed per square meter of building area.

Table 2: Building services

Typology	Heat	Cool	DHW	Light	Vent
Residential	•		•	•	
Office	•	•	•	•	•
School	•		•	•	
Commercial	•	•	•	•	•
Supermarket	•	•	•	•	•
Industry	•	•	•	•	•

Finally, the archetypes are applied to the existing buildings and aggregated at different scales using GrassGIS: building, TCS, municipality and aggregation of municipalities, providing a wide knowledge of the performance of the territory. Inspections on building shape and intended use were made in the GIS of the province where the attribution of archetypes was not satisfactory. Starting from the building level, the aggregation of the data is made with the weighted average of KPIs within a given area. Figure 2 shows the buildings

energy performance of a selected area as the result of the application of the energy model.



Figure 2: Buildings' energy performance

Environmental model

The environmental model assesses the overheating risk and the runoff index of the urban areas. The analysis is carried out at the TCS level. A customized version of the Urban Weather Generator (UWG) engine (Bueno et al., 2013) was used for UHI evaluation. UWG uses the U.S. DOE reference buildings for the estimations of the hourly urban canopy air temperature and humidity. The archetypes characteristics can be customized to reflect the characteristics of the current context. UWG is widely applied in European cities for the estimation of urban climate (Bueno et al. 2014, Gunawardena and Steemers 2019)

The information on the archetypes provided by the energy model is used to feed the tool creating customized reference buildings. The customized version is founded on the study proposed by Nakano, 2015.

UWG transforms hourly air temperatures of a surrounding rural area by considering a series of properties of the selected urban canyon: building geometry and intended use, urban materials, vegetation coverage, anthropogenic heat from traffic, atmospheric heat transfer from urban boundary and canopy layers.

For the identification of the urban archetypes, the area is classified according to the land coverage typology, identify by DUSAF (land use and coverage), a regional geographical database made available by Lombardy region that classified the land use and coverage and a percentage range that express the incidence of a specific coverage on a TCS (land coverage ratio). Each land coverage is expressed by the ratio occupied by artificial artefacts (buildings, streets and more). Thus, for example, "Dense residential" means that impervious areas occupy more than 80%; "Sparse residential" means that impervious areas are between 50% and 80% and so on.

Table 3: Urban archetypes features

Land coverage	Land coverage ratio
Dense Residential	90-100%
Medium-dense Residential	80-90%
Sparse residential	70-80%
Industrial-Commercial	60-70%
Services	50-60%
Pocket parks	40-50%

	30-40%
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Table 3 reports the list of features to define the urban archetypes. The archetypes are defined for the urban areas, excluding natural coverage such as rural areas, forests and more. With this classification, a total of 40 urban archetypes are identified.

The urban archetypes are characterized with the following parameters, that feed the UWG and used for the calculation of the runoff index:

- Building type;
- Building age;
- Average height [m];
- Site coverage [%];
- Façade to site [-];
- Vegetation coverage [%]

The two most frequent building types and construction period are identified for each urban archetype using the information of the energy model (table 1). The average height of buildings within the archetype is calculated as the weighted average of the buildings included in the archetype. Thus, for example, if the i-th urban archetype is characterized by 30% of multifamily buildings and 70% of apartment blocks the average height is the weighted average of the two values. The surface coverage is the percentage of land occupied by buildings and it is the ratio between buildings footprint and the area of the archetype. This index is calculated by combining the percentage expressed by the land coverage and the values reported by the land cover ratio.

The façade to site ratio expresses the ratio between the area of the vertical walls of buildings within the archetype and the area of the archetype itself.

The vegetation coverage expresses the percentage of natural areas (grass and trees) within an urban archetype. DUSAF provides values of vegetation coverage for any classes, many related to natural ecosystems. For the other areas, the value is calculated by accounting the surface occupied by urban green areas, tree foliage, agricultural areas, forests, water bodies, unpaved roads.

Figure 3 shows an example of urban archetypes for a Medium-Dense Residential.



Figure 3: Urban archetypes: Medium-Dense Residential.

The urban archetypes are then associated with the TCSs and aggregated at different scales using GrassGIS: TCS, municipality and aggregation of municipalities.

The risk of overheating is defined for each archetype as the difference between the air temperature of the rural station, selected as reference, and that the air temperature calculated with UWG on the hottest day. Figure 4 shows the overheating risk at TCS level where the colours express different ranges of temperature between the rural and the urban area.

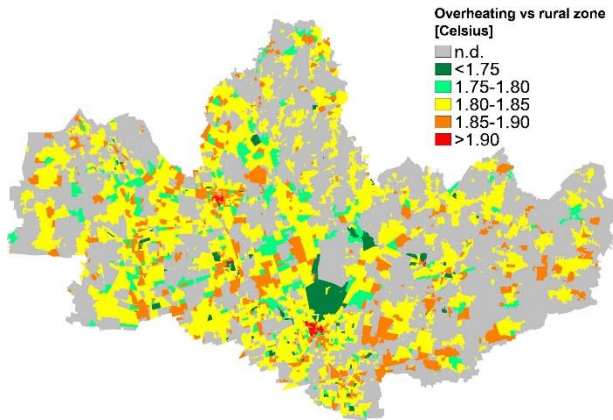


Figure 4: Overheating risk at TCS scale

The calculation of the runoff coefficient is based on the values provided by the American Society of Civil Engineer and Water Environment Federation (ASCEWEF). Table 4 shows the categories and the runoff coefficients assumed for the current analysis based on the categories provided by the available database. The values reported in column “Runoff (used)” are calculated considering the ratio of built and permeable in each area. For classes not included in Table 4, a linear interpolation was carried out between 0.15 to 1.00 considering the mean vegetation coverage of the class (from 100% to 0%).

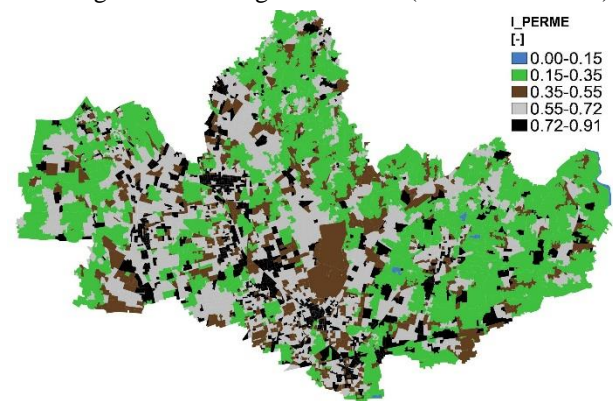


Figure 5: Runoff coefficient at TCS scale

Figure 5 shows the distribution of the runoff coefficient on the provincial territory.

Table 4: Runoff coefficients

Category	Runoff (ASCEWEF)	Runoff (used)
Buildings footprint	0.95-1.00	1.00
Streets	0.70-0.95	0.95
Railroad yard	0.35-0.20	
• Urban areas		0.35

• Tracks non-urban area		0.20
Cemeteries	0.20-0.35	0.25
Lawns	0.10-0.25	0.15
Unimproved	0.13-0.17	0.15

Identification of the intervention scenarios

Since the goal of the study is the evaluation of the impact of building expansion on the energy and environmental performance of the considered municipalities, intervention scenarios must be defined. Each municipality identifies the areas for new buildings in the territorial administration plan, with the definition of a series of urban indexes (building typology, height, distances, coverage ratio, etc.). Starting from the requirements provided by the territorial administration plans and the most frequent characteristics of recent buildings and neighborhoods, intervention scenarios are proposed for the expansion areas. These scenarios take into account all intended uses and are created on the basis of the information of local urban plans.

This task focuses on the properties of the buildings built after 2003 and on the properties of the TCS where a major part of buildings is constructed after the same year. In particular, the following rules are selected:

- building typology: the most frequent building typology is the reference. As a consequence, the correspondent building archetype dimensions and properties are considered;
- building fraction: the mean BF value of the considered TCS is the reference;
- vegetation coverage: the mean vegetation coverage of the considered TCS is the reference. As a consequence, the associated runoff coefficient is calculated according to the Environmental model.

To assess the impact of new buildings on energy and environmental performance of municipalities, the archetype buildings and urban areas database is updated with the new requirements by the standards, and the energy and environmental simulations are carried out for the archetypes with the thermophysical characteristics. In particular, new buildings are designed with the same shape and geometry of the existing ones but with performance complying those of a near Zero Energy Building (nZEB), as required by the legislation in force. The new neighborhoods are then simulated with UWG, to evaluate the overheating risk.

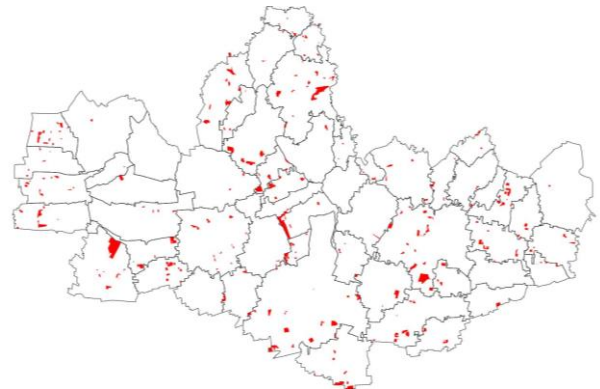


Figure 6: Expansion areas

The GIS tool was then updated with the new values of KPIs. As a result, each municipality has a specific reference intervention scenario. Within the province territory, about 300 areas of expansion are identified, covering less of the 2% of the whole province territory area. Figure 6 shows the locations of the expansion area.

Results

In this section, the results aggregated at the level of municipality are presented. This level is the most suitable to assess the impact of new interventions scenarios.

The KPIs for the new scenarios are represented as the variation (percentage or absolute value) respect to the baseline scenario.

Primary energy consumption and CO₂ emissions at municipal level are reported in figure 7 and figure 8.

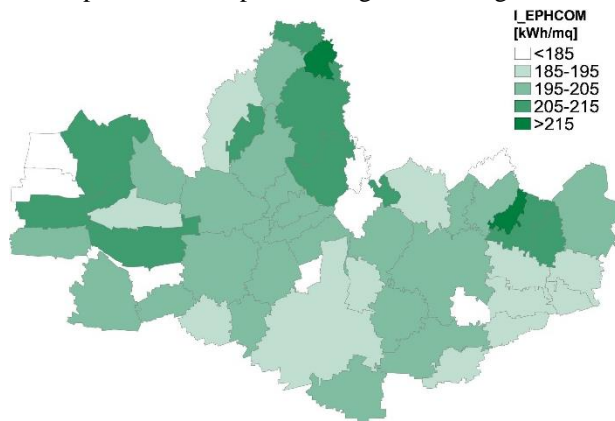


Figure 7: Primary energy consumption at municipal level

Most of municipalities have an energy index of 195-205 kWh/m²y and CO₂ consumption. In general, the older the municipal building stock and the higher the extension of non-residential buildings, the higher the primary energy consumption and CO₂ emissions. Non-residential buildings, in particular industrial, commercial and supermarket, have a high electrical consumption due to lighting and HVAC systems. The building stock of the province is mainly composed of old residential buildings and industries spread over the territory that cause a high primary energy consumption.

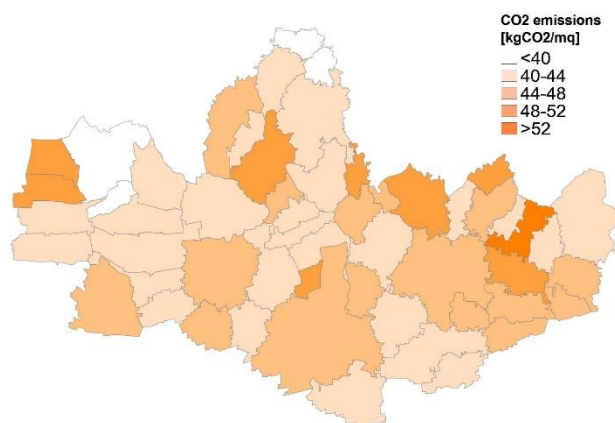


Figure 8: CO₂ emissions at municipal level

Figure 9 shows the percentage difference due to the application of the intervention scenarios to each municipality for energy consumption. The interventions are applied to the area of building expansion provided by the territorial administration plan.

Most of municipalities could achieve a reduction in primary energy consumption less than 2%. The major improvement with a reduction of primary energy consumption higher than 9% is reached in three municipalities, where the rate of the expansion areas is the highest and where new constructions are mainly residential buildings.

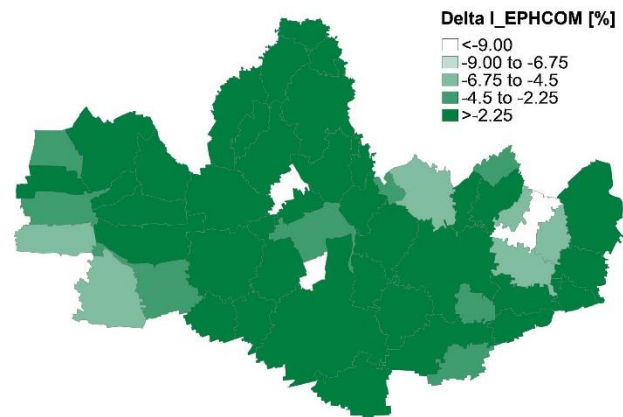


Figure 9: variation in primary energy consumption after the intervention scenarios

At municipal level, the overheating risk is accounted as the ratio of the surface of TCSs within a municipality with a difference in air temperature between the urban and the rural area higher than 1.80°C, considered as the threshold between the maximum value calculated for the park archetypes and all others. The categories of the risk are then accounted as the percentage of TCSs that present the overheating risk. Figure 10 shows the overheating risk of the municipalities of the province. Only TCSs reported in table 3 are considered for this calculation; this means that natural areas, such as countryside, are not taken into account.

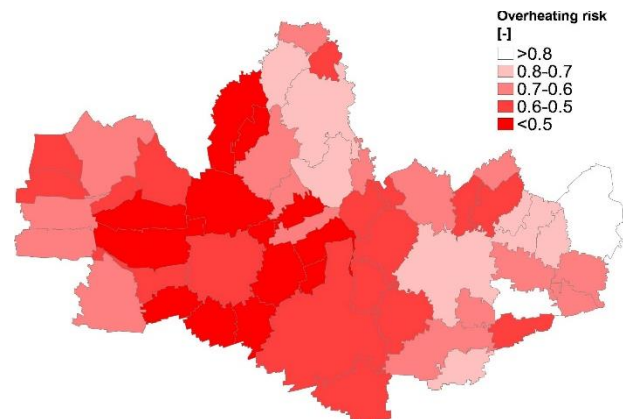


Figure 10: Overheating risk at municipal level

Red colour represents the highest overheating risk (less than 50% of TCSs without overheating risk), white colour the lowest (more than 80% of the TCSs without overheating risk). The values range from a minimum of

0.30 to a maximum of 0.88, with a high number of municipalities with “high” (<0.50) or “medium” (<0.6) risk. The municipalities with the highest percentage of “parks and gardens” show the lowest overheating risk.

The effect of the intervention scenarios on the expansion areas is presented in figure 11. The variation of the indicator is in the range 0.012 ÷ -0.047. Positive variation means a reduction of the overheating risk, negative variation an increment of the risk. The impact of new buildings on mean overheating risk is very low.

The average runoff coefficients for each municipality are reported in figure 12. An average municipal value greater than 0.55 indicates a prevalence of impermeable surfaces. The range varies from a minimum of 0.274 to a maximum of 0.621, with 6 municipalities with an average runoff coefficient higher than 0.55. The application of the intervention scenarios shows a low impact of new constructions on this theme, with a variation lower than 0.005 in runoff coefficient for most cases.

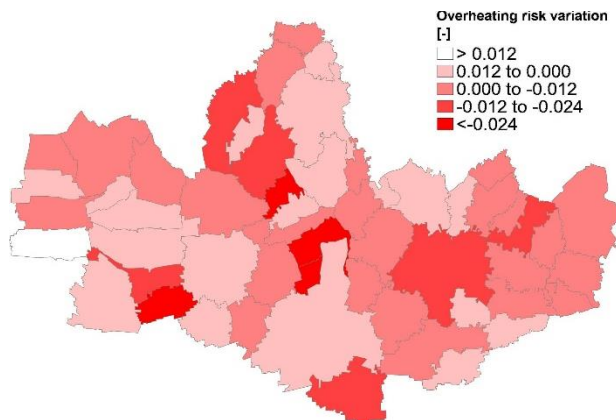


Figure 11: variation of overheating risk after the intervention scenarios

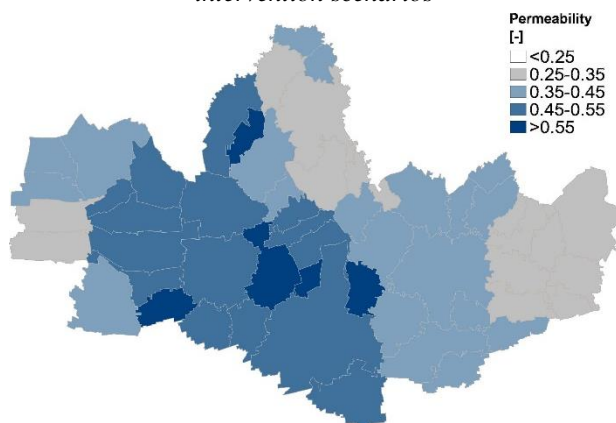


Figure 12: Runoff coefficient at municipal level

The analysis of the intervention scenarios (figure 13) shows, in all the municipalities, positive variations, reflecting an increment of the soil imperviousness. The range of values varies from zero to 0.065.

Unlike registered in UHI risk assessment, the runoff analysis does not show critical values both in the ex-ante and in the ex-post scenario for the same municipality.

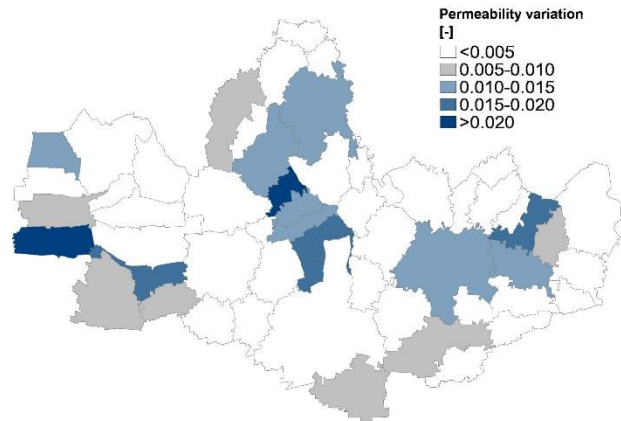


Figure 13: variation of runoff coefficient after the intervention scenarios

The results show a general improvement of the energy performance of buildings at municipal level. Most municipalities indeed record a reduction in primary energy consumption higher than 9%. This can push the policies towards the construction of new buildings with high performance. On the other hand, new expansion areas can have an impact on the environment. Looking at the overheating risk, interventions on new expansion areas do not produce a great effect. Indeed, the variation is low, but the negative effect is higher than the positive. Moreover, new buildings mean an increase of impervious surface with a consequent increase of the runoff coefficient of a municipality. However, in the case study, the variation of the runoff coefficient is relatively moderate, due to the small expansion area in almost municipalities.

Conclusion and development

The article presents a model for the analysis of the current energy and environmental performance of urban areas demonstrating how it is possible to implement a simplified model able to support public authorities in evaluating the impact of new expansion areas and driving future urban policies. The methodology is developed to be replicable in several contexts, using information on buildings and urban areas made available by local public authorities, indicators and calculation procedures widely recognized and used. The territory of the province of Monza and Brianza was chosen as case study. The reference performance indices are chosen to reflect the current needs of the public authority. The outcomes of the study can be used to drive urban policies, balancing new interventions as a function of the impacts on the territory.

The aim of this study is a comparison of the energy and environmental trend of municipalities within the province to provide Public Authority with a tool to drive future urban policies. The step forward of this study is the detailed evaluation of the performance of the new urban areas in order to identify development strategies that will meet the energy and environmental target of 2030 and 2050. Future developments provide the evaluation of the customized UWG model to better reflect Italian building stock, against field data and the integration of new indices for a better picture of the performance of urban area, the

definition of a single municipal reward index that that aggregate energy and environmental items.

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