Summary

Higher level of liveability and sustainability are the main goals in urban areas, where the building stock account as a major source of climate changing emissions (IEA, 2020). They can be reached through the reduction of GHG emissions, the implementation of the energy security and affordability (e.g. energy poverty) and the liveability of outdoor spaces. The increase in distributed renewable energy production and the reduction of energy consumption is encouraged by the UN Sustainable Development Goals (SDGs), the European Green Deal and the decarbonization plans of the European Climate Pact. Nowadays, it is strongly evident the importance of resilient energy systems in the attempt of climate change, pandemic, and energy crisis. More sustainable and resilient cities should rely on national and regional strategic planning, in which the energy issue is integrated within the decision-making processes, as it can drive to the economic development and social innovation of local communities. In Italy, to address the vulnerabilities generated by the post-pandemic crisis, the National Recovery and Resilience Plan (PNNR) has been launched: all the six strategic topics include the concept of energy sustainability and funds are allocated to energy related projects at local scale. Therefore, sustainable energy policies should be defined to be adaptable to every context and scale. The energy assessment should consider simultaneously all different scales from the territorial to the building level, as the territorial energy planning should become a fundamental component of the existing territorial regulatory framework. This can occur referring to:

- a place-based approach that highlight opportunities and criticalities specific to each context to optimize the local energy demand and supply from the available RES energy mix,
ensuring the long-term sustainability of local economic development.
- a holistic approach, able to integrate with the existing environmental, social, and economic policies and the territorial and urban plans to ensure the sustainability of interventions.

Therefore, the energy planning of territories requires supporting models and tools in exploring the spatial distribution of energy consumption, local RES, GHG emissions and liveability of urban environment (e.g thermal comfort conditions), integrating different levels of analysis at proper scales and comparing different scenarios. Decline energy policies to each specific context can contribute in overcoming local constraints and defining flexible measures. Referring to the scientific research field of Urban-Scale Energy Models (USEM), all different parameters that contribute to the electrical and thermal energy consumption of buildings must be considered to meet the local energy demand with the available RES generation, optimizing the morphology of the built environment and the available local energy production. A mutual influence between urban context and every building exists: urban morphology and local climate are crucial to assess the building energy performance at different level. In fact, the novelty of this kind of modelling consists of the conversion of energy-related variables from validated Urban Building Energy Models (UBEM) in new input parameters defined at a larger scale to assess energy consumption and producibility at district, urban or territorial scale. These models make use of Geographic Information System (GIS) software and tools to process different data, scaling through different spatial levels. They provide for the possibility to apply a very flexible methodology, adapting it to the peculiarities of each case study and allowing its replicability. The advantage of a GIS-based methodology stands in achieving reliable results with short-time simulations, as required in larger-scale energy assessments.

This research takes part from an existing GIS-based engineering energy model already validated within the previous work of my research group. It has been designed to evaluate the space heating energy consumption both at building and district scale at monthly and hourly level, as it is based on

a dynamic-energy balance of buildings with the calibration and optimization of some parameters (sky view factor, solar exposition, urban canyon aspect ratio) to consider the urban context.

The main objective of this work is the implementation of the GIS-based engineering energy model, modelling the ventilation loads and the number of air changes per hour (ach), according to the building characteristics, the urban context, and the local climate conditions. Since the ventilation aspect has not yet been studied on an urban scale in the GIS-based engineering energy model, the aim of this research is to delve deeper into the evaluation of ventilation loads at neighbourhood scale considering how local climatic conditions and urban morphology influence the air flow rate inside each building, which consequently affects building energy performance, indoor air quality and thermal comfort conditions. According to this, the research activity has been organized in steps to investigate: i) how the terrain roughness and obstacles affect the wind speed and direction inside urban canyons at urban scale, influencing wind path and momentum, generating windward/leeward zones, turbulence, and pressure variation on building facades; ii) how the combined effect of wind-driven and buoyancy can generate air flows inside building zones, applying parametric models at building scale to calculate the air flow rate due to infiltrations through building envelopes; iii) how the ventilation loads due to infiltration, intended as thermal gains or losses, affect the monthly and hourly variation of the Air Change per Hours (ACH) parameters and consequently the thermal energy balance equation for building space heating and cooling.

Regarding the first step, this work investigates specific GIS tools and remote sensing techniques to retrieve physical-based model at urban scale based on interactions with spatial geometries. Q-GIS plug-in based on morphometric methods is studied allowing to define the spatial distribution of aerodynamic parameters as a function of morphometric parameters with digital surface model (DSM) as input data and the real environment as application field. Starting from it, a place-based methodology is proposed to calculate: i) the wind speed variation at local scale as a function of roughness elements morphology, ii) the spatial distribution of the height of boundary canopy layer at neighbourhood scale to apply proper wind profile laws, iii) the horizontal and vertical distribution of incident wind speed along buildings' facades to determine air flow rate inside building (considering only the natural wind-driven effect). The GIS place-based methodology is applied at building and bock of building scale to a case study in Turin and results are compared with the one of validated parametric tools (*Cpcalc+)*. From the analysis of the main limits of this methodology, concerning the impossibility of adjusting the wind speed inside urban canyons, derives the second step of investigation regarding the evaluation of wind paths and momentum inside urban street canyons where turbulent flows occur due to the presence of roughness elements (buildings).

A lack of investigation in this research field regards the evaluation of urban airflows pattern in non-isothermal conditions. The proposed methodology is applied at urban level to several zones in the city of Turin, after having identified classes of the urban canyons as representative of the whole city, considering two important parameters: the aspect ratio and the canyon axis orientation. Seasonal hourly variations of the local climatic conditions are assessed to include all the effective hourly variations during a whole climatic year. The results of these analyses carried out in GIS constitute the boundary conditions provided to the research group of the DIMEAS department which is responsible for the 2D CFD simulations that are processed. The goal of CFD analysis is to acquire velocity vector fields in the dominium, considering the combined effect of cross wind-driven and thermal buoyancy in different local climatic conditions, and to evaluate how vortical structures are affected by the urban geometry. The objective is to adjust the reference hourly wind speed obtained from local weather station at specific points in the canyon positioned near the windward and leeward facades of buildings at interesting heights above the ground. Results from CFD simulations allow to describe the boundary conditions of the air flow model at urban scale that implemented in the third step of this research.

This part of the work concerns the definition and application of an air flow lumped parameters model that is designed to consider the combined effect of cross natural ventilation, wind-driven and buoyancy on air flow rate at building level. Initially a single-zone model is analysed, considering only the effect of wind-driven cross-ventilation; levels of complexity are gradually inserted into the model, moving to multidimensional models: a two-zones air flow model, including the buoyancy effect and then the three-zones air flow model. The last model represents a good compromise for the description of the physical phenomena, the number of input variables, the detail of the characteristics of the building, whose schematic description is simple enough to apply the model's balance equations to all the buildings in an urban area. The building is schematized in a finite number of interconnected zones, represented by nodes and links, which describe the displacement of the air flow in space. Nodes and links are the elements of a network system whose relationships are describe in mathematical terms by the zero-dimensional multizone lumped parameter model based on the theory of oriented graphs. In a three-zones air flow model, ten links connect two heated zones representing the apartments identified below the local displacement height, one no-heated zone, representing the building shaft, and four external nodes, representing the outdoor environmental conditions around the building's facades. The calculated air flow rate is due only to infiltrations, depending on the characteristics of leakages, openings, and buildings; hourly pressure variations consider both dynamic and potential contributions, and the stack-effect, according to different climate conditions for each class of urban canyon. Based on the theory of mass and energy conservation, the non-linear equations system associated to the network, is solved by an iterative procedure using the Newton-Raphson numerical method. In particular, the *fsolve* function and the trust-region algorithm in *MatLab* software are chosen as a numerical method to find the zeros of the functions. Several trials have been done to define the proper tolerance criteria and initial values, that are fundamental to achieve model convergence. The resulting hourly air flow rate is then used to calculate the hourly air changes per hours (ach) in each of the three indoor zones and for the whole building. According to the hourly variation of local climate condition and the characteristics of the urban canyon in which a building is sited, this methodology allow to evaluate the hourly variation of the number of ach for each building in a case study zone at urban scale.

The results of the 3-zone air flow model constitute a new dataset that can be used as optimization and calibration parameters of the GIS-based engineering energy model for the hourly space heating consumption of residential building. It provides a wide and exhaustive case history describing the hourly variation of ach values for any building examined, that can replace the fixed ach values used in the energy model. Then, int the energy assessment of the energy performance of buildings, the contribution of each thermal gain and loss in the thermal energy balance can be evaluated separately, with a focus on ventilation loads. Relying on open-source software with high level of integrability provides for the possibility to implement the proposed methodology with existing plug-in for application at larger spatial scale with simulations that last just few hours. Among the possible applications of the presented place-based methodology, there is its integration in a digital platform to simulate urban energy scenarios, combining ventilation assessment. It provides for the possibility of mapping an entire city, helping policy makers, urban planners, public administration, and citizens in architectural and urban planning capable of exploiting the morphological peculiarities of the built environment to increase the energy efficiency of buildings and make urban space more liveable.