Thermodynamics for physical processes and energy environmental sustainability assessment at urban scale

Carla Balocco

Abstract: In the extreme environmental scenario, due to Global Warming (GW) and pollution, and in the necessary condition of energy saving and energy-environmental quality protection, this research proposes a method as a useful and effective tool for environmental, urban/architectural, energy and integrated Nature Based Solutions (NbS) design, applied at small and large scale, i.e. respectively, to the complex building-plant system and its surroundings (built, unbuilt and/or green system), and building, building stock, district and urban-built-up and/or green areas. The simple method proposed, links applied thermodynamics to physics-informed modelling of urban built-up and green areas, and allows the quantification of the energy sustainability of green ecosystem services and/or NbS in any urban area and their areal distribution in different built-up zones. The method is an effective operational tool for physical processes and energy environmental sustainability assessment at urban scale, focused on the reduction of anthropogenic impacts, urban heat islands (UHIs) mitigation, and climate change adaptation. Moreover, it provides comprehensive insights into the optimization of NBS planning based on thermodynamic energy footprint accounting, facilitating the improvement of mitigation of urban areas' vulnerability to GW.

Keywords: Climate-responsive urban areas, Energy sustainability, Greenery biophysical modeling, Thermodynamics, Urban heat island mitigation.

1. Physics and Thermodynamics Framework

In 2021, the EU adopted its first European Climate Law (Regulation EU 2021/1119). It set Europe's goals of becoming climate neutral by 2050, as well as a target of 55% less emissions by 2030, compared to 1990 (Regulation EU 2021/1119). The transition to clean energy and technologies is an incentive for environmental and energy sustainability, biodiversity protection, safeguard of the health of nature and people, but also economic growth and innovation, climate change mitigation, reduction of anthropogenic effects and GW. As required by the Climate Law in February 2024, an additional interim target of 90% less emissions by 2040, is envisaged.

Accordingly, scientific studies in the literature have widely demonstrated the beneficial implications of NbS on the Enhanced Weathering (EW), human health, Urban Heat Island (UHI), and other climate change related phenomena (Santamouris 2020; Cui et al. 2024; Mahmoud 2011; Yang et al. 2016; Chàfer et al. 2022; Choi and Yeom 2017).

International and National policies have recently planned reforestation interventions in urban and sub-urban areas. The International Union for Conservation of Nature (IUCN), highlights NbS as actions that protect, sustainably manage, and restore natural or modified ecosystems while addressing social challenges and providing benefits for both human well-being and biodiversity (IUCN 2020). Consequently, a method to quantify quality and effectiveness of integrated green solutions and NbS is necessary. This entails the possibility of pursuing the objectives of the European Green Deal and the Sustainable Transition by strongly supporting the decision-making policies of local authorities and public administrations.

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The physical-real knowledge of phenomena and the characterization of the urban microclimate at hyperlocal scale (i.e. under the canopy layer where mass and energy exchanges interact in transient conditions with fluid dynamics and variable and impulsive external/internal forcing) is possible by means of applied Thermodynamics (Balocco et al. 2025; Cureau et al. 2024; Piselli et al. 2022).

This allows to physically treat the huge amount of environmental data, and to define sustainable energy planning strategies at the urban scale and/or of the single building, block or district.

The identification of the most suitable NBS typologies, their optimal locations and implementation are identified by the proposed methodological approach application. It is based on applied physical informed modelling at small and large urban scale. It is a systemic thermodynamics method based on environmental energy physics that allows the quantification of the energy sustainability and effects of green ecosystem services and/or NbS integration in any urban area.

2. Materials and Methods

2.1. Thermodynamics for the physical process and energy environmental assessment

Thermodynamics has wide applications to various fields, ranging from engineering to natural living and inanimate systems, to social organization and economics, and to environmental energy management. It is fundamental for environmental data processing and energy environmental sustainability quantification at urban scale.

There are many ad hoc statements of optimality (min, max) and goal-seeking (optimal) that have been used in physical science. They continue to be used because they are effective in predictive, quantitative and parametric analysis. Sometimes these applications themselves lead to misunderstandings. They are mutually exclusive, e.g.: entropy generation minimization and the pursuit of greater efficiency are used commonly in biology and engineering (Bejan 2000; G., Balocco and Grazzini 1997; C., Balocco and Grazzini 2000); entropy generation maximization, not minimization, is being invoked in geophysics (Paltridge 1975); maximization of 'fitness' and 'adaptability' (robustness, resilience) are used in biology (Weibel and Hoppeler 2005); minimization of flow resistance is invoked in river mechanics, physiology and engineering; maximization of flow resistance is used regularly in physiology and engineering (Bejan 2007; Bejan and Merkx 2007); minimization of travel time is used in urban traffic (Balocco and Colaianni 2018); minimization of effort and cost is the core idea of social dynamics; maximization of profit and utility is used in economics; maximization of territory is used for rationalizing the spreading of living species, deltas in the desert or empires; uniform distribution of maximal stresses (irreversibility and heat and mass transfer balances) is used as an 'axiom' in rationalizing the design of animal bones and botanical trees; maximization of growth rate of flow disturbances (deformations) is invoked in the study of hydrodynamic instability and credited as the 'origin' of turbulence (Ciacci et al. 2023; D'Amato and Korhonen 2021).

Moreover, literature studies have highlighted that the energy saving obtained by the reduced thermal loads of the HVAC systems, due to the presence of green systems, must be compared with the costs of energy saved with green systems installation and maintenance (Balocco and Leoncini 2023). Furthermore, recent studies have shown that any intervention choice based on general green-washing, fails to produce significant energy consumption (Schwaab et al. 2021).

The existing literature lacks simple tools that can support decision-makers in adopting effective programming of interventions (Schwaab et al. 2021; Gratani et al. 2018; E., Costa-Filho et al. 2021).

Heat and mass transfer, and energy and/or entropy balance of any system and/or organism have important ecological consequences that are necessary to understanding responses and possibility of adaptation to climate change.

In this framework, thermodynamics is the effective tool to identify sustainable environmental (urban and greenery) planning strategies.

Thermodynamics allows the comprehension of physical processes of complex systems, starting from the knowledge of the microclimate at hyperlocal scale, and solving data granularity. Both at large and small scales, it is not possible to neglect the interactions between fluid dynamics and heat and mass transfer. This allows to represent and quantify the real physical complexity of any system (building, city, greenery) and its connected sub-systems.

2.2. Urban built-up and green areas as thermodynamic systems

If the concept of balancing exchange of energy, mass and resources between systems/organisms and their environment is simple, their implementation, referring to all the interacting physical processes, is much less so. Our method starts from the consideration that all natural living and structured-built systems – the latter as a manifestation of the anthropogenic burden on the environment – continue to respond to climate change, which is difficultly predictable. Considering thermodynamic processes, systems can shift their distributions and energy flows in opposite directions than expected. This suggested us to apply physical metrics and implement thermodynamics with multi-physics approaches and multi-domain analyses application.

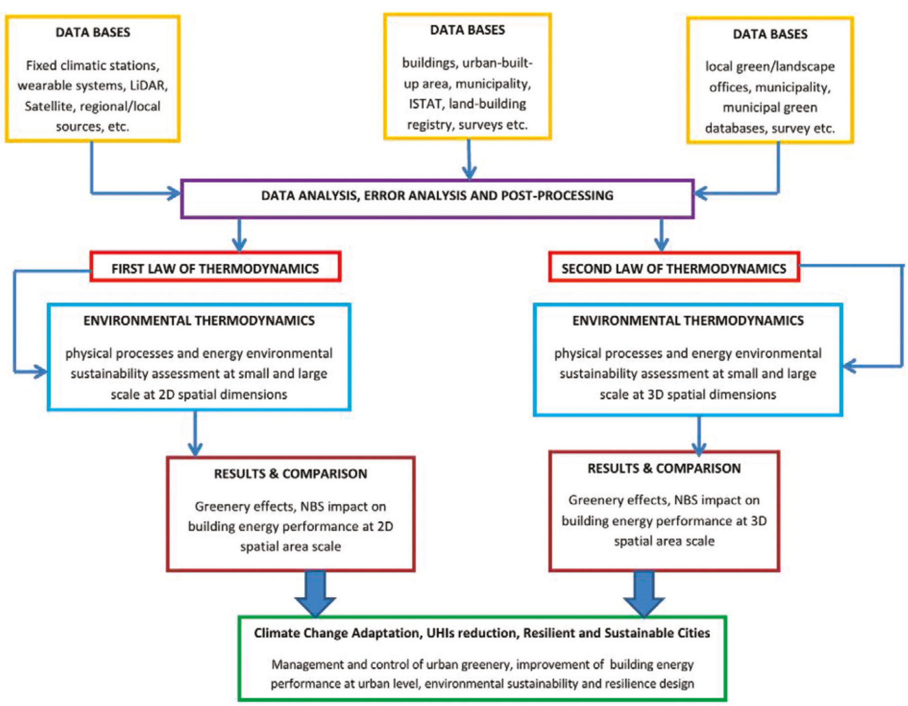

Fig. 1 – The flow chart on the method fundamental process.

The obtained differences, dynamics flows and changes constitute the fundamentals for thermal stress models, predictive models and energy-environmental sustainability quantification. The method is quick, simple and easily applicable and based on the following interconnected phases: Identification of the open thermodynamic system and its different and connected sub-systems; Definition of the physical boundary of the study; Energy balance based on the First Law (or Second Law) of Thermodynamics; Boundary conditions identification; Heat and mass transfer evaluation; Evapotranspiration and/or condensation (phase changes) calculation; Turbulence and fluid flows modelling; Soil heat transfer modelling; Governing equations and boundaries setting; Steady-state analysis to determine the initial conditions of balances for transient analyses; Iterative procedures implementation; Results post-processing; Data error analysis; Results analysis.

Figure 1 shows the flow-chart i.e. the fundamental structure of the method.

Given the complexity of natural systems connected and interacting with ur-ban-built-up ones, but in particular, the different data base interfacing, data driven and big-data available today, and all the necessary information sometimes derived from literature evidences, the method's implementation requires simplifications that however guarantee validity, meaning and physical compliance. It is easily implementable and usable by public administrations, not requiring trained and specialized personnel.

3. Some Fundamental Applications: Results And Discussion

In this section important examples of the method's application, recently published, are shown and discussed. Results, mainly indications, comparisons and discussion in the perspective of Physics and Thermodynamics analysis and implementation are provided. Specifically, the first example is the method's application at small scale (i.e. single building, groups of buildings, block, neighborhood), the second and third examples are the method's application at large scale (urban area, metropolitan area, municipality).

The first example is a small scale method's application (Balocco and Leoncini 2023) based on energy, environmental and economic impact evaluation for different regeneration proposals, combining a green system integration. The case study is the Don Milani primary school in San Lorenzo in Greve expansion zone of the metropolitan area of Florence. This study allows to extend the validity of the method to similar cases and conditions and to provide a basic tool to Municipalities and Public Administrations as basic knowledge for future projects oriented towards the energy transition, and specific tailored training. The method is composed of two interconnected phases.

The first phase concerns the energy analysis of the existing state and critical issues identification: three-dimensional modelling of the school building; boundary conditions definition (e.g. climate data, built environment and surrounding greenery data); thermo-physical features based on current legislation and the census of the National Institute of Statistics (ISTAT); model validation.

The second phase concerns the identification of green energy solutions, NbS integrations, plant systems revamping (air conditioning and lighting) and improvement of the thermo-physical and energy performance of the building; multi-scenario analysis; results analysis and comparison; energy costs and environmental impact analysis; comparisons between the existing state and the proposed energy efficiency scenarios; potential and effects of NbS solutions in relation to the green system.

Interventions with low interference on regular school activities are proposed, taking into account the environmental and social costs of the construction site, also due to the movement of students and school staff. Building refurbishment: strong insulation of all the external walls (reduced thermal transmittance from 0.75 to 0.20 W/m^2K); existing windows replacement with new thermal break ones (thermal transmittance reduced from 3.60 to 1.30 W/m^2K); attic insulation (reduced average thermal transmittance from 1.45 to 0.20 W/m^2K).

The result obtained is the new Energy Class D, corresponding to 120 kWh/m^2 year. The reduction in the use of primary resources is 25% equal to the reduction in equivalent CO2 emissions. At the same time the internal environment improvement, due to more homogeneous thermal field, average radiant temperature close to the set-point temperature, temperature gradients attenuation, especially near the windows, are the scope obtained. Using the PMV and PPD indices (respectively, Predicted Mean Vote and Predictable Percentage of Dissatisfied, UNI EN ISO 7730-2006), the operating temperature inside the classroom more unfavorably exposed to solar radiation is calculated. Therefore, during winter conditions, a student placed in the center of the classroom in its current state, i.e. without insulation interventions, perceives a temperature of 17.6 °C, while in the energy regeneration conditions, she/he would perceive 19.7 °C.

The cost for the solutions implementation, referring to the BAU (Building As Usual) approach and without benefiting from any form of incentive, is estimated to be higher than €1M. The unit amounts applied to the calculation basis are €170/m^2 for external insulation, €600/m^2 for window frames replacement and €120/m^2 for attic insulation.

This set of interventions cannot have recovery margins beyond the expected useful life, estimated at 20 years pursuant to EU Delegated Regulation 244/2012.

The building is more than 50 years old, during which only maintenance work has been carried out to allow its regular use. Multiple scenarios are designed with effective solutions (thermal system), combined with the integration of sustainable strategies (PV system) and greenery (NbS).

The following scenarios are then implemented and simulated. The reference scenario: maintenance of the current gas-fired mono-functional thermal power plant, with heat generator replacement (condensing boiler, 480 kW, efficiency of 95% at nominal power and 105% at reduced load). A modulating proportional regulation is implemented, with an external climate probe with a compensation curve.

The plant retrofitting strategies (named alternative scenario, AS) are: AS1(hybrid system, consisting of a 480 kW gas-fired condensing boiler and a 160 kW air-to-water aerothermal electric heat pump); AS2: "all electric" (air-water heat pump sized to cover the total thermal load (480 kW) with an average seasonal COP of 3); AS3: equal to 2), but with a PV system on the roof (monocrystalline silicon modules, 90 kWp peak power); AS4 includes all choices of 3) combined with the above PV system on the roof; AS5 green roof solution (integration of greenery as an extensive covering).

In particular, a simplified model for green coverage simulation is used, assuming the horizontal homogeneity of the slab and heat and mass flows mainly vertical, adopting one-dimensional equations to describe the thermal behavior of each layer at semi-steady state conditions.

The extensive solution is modelled taking into account a traditional structure (i.e. total thickness 16 cm, substrate thickness 12 cm, flow coefficient < 0.36, volume of water available for plants ≥ 55 l/m^2, usability ratio ≥ 0.84%, efficiency ratio ≥ 0.56, maximum water retained ≥ 65 l/m^2, system thermal resistance ≥ 0.47 $(m^2K)/W$, substrate permeability ≥ 15 mm/min, substrate cation exchange capacity ≥ 15meq/100 g.

For all the proposals the Building Automation and Control System (BACS) is implemented: it provides a centralized regulation, operating on the flow temperature of the heat transfer fluid, and a peripheral regulation for each terminal equipment.

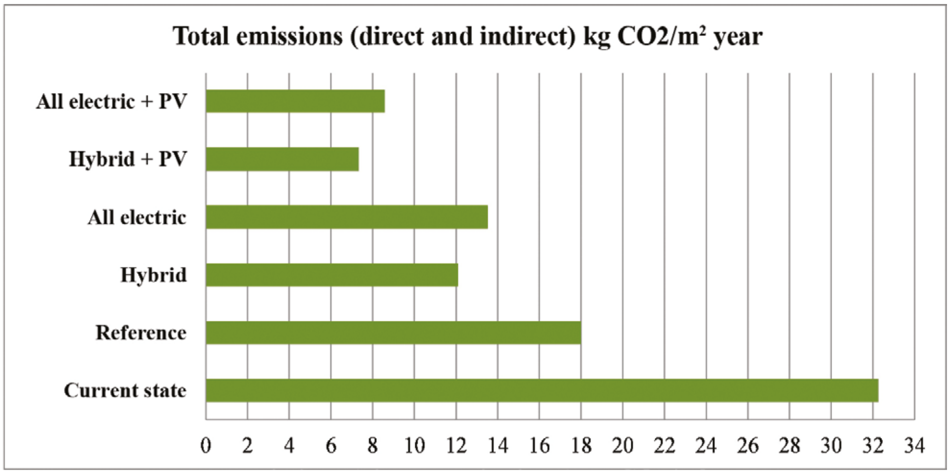

Fig. 2 – Energy efficiency of the proposed solutions.

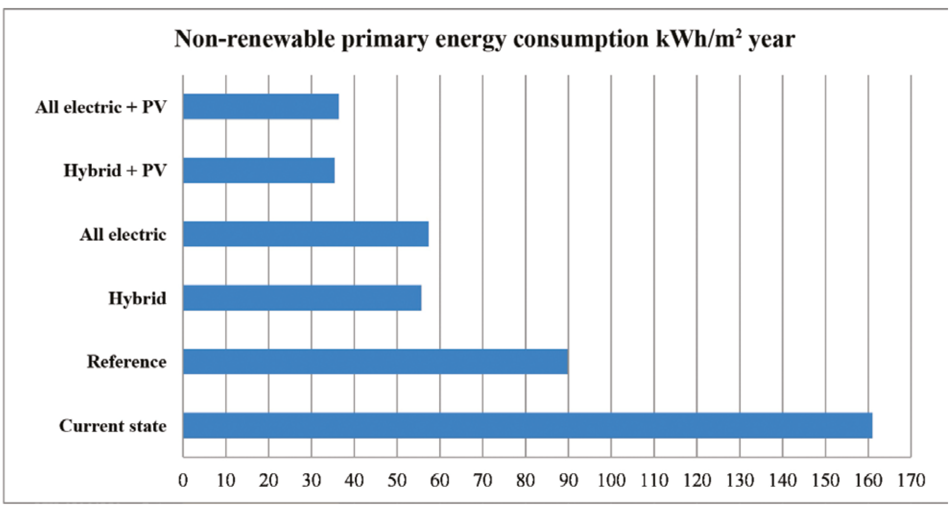

Fig. 3 – Environmental impact of the proposed solutions.

Figure 2 and Figure 3 show, respectively, results for the interventions on the energy efficiency and environmental impact.

The Life Cycle Cost (LCC) analysis allows choosing between a hybrid system and an "all-electric" system, and between drawing from the grid or self-producing the necessary electricity. The resulting Discounted Cash Flow-DCF value indicates that the hybrid system solution powered by PV is better, because it represents the best compromise between investment costs and operating costs (Figure 4). On the other hand, this solution oriented to the maximum use of renewable sources, provides a great energy autonomy to the school.

The extensive green roof is not considered for the LCC analysis and in combination with the proposed solutions, because it is not so significant compared to the advanced insulation alone. It is well-known that green roofs and cool-roof solutions allow to significantly reduce the surface temperature values but for very large surfaces.

In particular, while cool-roofs are more effective in terms of UHI mitigation, green roofs, especially the extensive type, can have an impact on the reduction of the building annual primary energy requirements when the coverage is appreciable compared to the total dispersing envelope surface. From a thermal point of view, greenery integration shows its effects on the external forces mainly for solar gains reduction therefore as an important regenerative and resilience solution.

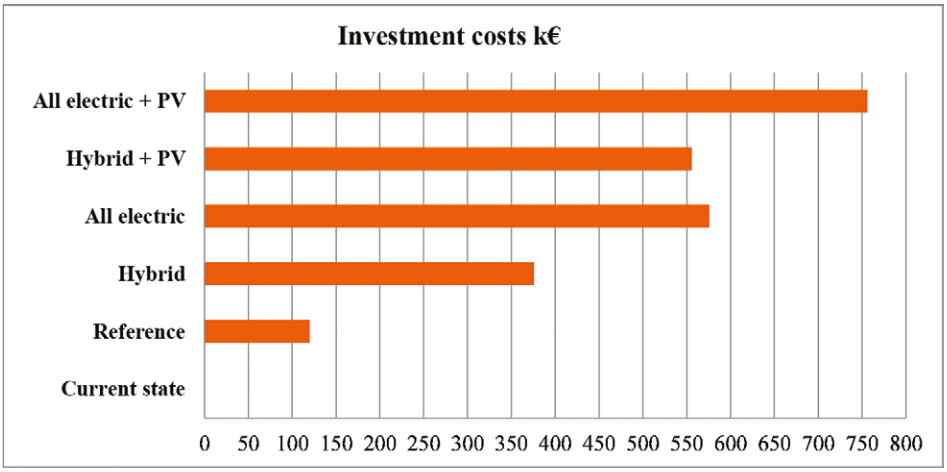

Fig. 4 – Investment costs for the proposed solutions.

A reduction in solar gains of 0.7 kWh/m^{2}year (assuming an average solar absorption factor of 0.3) capable of containing the overheating of the first floor, together with a 5% reduction in annual CO2 emissions, due to the green roof alone, compared to the current state, has been reached.

The extensive green roof has an appreciable impact on the increase in mass and thermal inertia of the floor. Therefore, the integration of the proposed efficiency solutions with a green system, in the surrounding area of the school, and NbS, has produced a UHI significant reduction with highly positive effects on biodiversity conservation, life quality and people's health.

Trees with significant leaf density (e.g. tall beech trees), in reference to literature on the subject, have produced a CO2 absorption of 10-20 kg/year, 17.50-9.5 kg/year of O3, 8.89-16.12 kg/year of NO2, within a growth cycle that reaches its maximum in a time interval between 20 and 40 years. Literature references [23-25] indicate that a developed lime tree is able to absorb 140 kg (CO2)/year, as well as an elm.

The neighbourhood of Don Milani school is located in the South-West of Florence, near agricultural areas, with a sparsely populated urban fabric and large unbuilt spaces. The school has an empty area treated as a lawn of 3500 m^2 (beyond the entrances). In this area, 70 tall trees with a dense mesh have been proposed to be planted, guaranteeing a total of 9800 kg (CO2)/year absorbed. Currently the school (building-plant system) generates direct and indirect emissions of 115000 kg (CO2)/year.

The systemic integration of vegetation with NbS has produced a buffer effect on external forcings, and damping effect on climate change. All the proposed energy regeneration scenarios involve a drastic reduction in emissions, reaching up to 25000 kg (CO2)/year for the hybrid system scenario combined with photovoltaics. Therefore, to create a school with zero impact, less than one hectare of intensive tree cultivation would be sufficient. All this, was suggested to be planned considering the different times needed for greenery and building-system.

The second example concerns large scale method's application, with a top-down and bottom-up implementing processes (Balocco et al. 2025). The implementation needs evaluation and processing of data and/or digital information on the studied urban area: e.g., standard meteorological data/files or real measurements acquired from the local meteorological stations closest to the investigated areas, the buildings characteristics as the surface area in plan, height, volume, prevalent intended use, as well as green areas for specific plant species. The next phase was the georeferencing and modelling with Geographical Information Systems (GIS).

Depending on the useful, available, and traceable information, two different but equivalent modelling processes by applying environmental thermodynamics are implemented: the "top-down" considers the urban context as a 2D footprint of greenery and buildings, or at a two-dimensional areal scale. It is of immediate application and is applied to evaluate the enthalpy variations on a large scale in the summer period, even when the information on buildings is not complete or scarce; the "bottom-up" considers the urban context and the volumetric morphology with details on the buildings, i.e., it is at a 3D volumetric areal scale. It requires a more in-depth analysis at the district level to evaluate the variation of air enthalpy connected to the air exchange volumes for the summer cooling of each building. In both approaches, the first fundamental energy balance is applied to the green cover under the hypothesis of considering leaf surfaces as continuous, uniform, and homogeneous-isotropic.

The balance involves only the 'urban forest' type as a green surface system, as it is the only configuration capable of having a real impact on the energy issue in the urban context, thus excluding low shrubs, hedges, and grass. The balance therefore allows for the determination of the surface temperature of the greenery in a simplified way, determining how a leaf surface exchanges thermal energy (i.e., latent heat and sensible heat) with the environment, disregarding the morphology, the set of physiological and water processes of the plant itself and interaction of its leaves with the soil and atmosphere. In particular, the evapotranspiration processes of the leaves surface is evaluated referring to literature evidences (Costa-Filho et al. 2021; Balocco and Petrone 2018).

The second resulting energy balance is applied to the building–plant system, to assess the HVAC–plant energy consumption due to the thermo-hygrometric treatment of the air, and the consequent environmental impact linked to the external air enthalpy variation due to the green system. To study the thermo-hygrometric effects of any green system in different built urban areas, the set of governing equations expressing the above two balances at semi-steady-state conditions at periodic regime, is implemented, applying it to the green surface and, in a subsequent phase, to the building–plant system.

All the basic governing equations are solved by a finite element code using an iterative procedure.

The studied area is a portion of the city of Florence, identified and characterized using the database of the Municipal Environmental Energy Plan (PEAC), and QGIS software (version 3.40.1-Bratislava) interfacing with data from the GEOscope Observatory (Regione Toscana n.d.) Tuscany Region. Results obtained are the following:

- the leaf surface temperature tends to be always lower than the external air temperature, except in some particular conditions, i.e., when the relative air humidity is very high (RHa > 0.8);
- without solar radiation, the whole leaf coverage reaches the equilibrium condition with the surrounding environment;
- an increase in wind speed leads to an increase in thermal exchange between the leaf surface and the air, reducing the achievable temperature difference (e.g., with Ta equal to 28 °C and all the other parameters constant, if wind speed varies from 1 to 10 m/s, Tl changes from 27.4 °C to 27.7 °C);
- if the wind speed is zero, one term of the balance becomes meaningless;
- the GHI (Global Horizontal Irradiation, expressed in W/m^2) data must be used because it is not possible to accurately determine the average solar radiation striking leaves oriented in different directions; accordingly, for greenery analysis through the GEOscope Observatory platform (Regione Toscana n.d), the leaf surface is considered as a ground area, i.e., green coverage.

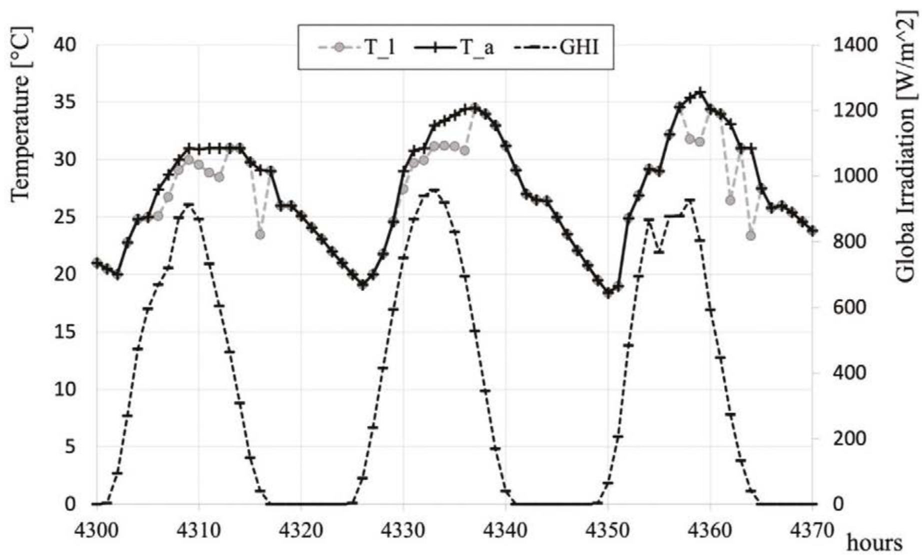

Fig. 5 – Trend plot of air temperature, global solar irradiation, and the leaf surface temperature for the three summer days (29–30 June and 1 July).

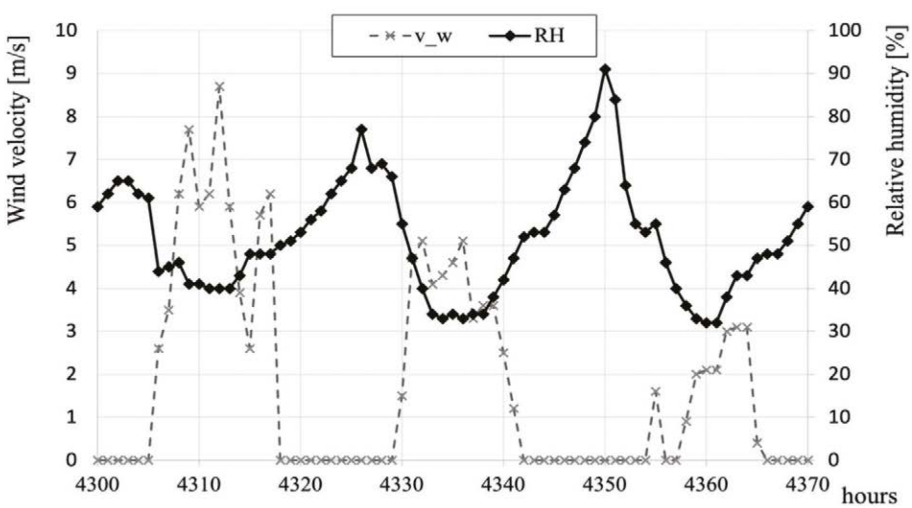

Fig. 6 – Trend plot of Plot of wind velocity and air relative humidity for the three summer days (29–30 June and 1 July).

It obtained the basic trends of temperatures of the external air and leaf surface, air relative humidity, global horizontal solar radiation, and wind velocity that are shown in Figures 5 and 6 for representative summer days (29–30 June and 1 July). The method, by means of the top-down and bottom-up processes, is applied to two important areas of the city of Florence. The first area is a neighbourhood structured around the tree-lined park of Vittoria Square (Figure 7), and the second area is the avenue, also tree-lined, extending from Libertà Square to Beccaria Square (Figure 8). In Vittoria Square, it is assumed that the treetops completely cover the space below the park (as they did originally and as they will most likely be in the years to come, when the new trees have fully taken root in the ground, developed in height and volume of root and leaf systems; in essence, they will have achieved a "mature age") and that it is config-

Fig. 7 – Map of buildings and greenery; the blocks around the park of Vittoria Square (background: city map, pink: urban built-area, violet: buildings involved by the calculation; green: trees position).

ured as a “concentrated context” in which to implement the simplified approach that starts from the buildings overlooking the square itself.

In particular, the existing buildings are identified, georeferenced and, basing on their intended use, the following mean air changes for indoor air quality and correct ventilation conditions are assigned (EN 16798-1:2019; Decree of the President of the Italian Republic 16 April 2013, n. 74): 1 volume/h for residential; 3 volumes/h for offices and accommodation facilities; 4 volumes/h for schools, considering the priority of class-rooms; 6 volumes/h for commercial activities.

Starting from the evaluation of the modified external air temperature of the green areas due to the evapotranspiration of the leaves’ coverage, governing equations of all the energy balances are implemented with an hourly calculation.

The top-down approach is applied taking into account overall surface covered by the canopy trees is equal to 5628 m^2 for Vittoria Square and 34560 m^2 for the second case study. Therefore a significant reduction in thermal power is obtained, which, when hourly integrated during the summer season, provides 415 MWh and 2675 MWh, respectively. When applying the bottom-up approach, the main characteristics of the buildings, i.e., ground area, height, volume, and intended use, and effective results for greenery systems are obtained (Barradas 1991; C., Bartesaghi Koc et al. 2018; R., Baraldi et al. 2019).

With a view to the energy transition, in accordance with current regulations for air quality, hygiene and health in confined environments, as foreseen after the COVID-19 pandemic by WHO, RHEVA, ASHRAE, AICARR, and ISS, it is assumed that the buildings are equipped with air conditioning systems of the type Variable Air Volume-Controlled Mechanical Ventilation (VAV-CMV) without the air recirculation condition.

Therefore, the reduction in energy consumption of the plant for the existing different types of buildings is calculated. The air enthalpy variation, in the absence and in presence of greenery, is calculated, and the resulting energy saving obtainable for each kilogram per second of air treated by the HVAC system is quantified.

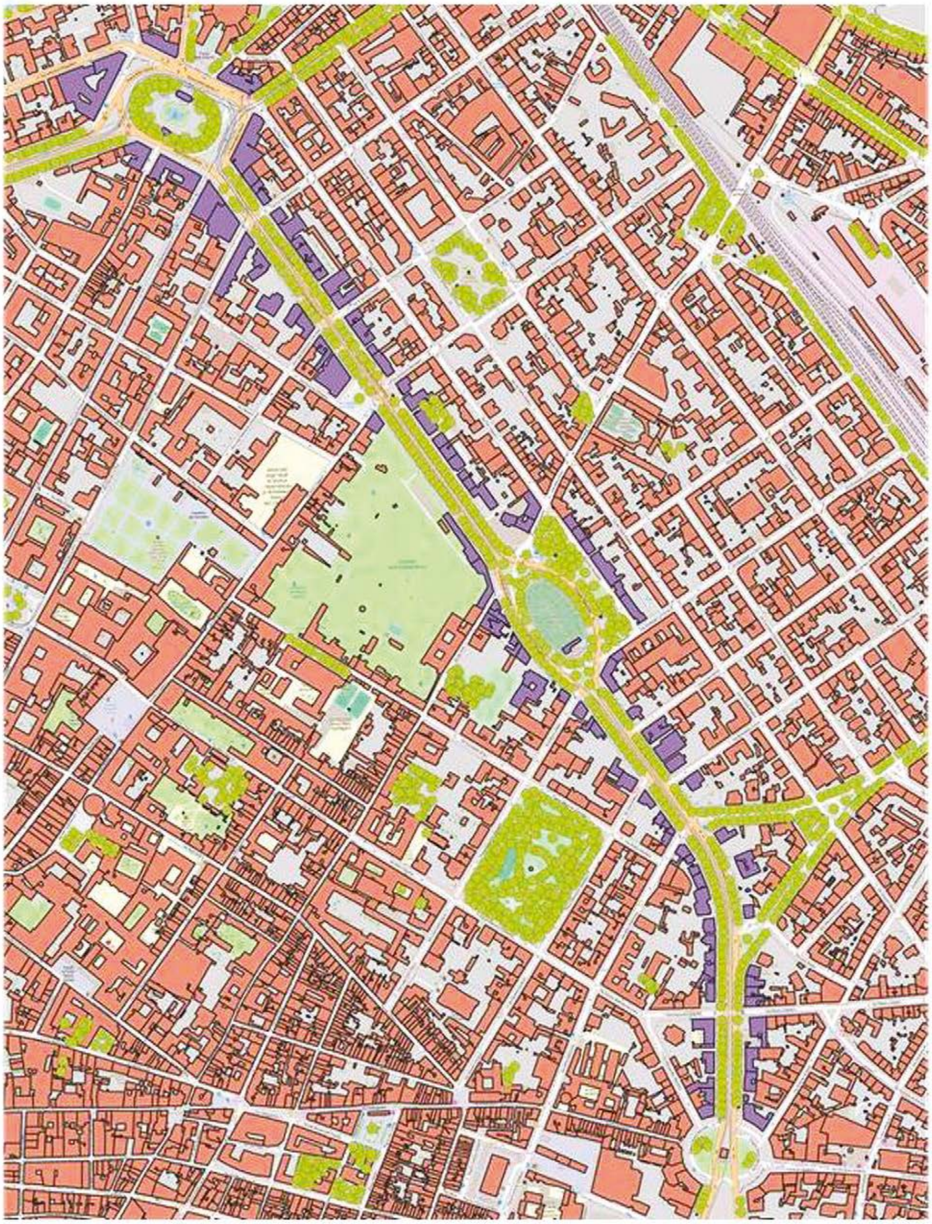

Fig. 8 – Map for avenue, greenery, and building blocks from Libertà Square to Beccaria Square (background: city map, pink: urban built-area, violet: buildings involved by the calculation; green: trees position).

Using the climatic data of Florence, the external air temperature reduction, connected to the presence of the leaves' coverage, leads to an external air enthalpy reduction of 1965 kJ/kg. This last value is obtained considering the plant system operation for all the summer daytime hours in which the external air temperature is higher than 26 °C. This temperature value is set by the Italian Decree Law (2013) as the standard average set-point. For the area of Vittoria Square, 35 building blocks with different intended uses are identified, which affect the amount of air-change volumes.

They are mainly residential (26%) and include some commercial businesses (10%), accommodation facilities and offices (17%), schools and institutes (43%), and for a single case, a small private hospital (4%). In this case, the energy consumption reduction is 504 MWh. For the avenues from Libertà Square to Beccaria Square, 114 buildings are selected.

In this area, the percentage of air-change volumes for residential is 12% and for professional offices and accommodation facilities is 41%, while commercial activities account for 17% and schools/institutes account for 30%. It is important to note that for the whole summer season, the obtained energy consumption reduction is 2350 MWh.

The two methods are equivalent and consistent: small differences are completely within the expected accuracy range for the simplified biophysical and thermodynamic modelling used. For the area of Vittoria Square, the difference between the energy saved (MWh) is 18%, and for the avenues from Libertà Square to Beccaria Square is 12%.

Findings show that urban green spaces play a crucial role in the conservation of bio-diversity, favouring ecological balance and promoting a more sustainable urban environment, in line with most of the literature on the subject (Xian et al. 2024; Zhu et al. 2023; Callaghan et al. 2021).

4. Integrating Green Spaces and NbS: Reflections, Comparisons, and Perspectives

The integrated methodological approach, of simple and easy implementation, useful for quantifying energy-environmental sustainability of urban areas was applied to different urban built-up areas with and without greenery. It is based on applied thermodynamics and physics-informed modelling, connected to high-resolution climate at urban scale, identification and characterization of plants for specific species and vegetation, and spatial georeferencing techniques, for energy exchange evaluation within the urban context. Its real applications have demonstrated the physical effectiveness of the extension of greenery, Nbs integration and any urban regeneration intervention to counteract heat islands and facilitate climate adaptation and resilience.

Energy balances of the studied system can be divided into multiple balances connected to the component sub-systems, some of which can be implemented without advanced functionalities. Therefore, small-scale and small-sized models can handle the simplest subroutines, allowing the application of large-scale and large-sized models on more complex system dynamics.

The effectiveness of the proposed method lies in the new paradigm for "collaboration", the thermodynamic interfaces between small-scale and large-sized models. This "collaborative" and dynamic adaptive paradigm allows the development of sustainable grid-connected environmental energy choices integrated with fine-tuning choices, as it proceeds and develops over time also in relation to different futures scenarios.

In general, the results (especially at small scale) show that the larger and more extensive the vegetation in densely built-up urban areas, the more effective and efficient the possibilities of reducing the load by lowering the enthalpy of the external air. As a matter of fact, it is possible: heat recovery of the exhaust air, adiabatic pre-cooling of the exhaust air; post-heating of the dehumidified air by means of external air.

The adoption of these measures reduces summer consumption for external air thermo-hygrometric treatments, while maintaining the related consumption for ventilation, absolute humidity and pumping control.

Findings (especially at large scale), demonstrate that urban green spaces play a fundamental role in regulating temperature, counteracting the UHI and contributing to citizens wellbeing as also reported in (Bartesaghi Koc et al. 2018; Baraldi et al. 2019; Xian et al. 2024; Zhu et al. 2023; Callaghan et al. 2021). Indeed, results highlight that greenery and NbS integration would address a series of engineering and energy challenges.

Refurbishment and retrofitting interventions (for existing buildings to meet the current nZEB energy requirements) with low environmental impact would be effective in achieving urban resilience and implementing environmental and energy sustainability practices. NbS integration in urban areas would be beneficial to this goal, only when wisely designed, based on thermodynamics applications and assessment evidence: this allows the quantification of external air cooling and different surfaces through shading and evapotranspiration processes.

In particular, the proposed method at the two scales of analysis and implementation (bottom-up and top-down) was also used as an effective tool for economic planning.

It provides quantitative fundamentals to find out the necessary compromise between the construction of ecological systems and benefits in terms of energy saving, environmental sustainability and associated economic feasibility. Moreover, the energy balances do not impose specific constraints on boundary conditions, making the proposed approach highly adaptable and applicable to various urban settings, by means of real physics and thermodynamics. All the real examples explained and discussed above, have shown the most significant reductions in air enthalpy with a substantial increase in green surfaces, vegetation/greenery that work as a natural thermal regulator, effectively mitigating the heat fluxes, amplified within cities due to global warming and significant mutual radiative heat exchanges.

The operability of the proposed strategy is all the more effective, when more closely connected to a truly sustainable smart city, from a systemic point of view for energy transition and the green economy. This latter can be achieved through the integration of ecosystem services, widespread and large-scale NbS, and advanced technologies. It must be noted, that it is necessary to take into account climate variations and energy environmental dynamics/changes over years, in parallel with the time necessary for the complete development/growth of plants.

Thermodynamics-informed method allows a simple implementation for the identification of the most important and suitable interventions for building-plant system energy efficiency and regeneration, climate change adaptation, and UHI mitigation. It is not a deterministic tool, but it allows the construction of an homogeneous scale, of physical significance, for the identification of the most critical and vulnerable areas on which to intervene as a priority. Moreover, it provides comprehensive insights into the optimization of NBS planning based on thermodynamic energy footprint accounting, facilitating the improvement of mitigation of urban areas' vulnerability to GW.

However, the successful implementation of such measures relies on strong institutional/municipal support. Municipalities must actively promote and support urban greening initiatives, recognizing the need for a paradigm shift in public perception of urban spaces and their role in well-being and life quality. This transition requires addressing critical issues such as mobility planning and long-term maintenance, ensuring that green ecosystem services become a fundamental element of sustainable urban development.

Findings deduced from experiences of application in the territorial reality, but also in the administrative, political-social one provide a comprehensive perspective that can provide useful support to architects in improving the urban thermal environment. The problem-solving process implemented with the proposed method, can be extended to built-up environment optimization professionals providing insights for climate-adaptive urban design.

Future developments of the proposed method, which we are currently experimenting with within a LIFE project applied to the city of Florence (LIFE23-CCA-IT-LIFE ESCAPOS "Environmental energy for Strategic CApillary urban POlicieS", https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE23-CCA-IT-LIFE-ESCAPOS-101157553/environment-energy-for-strategic-capillary-urban-policies) concerns the application of thermodynamics for the study of complexity of the physical processes linked to NbS integration, by means of machine-learning techniques.

References

Balocco, Carla, e Giuseppe Grazzini. 1997. "A Statistical Method to Evaluate Urban Energy Needs." *International Journal of Energy Research* 21, 14: 1321-30. https://doi.org/10.1002/(SICI)1099-114X(199711)21:14%3C1321::AID-ER337%3E3.0.CO;2-Q.

Balocco, Carla, e Giuseppe Grazzini. 2000. "Thermodynamic Parameters for Energy Sustainability of Urban Areas." *Solar Energy* 69, 4: 351-56. https://doi.org/10.1016/S0038-092X(00)00069-4.

Balocco, Carla, e Giuseppe Petrone. 2018. "Heat and Moisture Transfer Investigation of Surface Building Materials." *Mathematical Modelling of Engineering Problems* 5, 3: 146-52. https://doi.org/10.18280/mmep.050303.

Balocco, Carla, e Alessandro Colaianni. 2018. "Assessment of Energy Sustainable Operations on a Historical Building. The Dante Alighieri High School in Florence." *Sustainability* 10, 6: 2054. https://doi.org/10.3390/su10062054.

Balocco, Carla, e Lorenzo Leoncini. 2023. "Il Sistema Verde: Soluzioni per la Tutela dell'Ambiente e la Riduzione delle Emissioni di CO2. L'esempio di una Scuola Esistente." *L'Italia Forestale e Montana* 78, 3. https://doi.org/10.36253/ifm-1102.

Balocco, Carla, Giacomo Pierucci, e Cristina Piselli. 2025. "Green System Effects on Energy Environmental Sustainability of Urban Built-Up Areas." *Energies* 18, 7: 1640. https://doi.org/10.3390/en18071640.

Baraldi, Rita, Luisa Neri, Federica Costa, Osvaldo Facini, Francesca Rapparini, e Giulia Carriero. 2019. "Ecophysiological and Micromorphological Characterization of Green Roof Vegetation for Urban Mitigation." *Urban Forestry & Urban Greening* 37: 24-32. https://doi.org/10.1016/j.ufug.2018.03.002.

Barradas, Victor L. 1991. "Air Temperature and Humidity and Human Comfort Index of Some City Parks of Mexico City." *International Journal of Biometeorology* 35, 1: 24-28. https://doi.org/10.1007/BF01040959.

Bartesaghi Koc, Carlos, Paul Osmond, e Alan Peters. 2018. "Evaluating the Cooling Effects of Green Infrastructure: A Systematic Review of Methods, Indicators and Data Sources." *Solar Energy* 166: 486-508. https://doi.org/10.1016/j.solener.2018.03.008.

Bejan, Adrian. 2000. *Shape and Structure: From Engineering to Nature*. Cambridge: Cambridge University Press.

Bejan, Adrian. 2007. "Constructal Theory of Pattern Formation." *Hydrology and Earth System Sciences* 11, 2: 753-68. https://doi.org/10.5194/hess-11-753-2007.

Bejan, Adrian, e Gilbert W. Merkx. 2007. *Constructal Theory of Social Dynamics*. New York: Springer US. https://doi.org/10.1007/978-0-387-47681-0.

Callaghan, A., G. McCombe, A. Harrold, et al. 2021. "The Impact of Green Spaces on Mental Health in Urban Settings: A Scoping Review." *Journal of Mental Health* 30, 2: 179-93. https://doi.org/10.1080/09638237.2020.1755027.

Chàfer, Marta, Chun Liang Tan, Wong Nyuk Hien, Anna Pisello, e Luisa F. Cabeza. 2022. "Mobile Measurements of Microclimatic Variables Through the Central Area of Singapore." *SSRN Electronic Journal*, ahead of print. https://doi.org/10.2139/ssrn.4065782.

Choi, Joon-Ho, e Dongwoo Yeom. 2017. "Study of Data-Driven Thermal Sensation Prediction Model as a Function of Local Body Skin Temperatures in a Built Environment." *Building and Environment* 121: 130-47. https://doi.org/10.1016/j.buildenv.2017.05.004.

Ciacci, Cecilia, Neri Banti, Vincenzo Di Naso, e Frida Bazzocchi. 2023. "Green Strategies for Improving Urban Microclimate and Air Quality: A Case Study of an Italian Industrial District and Facility." *Building and Environment* 244: 110762. https://doi.org/10.1016/j.buildenv.2023.110762.

Costa-Filho, Edson, José L. Chávez, Huihui Zhang, e Allan A. Andales. 2021. "An Optimized Surface Aerodynamic Temperature Approach to Estimate Maize Sensible Heat Flux and Evapotranspiration." *Agricultural and Forest Meteorology* 311: 108683. https://doi.org/10.1016/j.agrformet.2021.108683.

Cui, Yi, Mingqiang Yin, Xiang Cheng, Junqing Tang, e Bao-Jie He. 2024. "Towards Cool Cities and Communities: Preparing for an Increasingly Hot Future by the Development of Heat-Resilient Infrastructure and Urban Heat Management Plan." *Environmental Technology & Innovation* 34: 103568. https://doi.org/10.1016/j.eti.2024.103568.

Cureau, Roberta Jacoby, Carla Balocco, Ilaria Pigliautile, et al. 2024. "On Urban Microclimate Spatial-Temporal Dynamics: Evidence from the Integration of Fixed and Wearable Sensing and Mapping Techniques." *Environmental Research* 262: 119795. https://doi.org/10.1016/j.envres.2024.119795.

D'Amato, D., e J. Korhonen. 2021. "Integrating the Green Economy, Circular Economy and Bioeconomy in a Strategic Sustainability Framework." *Ecological Economics* 188: 107143. https://doi.org/10.1016/j.ecolecon.2021.107143.

EN 16798-1:2019. *Energy Performance of Buildings – Ventilation for Buildings – Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics (M1-6)*. Ljubljana: Slovenian Institute for Standardization, 2019.

European Parliament and Council of the European Union. 2021. *Regulation (EU) 2021/1119 of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ("European Climate Law")*. Official Journal of the European Union L 243, 9 July 2021: 1-17. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32021R1119 (2025-03-13).

Gratani, Loretta, Luciano Di Martino, Anna Rita Frattaroli, et al. 2018. "Carbon Sequestration Capability of *Fagus Sylvatica* Forests Developing in the Majella National Park (Central Apennines, Italy)." *Journal of Forestry Research* 29, 6: 1627-34. https://doi.org/10.1007/s11676-017-0575-4.

International Union for Conservation of Nature. 2020. *Global Standard for Nature-based Solutions: A User-Friendly Framework for the Verification, Design and Scaling Up of NbS*. First Edition. Gland, CH: IUCN.

Italian Decree Law. 2013. *Decree of the President of the Italian Republic 16 April 2013, n. 74. Regulation Defining the General Criteria for Operation, Control, Maintenance and Inspection of Thermal Systems for Winter and Summer Air Conditioning of Buildings and for the Preparation of Hot Water for Sanitary Purposes (13G00114)*. Roma: Presidency of the Italian Republic.

Mahmoud, Ayman Hassaan Ahmed. 2011. "Analysis of the Microclimatic and Human Comfort Conditions in an Urban Park in Hot and Arid Regions." *Building and Environment* 46, 12: 2641-56. https://doi.org/10.1016/j.buildenv.2011.06.025.

Paltridge, Garth William. 1975. "Global Dynamics and Climate – a System of Minimum Entropy Exchange." *Quarterly Journal of the Royal Meteorological Society* 101, 429: 475-84. https://doi.org/10.1002/qj.49710142906.

Piselli, Cristina, Carla Balocco, Ilaria Pigliautile, et al. 2022. "Microclimate Assessment at Real Experimental Conditions for Green Energy Urban Policy." *International Journal of Sustainable Development and Planning* 17, 5: 1381-87. https://doi.org/10.18280/ijsdp.170501.

Regione Toscana. s.d. "GEOscopio." https://www.regione.toscana.it/-/geoscopio (2025-03-13).

Santamouris, Matthaios. 2020. "Recent Progress on Urban Overheating and Heat Island Research. Integrated Assessment of the Energy, Environmental, Vulnerability and Health Impact. Synergies with the Global Climate Change." *Energy and Buildings* 207: 109482. https://doi.org/10.1016/j.enbuild.2019.109482.

Schwaab, Jonas, Ronny Meier, Gianluca Mussetti, Sonia Seneviratne, Christine Bürgi, e Edouard L. Davin. 2021. "The Role of Urban Trees in Reducing Land Surface Temperatures in European Cities." *Nature Communications* 12, 1: 6763. https://doi.org/10.1038/s41467-021-26768-w.

Weibel, Ewald R., e Hans Hoppeler. 2005. "Exercise-Induced Maximal Metabolic Rate Scales with Muscle Aerobic Capacity." *Journal of Experimental Biology* 208, 9: 1635-44. https://doi.org/10.1242/jeb.01548.

Xian, Zheng, Tomoki Nakaya, Kun Liu, et al. 2024. "The Effects of Neighbourhood Green Spaces on Mental Health of Disadvantaged Groups: A Systematic Review." *Humanities and Social Sciences Communications* 11, 1: 488. https://doi.org/10.1057/s41599-024-02970-1.

Yang, Li, Feng Qian, De-Xuan Song, e Ke-Jia Zheng. 2016. "Research on Urban Heat-Island Effect." *Procedia Engineering* 169: 11-18. https://doi.org/10.1016/j.proeng.2016.10.002.

Zhu, Wei, Jiejing Wang, e Bo Qin. 2023. "The Relationship between Urban Greenness and Mental Health: A National-Level Study of China." *Landscape and Urban Planning* 238: 104830. https://doi.org/10.1016/j.landurbplan.2023.104830.