sustainability

MDPI

Article

Climate Mitigation Strategies: The Use of Cool Pavements

Martina Giorio * and **Rossana Paparella**

Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Marzolo 9, 35131 Padova, Italy; rossana.paparella@unipd.it
* Correspondence: martina.giorio@unipd.it

Abstract: Recent statistical reports highlight an accelerating phenomenon of radical urbanization, and the forecasts estimate that within the next ten years, about 70% of the world's population will be located in urban areas, compared with 54% currently living there. This phenomenon will result in an increase in the constructed volume, with foreseeable adverse effects on the climate, the environment, and residents' health. The resulting growth of the emissions and the use of energy resources, combined with changes in the soil condition and absorption characteristics, leads to a focus on issues related to the sustainable development of cities. The effects of anthropogenic activity influence the materials' surface and air temperatures, contributing to the phenomenon of the increase of the average atmospheric temperatures near the earth's surface, with the consequent generation of the phenomenon of the urban heat islands (UHIs). This paper aims to examine, in a neighborhood context, the effects of mitigation strategies implemented through the application of cool materials on urban surfaces. Through simulations carried out in a case study, with the support of software such as ENVI-met and tools for Grasshopper such as Ladybug, and with the observation of data related to the evolution of the surface temperatures, the air temperatures, and other microclimatic parameters, the outcomes obtained with the use of cool pavements were analyzed. Finally, the comparison between the two scenarios, the current and the projected, allowed the evaluation of the overall efficiency of the proposed interventions.

Keywords: urban heat island; urban mitigation; climate mitigation; cool pavements; microclimatic analyses; regenerative interventions

Citation: Giorio, M.; Paparella, R. Climate Mitigation Strategies: The Use of Cool Pavements. *Sustainability* **2023**, *15*, 7641. https://doi.org/10.3390/su15097641

Academic Editors: Antonino Marvuglia, Maider Llaguno-Munitxa and Federico Amato

Received: 29 March 2023
Revised: 24 April 2023
Accepted: 4 May 2023
Published: 6 May 2023

1. Introduction

More than half of the world's population lives in urban centers, with this percentage rising every year. The phenomenon of increasing urbanization, i.e., the gradual displacement of the population from rural areas to more centrally located urban areas, is showing an almost exponential trend. This growth pattern is mainly related to global economic development, which began during the 19th century and continues to evolve; to cultural and anthropological aspects connected with the changing lifestyles of modern humans; to the search for economic prosperity; to the convenience and proximity of services/activities in urban areas; and to the pursuit of a better quality of life [1]. Since the mid-1950s, the total built-up area in the territory of the European Union has increased by 78%, while population growth has been only 33% [2]. This phenomenon, also due to the improper urban planning of the modern expanding urban agglomerations, has led to numerous problems from an environmental and socio-economic point of view, on a global scale. Projections by United Nations demographers indicate a 73.1% growth in the number of city residents worldwide for the first quarter of the 21st century, estimating that by 2050, nearly 70% of the world's population will be residing in cities [3]. These data have been published by the Population Division of the United Nations Department of Economic and Social Affairs (UN DESA, New York, NY, USA), in a report containing estimations and projections of rural and urban populations of different countries of the world and their major urban agglomerations [4]. Due to the high concentration of activity in highly urbanized areas, the energy demand is also consequently very high, and it is estimated that about 80% of the energy produced worldwide is consumed in cities, leading to a similar percentage of total greenhouse gas emissions [5].

Some studies have reported a causal nature of the relationship between global warming and higher rates of urbanization [6–8]. Indeed, a correlation has been found between increasing settlement density in urban areas and climate change at the local level, since morphological and structural changes in the urban fabric can affect the near-surface energy exchanges, leading to significant changes in the microclimate [9]. An alteration of the urban context can lead to major changes in soil permeability and wind profile. This occurs as a direct result of changes to the urban surfaces themselves and the introduction of new buildings that can modify or obstruct the natural wind flow [10]. The wind is a strong mitigating element of heat fluxes, and the introduction of new volumes into the urban context can curb this flow, creating new friction as a result of the roughness of surfaces and their elevation [11]. The issue related to the impermeabilization of urban surfaces is also of fundamental importance, because by modifying certain rainwater-absorbing characteristics of the soil and by changing surface materials, natural processes are altered, resulting in higher surface and air temperatures as a direct consequence [12].

For these reasons, both the research and the development of renewable energy are essential in order to address the environmental problems associated with the use of fossil fuels but also for the need to improve energy efficiency and overall sustainability in the cities themselves. The use of active solar systems can support the energy supply of buildings. In addition, a designed and conscious application of urban surface materials could significantly increase the overall potential at the urban scale using passive mitigation systems [13].

The Intergovernmental Panel on Climate Change (IPCC, Geneva, Switzerland) has declared that the past three decades have been warmer than any previous decade, ranking the first ten years of the 21st century as the hottest ever [14]. Temperatures in Europe have increased more than twice the global average, registering an average increase of approximately +0.5 °C per decade between 1991 and 2021 [14]. This phenomenon should be considered a direct consequence of the warming of the Arctic and the related melting of snow and ice, having a great impact on the northern part of Europe. This implies a major change in the Mediterranean region's climate, which, as it becomes progressively drier, does not facilitate the evaporation needed to mitigate the ongoing warming [15]. According to the most recent data released by the National Centers for Environmental Information (NOAA, Washington, DC, USA), the 2022 results as the sixth warmest year ever recorded for the globe, with a temperature of 0.84 °C above the 20th century average, and the preceding years, from 2013 to 2021, are all among the ten warmest years ever recorded. Since 1880, the global annual temperature has grown at an average rate of 0.08 °C per decade, with growth more than twice this rate (0.18 °C) since 1981, resulting in the Northern Hemisphere surface temperature in 2021 to be the sixth highest ever recorded [16]. In this way, the land part of the Northern Hemisphere reached a temperature of 1.54 °C above the average value of the past year, the third highest in the past 142 years [17].

Europe has set objectives to address global warming, providing the drafting of precise guidelines. According to European climate legislation, by 2030 EU countries must reduce greenhouse gas emissions by at least 55% compared to the levels reached in 1990, in order to mitigate climate change and achieve carbon neutrality by 2050 [18]. At the global level, the report provided by the World Economic Forum [19] presents an overview of mitigation opportunities in cities and recommends the adoption of an integrated systemic energy approach in response to the current environmental, economic, health, and social crises [19].

1.1. Objectives and Methodology

This paper focuses on systemic efficiency criteria. This includes applications such as efficient buildings, smart digital technology, clean electrification, and infrastructure, along with a circular economy approach to water, waste, and materials management; planning and digital technologies that integrate buildings, energy, transportation, and water systems become central landmarks [19].

To achieve this, it is important to identify strategies that allow for interventions at the local level, making a preliminary assessment of the various phenomena and stakeholders involved. The important climatic changes that have occurred in recent years can be attributed to the influence of anthropogenic intervention in the natural context. Through this work, it is analyzed, in a neighborhood context, how the replacement of paving materials can affect the urban microclimate with regard to surface temperatures, air temperatures, and human comfort. Specifically, a current (Actual Scenario—AS) and a projected (Cool Pavements Scenario—CPS) scenario were evaluated in order to be able to compare how the introduction of cool materials can improve various conditions compared to a current scenario in which traditional pavement materials are present. In order to define the following work, the various intervention possibilities were in the first stage analyzed and listed, evaluating firstly the physical characteristics and the main properties of the materials and then analyzing their applicability to the existing context, until the design choices were defined. After the planning process was completed, a detailed phase was carried out for the development of the study model and for the simulations of the two scenarios, to be able to compare and analyze the various results obtained. These microclimatic simulations were conducted using software such as ENVI-met 5.1.1 and tools for Grasshopper such as Ladybug, Honeybee, Dragonfly, and Urbano (Figure 1).

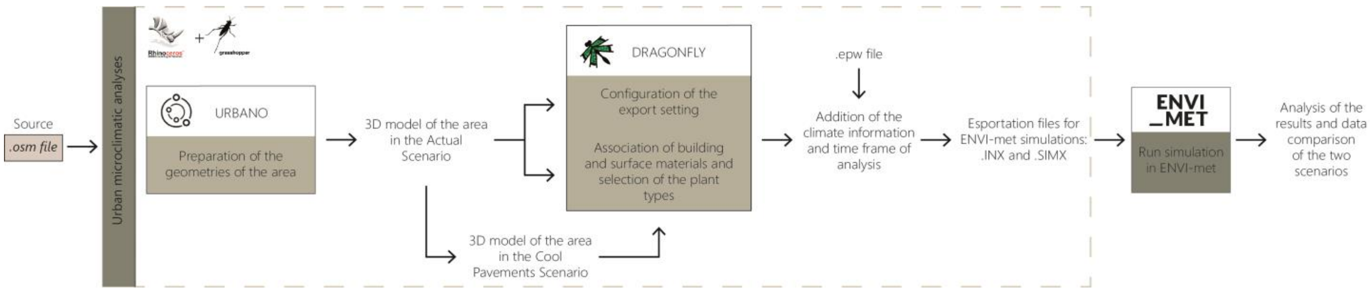

Figure 1. Workflow.

One of the most important outcomes pursued in this work is to identify the urban mitigation solutions that can lead to urban settings providing protection of people and infrastructure from extreme weather events and anomalous heat waves, in combination with efficient use of resources [20]. The purpose is to demonstrate both how much and in what form the current climate situation can be improved with the introduction of cool pavements and mitigation actions.

Additional works that investigate similar purposes to those in this paper, at the urban scale, were also consulted in order to better compare results, with the aim of research integration in this field. Several papers have evaluated these solutions in Italian contexts, such as in Teramo [21] and Monterotondo [22]. In both cases, the benefits given not only by cool materials but also with the addition of trees and green spaces were evaluated. Examples from other parts of the world were also considered that used numerical modeling software to simulate microclimate conditions as a result of the proposed interventions [23].

1.2. UHI (Urban Heat Island)

Urban heat island is defined as "a thermal anomaly occurring in urbanized areas where city temperatures are higher than those in surrounding rural areas" [24].

This is one of the most studied phenomena related to climate change [25]; it is dependent upon five main parameters (Figure 2): weather and climate conditions related to geographical location; urban geometries; thermal and radiative properties of urban materials; scarcity of permeable and green areas; anthropogenic heat [26]. The land use and the alterations introduced by human intervention are among the most relevant causes, as the transformation of the existing ground and vegetation into impermeable surfaces with increased density promotes a heat accumulation generated by the reflection of incident solar radiation [27]. One of the main functions of green areas within urban settings lies in shielding solar radiation that is neither reflected nor accumulated, reducing air temperature through evapotranspiration. However, building conformation can also affect air temperature, as tall and closed building curtains can block wind flows, obstructing cooling of urban infrastructure at night and leading to warm air stagnation [28]. Cities are also influenced by the high consumption of energy for anthropogenic purposes that provide, over the years, an additional heat fraction, affecting the balance of energy flows and leading to the propagation of UHIs. The contributing human activities are mainly related to the heating and cooling of buildings, the use of major machinery, as well as transportation and industrial processes [29].

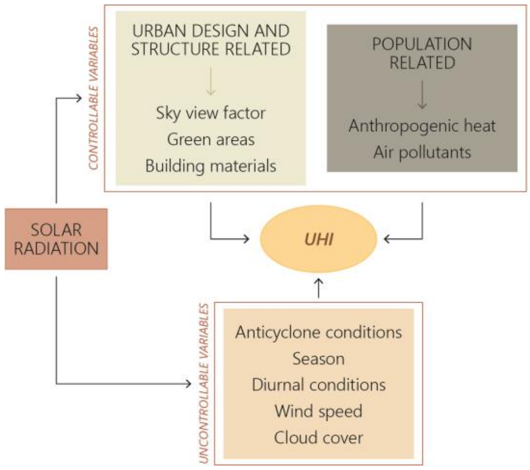

Figure 2. The different causes of the Urban Heat Island phenomenon.

As outdoor surface temperatures and atmospheric temperatures are directly related, another factor to be considered is the direct effect on air temperature caused by the heating of pavements, leading to a rise in atmospheric temperatures [30]. During the summer period (Figure 3), the real extent of this phenomenon is felt, as it creates in urban areas an unfavorable microclimate in which pavement absorbs solar radiation, stores this energy in the subsurface, and releases it as convection and infrared radiation to the surrounding context during the night, obstructing cooling [24].

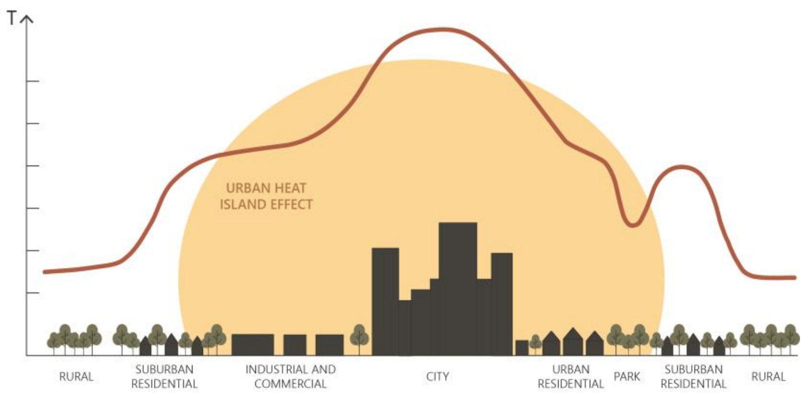

Figure 3. Schematic illustration of the UHI effect in an urban area.

In the daytime period, the main heat peaks are located near roads and population centers, while in the nighttime period, the temperature line becomes uniform in urban areas sloping down near rural areas [28]. Particularly during the summer period, areas with dark-colored asphalt overlays can reach peak surface temperatures around 48.0–67.0 °C [28].

High air temperatures near heated surfaces not only cause heat stress at the human level but also promote the development of quantities of ground-level ozone parcels, leading to reduced air quality. Indirectly, summer heat accumulation also affects the cooling energy loads for buildings, resulting in carbon dioxide emissions to the atmosphere and global warming as well as accelerated deterioration of infrastructure and materials [31]. Previous studies have demonstrated how different pavement materials contribute to the effect of urban heat island generation [32–34]. It was found that asphalt has the greatest impact, with an increase of 4.0 °C, followed by concrete with an increase of 3.0 °C, and finally grass with an increase of 1.0 °C in air temperature [35]. Most construction materials, due to their high thermal capacity, store heat in urban areas, releasing it later, when the surface temperature is higher than the ambient temperature, resulting in an increase of the night air temperature [36]. In denser urban settings with limited shading and vegetation, the phenomenon is quite common, especially during the summer period [36]. However, other external factors can influence the surface temperature of urban areas, such as vehicle loading caused by the heat flow due to tire friction, vehicle radiant heat flux, the vehicle-induced sensible heat flux, and the vehicle radiant heat shielding [37]. This can lead to a punctual increase of up to 1.0–3.0 °C, reaching a maximum value by the time the vehicle is parked. Another factor that can influence temperature values is the presence of vegetation, which can mitigate the UHI phenomenon through shading [38]. This is different from species to species, based on foliage and leaf size.

A lower air temperature can help to mitigate the UHI development phenomenon, and in this scenario, the role of building materials can be decisive in the containment of thermal gains and overheating [39,40]. By decreasing absorbed solar radiation, a more positive heat balance can be achieved by reducing thermal gains in the urban environment [41]. Adaptation and mitigation strategies also encompass the management and redesign of urban surfaces, assessing existing conditions and the relative materials used, designing replacements that include operations to increase vegetative cover, including water in outdoor spaces, converting roof and façade materials to cool materials, installing cool, reflective, or permeable pavements, and smart urban development [42]. There are also numerous works in the literature that describe the benefit of using green roofs for the mitigation of the UHI effect [43]. In many cities such as Toronto [44], Chicago [45], New York [46], and Tokyo [47], numerous research studies have been done considering the potentiality of using green roofs, and simulations have shown a significant decrease in air temperatures, of up to 3.0 °C, when implemented at the urban scale. It has also been shown that the use of green roofs and surfaces has positive impacts on the indoor thermal comfort of buildings and their energy demands [48].

This highlights that the effectiveness of the proposed solutions could be much higher when combined with other environmental design strategies that implement, for example, nature-based solutions. Especially in Italy, there have been several successful applications related to the integration of both of these mitigation methodologies, e.g., in Rome [49]. In this specific case, these interventions are carried out in a historic and heritage context. The quality of design solutions is another important issue to consider in the design stages when intervening in cities with important historical and architectural value. In these cases, it will be necessary to ensure that interventions are aesthetically pleasing and socially accepted. It is important to highlight that there may also be urban planning and landscape restrictions that constrain design choices and interventions. However, the use of green and natural solutions is helpful in achieving human well-being and historic preservation goals in a complex urban context.

At the urban scale, other actions that would be critical are related to turning urban areas into energy-efficient and sustainable areas, reducing the energy input required by buildings, optimizing industrial production processes, optimizing transportation, adopting efficient electrical and thermal systems from the generation system to the end users, and making building envelopes less sensitive to changes in outdoor temperature [50]. The use of renewable resources, such as solar, hydraulic, wind, and geothermal, when possible, is to be considered in combination with the interventions described above in order to achieve, as much as possible, the self-sustainability of buildings and improved performance at the urban scale. The introduction of these systems, however, needs to be studied carefully to verify any benefits or interferences with previously designed changes and the existing scenario.

There are also other mitigation mechanisms and strategies to achieve a general lowering of temperatures by modifying urban geometry [51].

1.3. Solar Availability

The portion of the sun's radiated energy that impacts the Earth's ground, defined as the horizontal surface, is known as global radiation and is composed of direct radiation, diffuse radiation, and reflected radiation from the ground surface or from the surrounding environment [52]. The intensity of solar radiation, expressed in Wh/m^2, varies substantially depending on the latitude of the location, the season, the time of day, and the composition of the air, which is strongly influenced by atmospheric conditions [53].

Therefore, solar irradiance studies of various areas are of fundamental importance in order to determine not only the availability of solar potential at the territorial level but also about the annual/monthly/daily/hourly amounts of solar radiation affecting the Earth. In this regard, various tools collect such data in global databases. A useful online tool is the PVGIS (Photovoltaic Geographical Information System) [54], which can be accessed from the website of the European Research Center, JRC of Ispra. The data result from complex algorithms, collected through satellite surveys, and are constantly updated. The surveying satellites are METEOSAT, which covers Europe, Africa, and most of Asia, and NSRDB, which covers North and Central America. PVGIS offers three different hourly-resolution solar radiation databases from which to choose in order to display and export the necessary data. Currently, the two satellite-based databases are:

- PVGIS-SARAH2 ($0.05° \times 0.05°$): database produced by CM SAF to replace SARAH-1 (PVGIS-SARAH). Covers Europe, Africa, most of Asia, and parts of South America. Time range: 2005–2020.
- PVGIS-NSRDB ($0.04° \times 0.04°$): results from a collaboration with NREL (Golden, CO, USA) under which the NSRDB solar radiation database was made available for PVGIS. Time range: 2005–2015.

In addition to these, there is also a global reanalysis database available:

- PVGIS-ERA5 ($0.25° \times 0.25°$): latest global reanalysis from ECMWF. Time range: 2005–2020.

The new solar radiation data analysis generally has greater uncertainty than satellite-based databases. Using this tool, it is possible to make some predictions about the performance of photovoltaic systems applied in a given area by inserting data about the system and its main characteristics, geometric and physical. However, these data represent very general quantities, and more in-depth analyses, including thorough simulations, are needed in order to be able to achieve more representative data.

2. "Cool Materials" as an Intervention Strategy

When radiation is projected upon a body, some of it is absorbed by the object, some is reflected, and the remainder is transmitted through the object [31]. From the percentage of absorbed radiation, part is re-emitted as long-wave radiation, and the remaining part is stored as heat by the body, called sensible heat [31]. Thermal exchange by radiation, therefore, includes a first component of reflected shortwave solar radiation, defined by albedo, and a component of longwave radiation (or infrared) emission, defined by thermal emittance; the summation results as the total radiation that is not retained by the object (Figure 4). Therefore, as its value increases, the material becomes cooler [55]. Due to all these processes, the emission of solar radiation can therefore significantly influence the temperature of the material's surface [56].

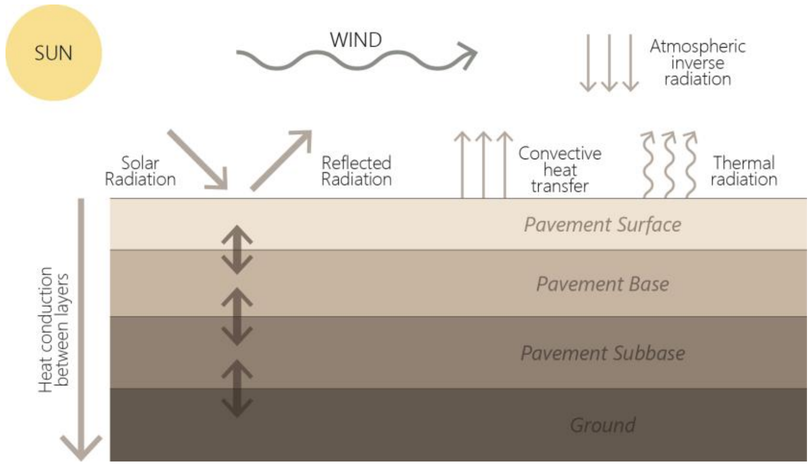

Figure 4. Heat exchange processes in a typical urban pavement.

The albedo represents the ability of a surface material to reflect solar radiation [57,58]. This can also influence the temperatures below the paved surfaces because, depending on the characteristics of the materials, more or less heat may be accumulated on the most external layer to be transferred to the pavement below [59]. Albedo is measured on a scale of zero to one, where zero corresponds to perfectly absorbent materials and one to perfectly reflective materials [60]. With a higher albedo, there is less energy stored in the body and therefore lower surface temperature [58]. The solar reflectance index (SRI) represents the capacity of a surface to reflect solar radiation and emit the absorbed energy as infrared radiation as a function of the increase in its temperature [36,61]. The values that it can assume are between 0, which corresponds to the properties of a black surface, and 100, which represents the properties of a white surface [62]. Albedo and thermal emittance are the main properties that determine the diurnal heat balance of materials [58], with the albedo impacting the maximum surface temperatures and the emission affecting the minimum temperatures [28].

With these assumptions, the characteristics of existing pavements within a predefined study area will be analyzed to compare their thermal behavior with the use of cool materials. This will be useful in order to analyze the impact of these solutions on the microclimate and thermal comfort conditions for the regeneration of urban surfaces.

Cool materials are characterized by high thermal reflectance and emissivity and are capable of reflecting a high percentage of solar radiation, allowing the elements behind to store less heat than conventional materials [63]. Possible cool pavement strategies include reflective materials, which can absorb lower quantities of solar radiation and emit less heat during critical times of the day through an increased surface reflection of the material, and permeable materials, which are considered cooling for their ability to reduce surface temperatures through the phenomenon of evaporation of water retained by the porosity of the material [64,65].

Though there are various intervention typologies that can be applied, not all materials are all suitable for every condition. A brief analysis of these materials' main characteristics allows for the evaluation of the applicability, at the design stage, of these systems to the various conditions presented within the considered case study.

2.1. Reflective Pavements

Reflective materials represent the most common type of cool materials, as they often include superior layering to existing pavement without necessitating the total replacement of materials [66,67]. In fact, in addition to intervening through new constructions with high albedo materials, existing surfaces can be treated with reflective paints and layers [68]. These interventions could include high albedo colored asphalt and concrete, thermo-reflective coatings, chip-coated pavements, whitetopping, and micro-surfacing [69].

The coloring of asphalt or concrete pavements can be achieved by applying a colored thermoplastic material [70], which reduces the quantity of thermal energy absorbed compared with conventional asphalt and increases the solar reflection [30].

Thermo-reflective coating for asphalt pavement represents a functional layer applied to existing surfaces to reduce heat accumulation through the reflection of sunlight, resulting in the inhibition of pavement temperature rise [71,72].

In chip-seal pavements, high albedo aggregates bind into the liquid asphalt, resulting in a more reflective surface [73]. Due to their low strength and durability characteristics, these types of pavements are used only on low-traffic roads, being more effective in applications on large and exposed areas, such as parking lots [74].

Whitetopping involves the application of a thin layer of Portland cement over the existing pavement [30] that contains fibers in order to achieve higher strength [75]. It can be used on roads with medium to high traffic flow [76].

Micro-surfacing consists of a rehabilitation technique involving thin-sealing with an asphalt mix layer, where light-colored materials can be used to increase solar reflectance. This provides a durable surface with a high grip, reduces maintenance costs, and increases pavement life. It is suitable for roads with all vehicular traffic conditions [74].

2.2. Evaporative Pavements

One of the main characteristics of this type of pavement is its high degree of permeability, which allows the retainment of water, remaining cooler as it reduces solar absorption. This phenomenon develops during hot periods of the day, with the transition from liquid to the gas phase of the water present inside or above the pavement, helping to lower the surface temperatures of the material and the external environment [28]. However, the temperature of permeable pavement in dry conditions is more uncertain because larger air voids increase the surface area available for convective phenomenon, while smaller cavities may promote the rise of moisture from the subsoil [77,78]. Under dry conditions, the daytime surface temperatures of permeable pavement are higher than those of impermeable pavement; however, the limited heat transfer to the subsurface layers reduces its heat loss during the night [31]. In this way, permeable pavements can mitigate the nocturnal urban heat island effect during the summer, whether in dry conditions or in wet and humid conditions [79]. Permeable pavements also increase road safety by reducing the surface water film that can occur as a result of atmospheric precipitation and increasing vehicle grip by improving water drainage [80]. The albedo tends to be lower compared to conventional materials due to surface roughness, which reduces net solar reflection [31]. Permeable pavement technologies, depending on the system and material properties, can be classified into porous asphalt, pervious concrete, permeable interlocking pavements with concrete or brick blocks, and water retention pavements [28].

Porous pavers consist of an asphalt mixture in which the percentage of fine aggregates is reduced, allowing the creation of cavities suitable for water passage [81]. The porosity percentage is between 18% and 25%, while ordinary asphalt reports a 2–3% presence of air voids [82,83]. This asphalt tends to be suitable only for low-traffic uses such as parking lots and sidewalks and not for road surfaces [84].

Pervious concrete is composed of a special cement concrete mix with a high porosity that allows water filtration into the subsoil [64]. This type of pavement has the same component mix as conventional concrete, changing the proportion of the elements [64]. It is particularly suitable for roads and highways due to its great drainage capabilities [85], reducing vehicle tire noise by 2 to 8 dB and keeping traffic noise levels below 75 dB [86].

Permeable interlocking pavements with concrete or brick blocks permit the creation of small openings between the elements to allow water flow. Benefits include not only the mitigation of urban temperature but also increased stormwater runoff, improving vehicle safety due to increased friction properties. This type of surface can be used for both driveway and non-driveway pavements [63].

Water-retentive pavements are particular concrete or asphalt pavements where rainwater is retained in the layer near the surface by a special filler [87].

Although the application of cool pavements can contribute to the reduction of surface temperatures, it is important to conduct a detailed analysis to estimate the impact of these surfaces on the surrounding microclimate for each specific site [88,89]. A recent report investigated the impact of the use of this pavement on the perception, at the pedestrian level, of thermal comfort [90]. This work showed that, as the albedo of a surface increases, it corresponds to a decrease in air temperatures near the surface, but at the same time it also corresponds to a greater amount of radiation perceived by the pedestrian [68]. This phenomenon is caused by the increased reflectivity of the surface material and can lead in some cases to an increase in the average radiant temperature [91]. This demonstrates the importance of evaluating not only the benefits brought by the designed modifications but also the potential negative and side effects that may result, including glare or unwanted solar gains, ensuring optimal application without increasing the thermal load on pedestrians along the road or to the side [92].

3. Physical and Geomorphological Characterization of the Study Area

In order to be able to apply these evaluations to a simulation context, a case study was identified. It is an area located in Padua, a northern Italian municipality in Veneto, at an altitude of 12 m above sea level. The population is approximately 207,000 inhabitants, as measured by ISTAT data for the year 2021 [93]. This area is located in the Po Valley, and the climate is defined as warm summer temperate (Cfa) according to the Köppen–Geiger classification [94]. However, global warming and climate change conditions are changing, and the climate maps are being altered, bringing local temperatures and conditions in Padua closer to a temperate transition to a Mediterranean (Cfsa) climate, characterized by heavy autumn rainfall and moderate summer dryness, with very hot summers and moderately cold winters.

According to the data published by the National System for the Protection of the Environment (SNPA), in 2021, Italy recorded the highest value of land consumption in the last decade [95]. The natural area is gradually decreasing every year, and land consumption is proceeding at the rate of about 2 sqm per second [95]. This largely uncontrolled development leads to negative effects on the land, environment, and landscape, promoting environmental risks related to global warming and air pollution [96]. In the Land Consumption Report published by SNPA [95], it was also observed that, comparing the data collected for the various regions, Veneto is the second highest region, after Lombardy, in terms of land consumption, reporting an increase equal to 11.90%. This percentage corresponds to the consumption of 218,230 ha, compared to 2,148,515 ha consumed at the national level, bringing a net increase in land consumption between the years 2020 and 2021 of almost 700 ha [97]. These high levels are despite two regional laws aimed at restricting land consumption in favor of the rehabilitation of disused areas: Regional Law No. 14 of 2017 and Regional Law No. 14 of 2019 [98]. The European Union, in this regard, is calling for soil protection and setting a very ambitious goal regarding zero net soil consumption by 2050, while at the Italian level, the same goal has been set for 2030 (Figure 5).

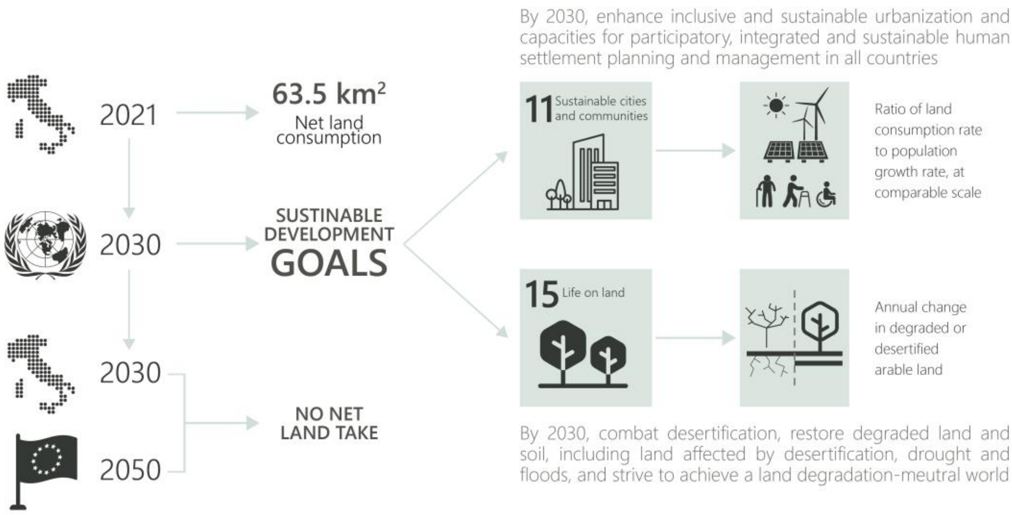

Figure 5. Main objectives and indicators at the global, European, and national level related to land use and degradation.

3.1. UHI and Padova

Changes that are made to natural surfaces are reflected within urban settings in the intensification of urban heat waves in summer and more extreme weather events in other seasons of the year. For this reason, the influence of pavement materials in these scenarios and how conditions change as a function of their alterations were first evaluated. Urban analysis of local climatic conditions, based on different spatial scales, is necessary to assess and identify possible climatic risks, determined, for example, by high temperatures. The multiplicity of materials inside the built environment produces, particularly during daylight hours, distinct patterns of climatic conditions. Intense solar radiation and high temperatures strongly disrupt the environment, increasing thermal stress at the pedestrian level [99]. Some groups at the University of Padua have, in recent years, analyzed the phenomenon of UHI generation in the Padua area [100], identifying the main factors influencing this process:

- the urban canyon pattern, which affects the shortwave heat transfer capacity of urban surfaces to the sky;
- the typically low albedo of urban surfaces, which increases the heat absorbed by buildings, sidewalks, roads, and roofs;
- the anthropogenic heat produced by vehicle motors;
- the greenhouse effect, amplified by the increased concentration of pollutants in the urban atmosphere;
- the scarcity of green areas, which increases sensible heat exchange with the air and decreases the evaporative cooling effect due to the lack of evapotranspiration from trees and grass.

The results reported from the analyses indicate that a non-negligible UHI effect is present even in a medium-sized city like Padua. An extensive measurement campaign was carried out at a weather station, covering more than 400 km during July and August 2012. The results highlight the UHI intensities of 1.0 ÷ 7.0 °C during the time period between 21:00–12:00, and a very small effect of 0.0 ÷ 2.0 °C was revealed during the daily sessions [101]. Height-to-width ratio, sky view factor, and type of surface determine the different heat exchange of surfaces with air and sky at urban sites compared with rural areas [102]. Therefore, optimizing urban morphology at the urban planning stage and in new construction, and improving management of the existing context is critical for climate change mitigation and adaptation and contributes to a resilient and sustainable living environment in the long term [103].

3.2. The Case Study

This work aims to evaluate the microclimatic impact and potential benefits of external surface re-functionalization interventions by comparing two scenarios, one related to the actual state and one related to a projected condition. The Piovego North University area, chosen as the case study, belongs to the University of Padua and covers a total area of about 46.250 m^2 (Figure 6).

(**a**) (**b**) (**c**)

Figure 6. (**a**) Veneto Region, City of Padova; (**b**) Central districts of Padova, study area in red circle (Google Maps); (**c**) Study area, University campus (Google Maps).

It is located in a central area of the municipality, near the train station and one of the main road junctions to the east, which connects the heart of the city with neighboring areas. The types of buildings in this area are various, with spaces used for classrooms, offices, libraries, and a canteen. These structures are aged and date back to approximately the 1970s. For this reason, there are often buildings that are not properly insulated or that present problems in terms of indoor comfort and in which it would also be necessary to plan an energy retrofit project. The built-up part of the site covers 34% of the available space, with 15.510 m^2, while the remaining area is divided between paved and green areas. The first covers 19.737 m^2, corresponding to 43%, and green areas cover the remaining 10.977 m^2, corresponding to 23% of the area (Figure 7).

Figure 7. Percentage and placement of existing surface types.

4. Microclimatic Analysis: Input Data

To identify the microclimatic characteristics of urban areas, it is necessary to proceed through simulations carried out with the use of numerical models, which can consider all conditions of the materials and especially the environmental factors that influence their behavior. For this reason, ENVI-met software was used. Before proceeding with the construction of the actual simulation model, an important step was to evaluate the input data that would be used as the basis for all simulations. The accuracy of these data represents a key issue, since it significantly affects the results obtained, leading to possible problems of an evaluative nature [104].

4.1. Materials

In order to carry out evaluations for design purposes, it is crucial to first analyze the state of the existing urban surfaces. In the literature, there are collections of data about the main physical and mechanical characteristics of various materials; however, for this work, an additional question was posed concerning the accuracy of the following data and how far the data can reflect the existing conditions. Thanks to analyses carried out in the field, with the collaboration of the Construction Materials Testing Laboratory of the Department of Civil, Building, and Environmental Engineering of the University of Padua, eight different types of pavements were identified within the entire area. Thermal tests were carried out on materials in place, using instruments such as thermo-cameras, and physical tests, analyzing cores extracted as test specimens, took place in the laboratory to assess more specific characteristics, such as density or volumetric heat capacity. Characteristics such as albedo and emissivity could also be measured. The main properties measured are presented below (Table 1).

Table 1. Existing material properties.

Type of Pavement	Albedo	Emissivity	Density (g/cm^3)
Asphalt mix—type 1	0.123	0.91	2.201
Concrete blocks—type 1	0.183	0.92	2.426
Concrete blocks—type 2	0.191	0.93	2.466
Concrete blocks—type 3	0.155	0.94	2.477
Asphalt mix—type 2	0.131	0.86	2.352
Asphalt mix—type 3	0.166	0.92	2.316
Asphalt mix—type 4	0.122	0.92	2.339
Asphalt mix—type 5	0.167	0.92	2.366

Concerning the material data for the design phase, we used data from the literature as detailed previously. These represent fundamental input data that were integrated into the material libraries already present by default in the ENVI-met program database.

4.2. Climate Data

The collection of climate data is as critical as the study of existing pavement, because it provides information on the weather conditions over the area. There are a variety of databases from which these data can be downloaded, which are collected in climate files in .epw format. The data collected from meteorological or satellite stations are recorded for every hour of every day of every year and are related to air temperature, relative humidity, solar radiation (both global and direct and diffuse), wind speed and direction, and information related to the geographical location of the survey point. The developers of Ladybug, a Grasshopper tool used in research work for solar radiation analysis, have created an official online library that can be consulted, bringing together data collected from a variety of weather file sources into a single global map [105].

This data resource represents only one of the available and searchable sources, such as Climate.OneBuilding.Org [106], Oikolab [107], and Shiny Weather data [108]. ARPAV [109], for the Veneto region, also provides some data but is limited to temperature and humidity, and PVGIS provides solar radiation data. The climate data used as input were provided by a meteorological station in an area with similar morphological characteristics to that analyzed in Treviso, because this library lacks a survey station in Padua. However, this could influence the results obtained. The date of 24 July 2020 was chosen as the simulation date, which is representative of the most extreme conditions recorded over the whole year, and the total simulation duration was chosen to be 24 h (Figure 8).

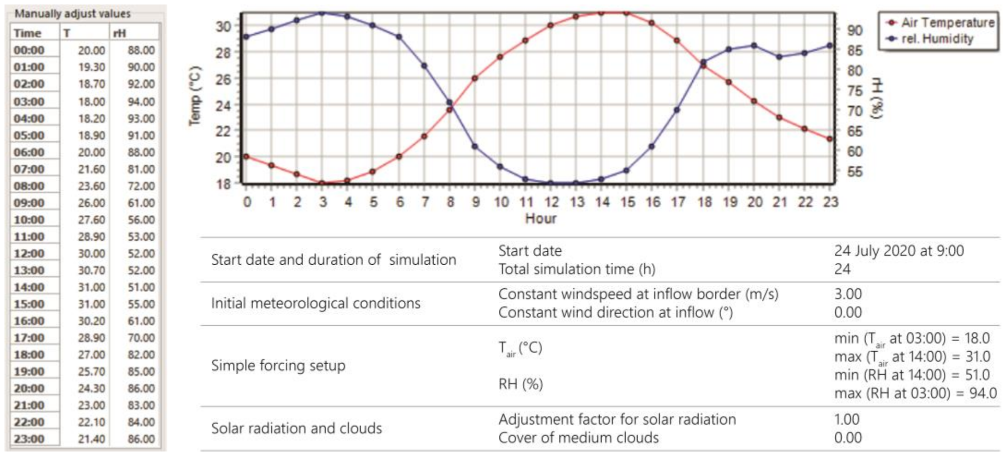

Figure 8. Input climate data.

4.3. Microclimate Simulation Software

Through the use of the ENVI-met software [110], all data can be grouped into a single numerical model, producing microclimate simulations that show, through different gradients of coloration, the conditions present directly in the model and thus in the buildings. Microscale atmospheric models are increasingly being used to obtain projections of the thermal and other benefits following the introduction of urban heat mitigation strategies [111]. The software is based on the calculation of fluid-dynamic characteristics, such as airflow and turbulence, and also the thermodynamic processes occurring at the ground surface, walls, and roofs of buildings, allowing the simulation of wind flow around structures and determining the complex microscale thermal interactions inside the urban environments [112]. The developed parameters provide numerical predictions of climate alterations in the outdoor environment, allowing an assessment of microclimatic changes and their impact on surrounding buildings. The results that can be obtained related to the effects of urban design strategies are varied and cover different areas of analysis, such as atmosphere, buildings, radiation, soil, solar access, surfaces, and vegetation. ENVI-met generates binary files that must be imported into a visualization program, called LEONARDO. Through this module, it is possible to visually reproduce simulation results that report information such as wind speed and direction, pressure, air temperature, humidity, solar radiation, foliage temperature, heat and vapor exchange, CO_2 distribution, pollution, water concentration, urban surface temperature, building surface temperature according to seven types of nodes (ENVI-met processes geometries composed of three layers and seven nodes, of which three are internal to the material and four are on the surfaces), heat transfer coefficients, and shading coefficients. Biometeorology data, related to thermal comfort indices (UTCI, PET, PMV), can also be obtained through an additional module: BIO-met. Simulation of the physical and physiological properties of vegetation is an important element, since the trees and green surfaces directly influence air temperatures and produce natural shading [113].

It is important to highlight that ENVI-met has some limitations, because the tools for the creation of the urban environment are limited to buildings, soils, paving materials, trees, and vegetation; there are no other tools for creating additional objects, such as block-independent shading structures. The software cannot simulate turbulent water mixing, so the use of water strategies is limited to stationary water bodies and cannot simulate fountains or water sprinkling systems. Model results are also highly dependent on the boundary conditions defined in the configuration file. It should also be considered that the model itself makes approximations. For example, it does not take into account anthropogenic heat released by cooling systems and traffic, leading to a potential underestimation of air temperature, mainly in heavily congested areas [114]. Another element that the model struggles to consider is related to the effect of multiple reflections and the resulting trapping of short-wave and long-wave radiation within urban canyons [115]. Therefore, this model can be considered a useful tool for urban climate analysis when combined with an adequate comprehension of its limitations.

In addition to the geometric input file of the area and the climate configuration file, a database is associated, in which the thermal and optical properties of surface materials are specified, as well as the stratigraphies of building elements and soils. Within this database, new materials can also be added or features of existing ones can be replaced, as needed.

5. Microclimatic Analysis: Input Data

5.1. Actual Scenario

For the creation of the three-dimensional model, the software provides two different modules for the development of the different domains of study, named Monde and Spaces; however, as both have great limitations on the creation of more articulated geometries, it was decided to create the model through a more sophisticated methodology. Through the use of Rhino 7 software and its implementation with Grasshopper, using tools such as Dragonfly, it was possible to create directly in this environment the elements used for the simulations in ENVI-met.

Starting from the realization of the geometries of the buildings, the first phase of the work involved the attribution of materials to the urban surfaces and buildings, while also specifying the underlying soil type. During this phase, the different tree species in the area were also identified and placed in their actual location. In addition, for the trees, there are already data provided by the software regarding height characteristics, foliage type, and stem size, so it was necessary only to associate geometries created in 2D with these databases. Once the material selection phase was finished, all the necessary parameters were defined to have files that could be transferred back to the ENVI-met environment and submitted to simulations. ENVI-met divides the entire working environment into small cubes, so it is essential to define the parameters for creating the grids and the dimensions of all the cells. Specifically, the model was divided into cells with a size of 2 m $\times$ 2 m $\times$ 2 m, for a total model size of 214 $\times$ 118 $\times$ 60 cells, also considering the inclusion of five nesting grids per side in order to mitigate effects that may be given by the influence of climatic conditions at the model domain boundary [116]. The geometric file containing the model has to be in .INX format, and the exportations are always conducted through Dragonfly. All other information essential to proceed with the simulations concerns environmental and climatic aspects. In this regard, it is necessary to create a .SIMX file which, based on the information directly derived from a linked .epw file, will report the location parameters of the project and all the weather conditions contained in the source file. In addition, within this file, it will be necessary to specify the simulations' start and duration, which in this case correspond in the first case to 24 July 2020, and in the second to 24 h of simulation. These two files are intrinsically linked, and the actual simulation can be initiated through ENVI-core, an additional module of the software, in which the created file can be read and analyzed.

5.2. Cool Pavement Scenario

This description represents an initial scenario corresponding to the current state; however, it is important here to evaluate, given these premises, how the same environment would perform by modifying urban surface materials through cool pavements. The technical data of the new pavements were chosen by consulting the literature. Based on the characteristics described in the previous sections, the materials that were considered most appropriate to select were: white-topping for road surfaces, as it has high resistance to heavy vehicular traffic and good skid resistance, and its albedo does not cause glare problems for drivers [76]; colored asphalt for outdoor areas, as it has a high load-bearing capacity and excellent mechanical strength [76]; pervious concrete for footpaths, as it is a suitable material for light transit volumes and medium to low albedo, to ensure the visual comfort of users [85]; and permeable interlocking concrete blocks, for car parking spaces and sidewalks (Table 2).

Table 2. Properties of materials assigned to different ground surfaces in the CPS.

Type of Pavement	Albedo	Emissivity	Heat Conductivity (W/m K)
Whitetopping	0.40	0.91	1.63
Pervious concrete	0.30	0.90	2.33
Colored asphalt	0.27	0.90	1.16
Permeable interlocking concrete blocks	0.50	0.90	2.00

The purpose was to create a continuous surface belt that permits the permeation of precipitation water into the subsoil, promoting groundwater recharge and reducing the volumes flowing through underground pipes. Reflective materials were chosen for the roads and private service areas because, as these areas constitute the majority of the surfaces, a solution was chosen that could be applied to existing materials, leading to a reduction in intervention time and consequently preventing the spaces from being out of use for long periods. The replacement of asphalt and concrete can lead to a more impactful intervention, but it also involves large environmental costs related to waste disposal. Evaporative solutions were chosen for parking areas and sidewalks, to increase the proportion of permeable surfaces in the area [112]. It was also found that, to mitigate the problem of radiative balance on pedestrians, the combined application of high-albedo pavements with green elements such as street trees and hedges is one of the most effective solutions [117]. The replacement was planned as specified in Figure 9.

Figure 9. Percentage and replacement of existing pavement with cool materials.

6. Simulation Analysis

Moving on to the analysis phase, the external surface temperatures of urban pavement and air temperatures were analyzed by comparing the two scenarios, corresponding to the actual state and the design scenario modified through the implementation of cool pavements, and analyzing each benefit or issue. The ENVI-met LEONARDO module allows the visualization of the results graphically and quantitatively.

6.1. Ground Surface Temperatures

During the analysis of the day of July 24, it was found that the maximum temperature at the urban surface level was at around 2:00 pm. During this particular period, in the current scenario, temperatures ranged from 38.1 °C to 51.3 °C. Areas characterized by the presence of vegetation and exposed to the sun were cooler by a few degrees than asphalted surfaces, while temperatures in shaded areas, whether by the presence of trees or buildings, varied by about ten degrees; these data confirm the cooling effect given by green surfaces and natural or artificial shading. The location of the trees is easily recognizable in the proposed results, as areas with significantly lower temperatures appear. It is shown that the green areas, kept identical between the two scenarios, enjoy a 0.1 °C lowering; this is not a perceptible value, but it emphasizes the ability of the surrounding materials to influence the surfaces that remained unchanged. The use of evaporative and reflective pavements produced an overall temperature decrease in the entire study area. The main materials that were used in this phase were whitetopping, colored asphalt, pervious concrete, and permeable interlocking concrete blocks. A higher decrease was recorded in north–south urban canyons, while in east–west oriented canyons, the decrease was significantly lower. Comparing before and after the pavement change, the largest cooling was measured at survey point PT.1 (Table 3; Figure 10). Here, when analyzing the changes during peak hours, temperatures decreased from 50.2 °C to 41.6 °C after the introduction of permeable interlocking concrete blocks. In the areas where whitetopping was included, temperatures varied by around 6.0 °C, and in the areas where pervious concrete was used, the difference was 3.3 °C. The smallest change was found in the introduction of colored asphalt, leading to a difference of up to 2.8 °C. This substantial difference in the cooling effect is mainly related to the lower albedo coefficient of about 0.27, compared with 0.40 for whitetopping as an example.

Table 3. Ground T_s in AS and absolute surface temperature difference (ΔT_s) between CPS and AS.

Point	Ground Surface Materials AS	Ground Surface Materials CP	AS: T_s (°C)				CPS: ΔT_s (°C)			
			09:00	14:00	17:00	21:00	09:00	14:00	17:00	21:00
PT.1	Asphalt mix—type 1	Whitetopping	33.6	51.3	39.1	26.5	0.8	5.5	1.5	0.1
PT.2	Concrete blocks—type 1	Perm. Interl. concrete blocks	33.9	43.9	33.9	26.3	2.7	3.6	1.7	0.7
PT.3	Concrete blocks—type 2	Perm. Interl. concrete blocks	34.9	38.1	32.9	25.9	3.7	3.1	1.5	0.2
PT.4	Concrete blocks—type 3	Pervious concrete	35.1	50.2	43.5	27.2	0.7	3.3	2.5	0.1
PT.5	Asphalt mix—type 2	Perm. Interl. concrete blocks	37.7	50.2	42.5	26.5	6.0	8.6	5.7	1.4
PT.6	Asphalt mix—type 3	Colored asphalt	24.8	43.6	35.0	25.2	0.1	1.6	0.5	−0.3
PT.7	Asphalt mix—type 4	Whitetopping	34.4	47.9	34.0	25.0	3.5	5.9	1.1	−0.3
PT.8	Asphalt mix—type 5	Colored asphalt	31.9	45.6	31.7	24.7	2.1	2.8	0.2	−0.5

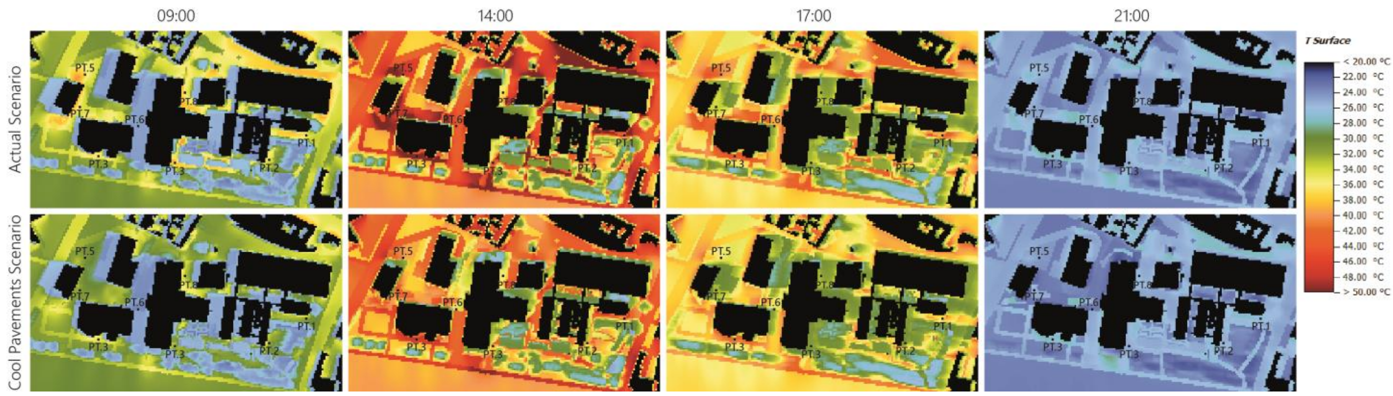

Figure 10. Hourly surface temperature (T_s) detection in AS and CPS.

For survey points 5 and 7, which are considered among the most significant, two graphs were extrapolated, showing the temperature trends in the two scenarios during all simulation hours and highlighting the differences in centigrade degrees (Figure 11).

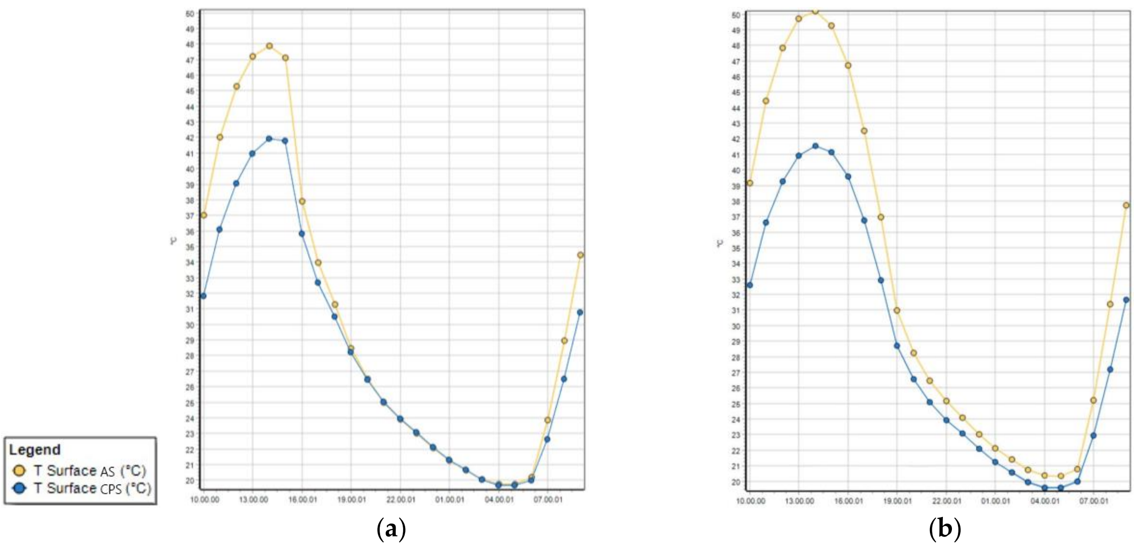

Figure 11. Temperature evolution in PT.5 (**a**) and PT.7 (**b**) of AS and CPS.

Evapotranspiration processes due to the presence of vegetation showed a consistent reduction in temperature. When these data were collected during the more extreme daily conditions, the benefits due to surface cooling were seen to be lower. Even during nighttime hours, permeable interlocking concrete blocks provided the best performance. In contrast, during this time range, surfaces where colored asphalt was used showed a slight increase of 0.3 to 0.5 °C. This occurred because reflection properties have a greater influence during daytime hours, while thermal properties are prevalent during nighttime hours [118].

6.2. Air Temperatures

To obtain a more complete overview of both scenarios, analyses were also carried out to evaluate the air temperature at the pedestrian level. These atmospheric analyses are based on the evaluation of the potential temperature at different elevations. This parameter is affected only by external factors, such as radiation or evaporation, simplifying the understanding of the phenomena involved. The decrease in surface temperatures involves, among other effects, the reduction of convective motions between soil and air, bringing, at the pedestrian level, a different heat load. In this case, the maximum temperature reached was recorded at 3:00 p.m., one hour later than the maximum surface temperature (Figure 12).

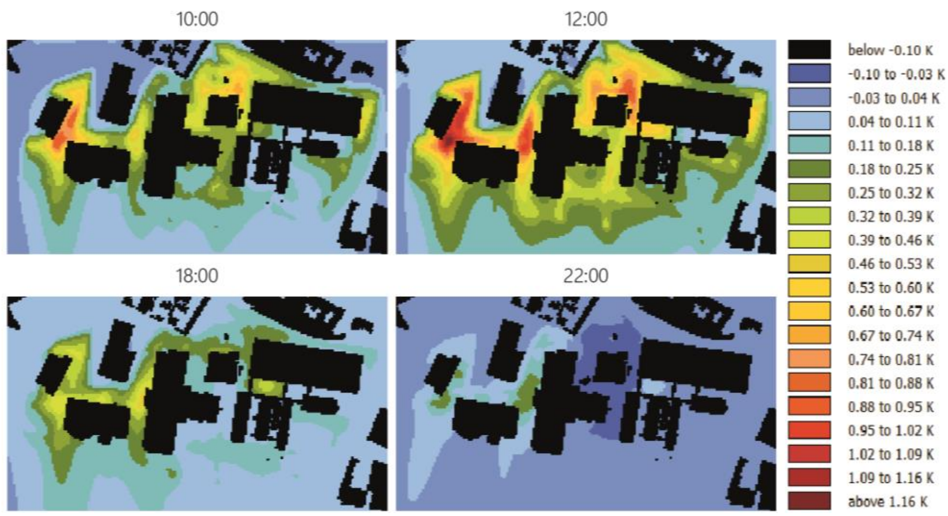

Figure 12. Potential air temperature absolute difference (ΔT_{air}).

The decreases from the current to the design scenario were slight, from 33.0 °C to about 32.0 °C at the most critical points. In this case, mitigation by greenery and trees was also evident. In the context of pavement replacement, areas with low SVF factor, such as narrow urban canyons, reported a decrease in air temperature by up to 0.3 °C, while the decrease was more significant in canyons with east–west orientation and high SVF [112]. All these results were also highlighted by previous studies, reporting a reduction in air temperature caused by the reflectance of pavements, in the range of 0.15 to 3.0 °C [63,119]. By analyzing the air temperature not only from the ground plan but also from the profile section (Figure 13), the altimetric trend of this result is more evident. Specifically, by exporting the east–west section, it is possible to visualize how urban surfaces and buildings affect air temperature trends. The benefit given by cold pavements on atmospheric temperatures is also noticeable at higher elevations, gradually reducing with increasing height, until it becomes uniform with the temperature of the sky vault at 30 m. The average height of the buildings is 14 m; thus, an analysis of the temperatures at an altitude of 20 m was performed. The maximum temperature at this height was recorded at 5 p.m., i.e., 3 h after the recorded maximum surface temperature of the paving materials. There is evidence of a decrease in daytime temperatures from 0.2 to 0.4 °C with the use of cool pavements. Overall, at an altitude of 30 m, the air temperature decreased to 0.2 °C during the daytime and 0.1 °C during the nighttime hours. After sunset, the ground and urban structure terminate the reception of energy from the sun while continuing to radiate stored latent heat in the infrared, thus getting cooler. The air in contact with the ground gradually becomes cooler in turn, generating a thermal inversion: this is a stable layer of cold air below a layer of warmer air, defined as a stable boundary layer.

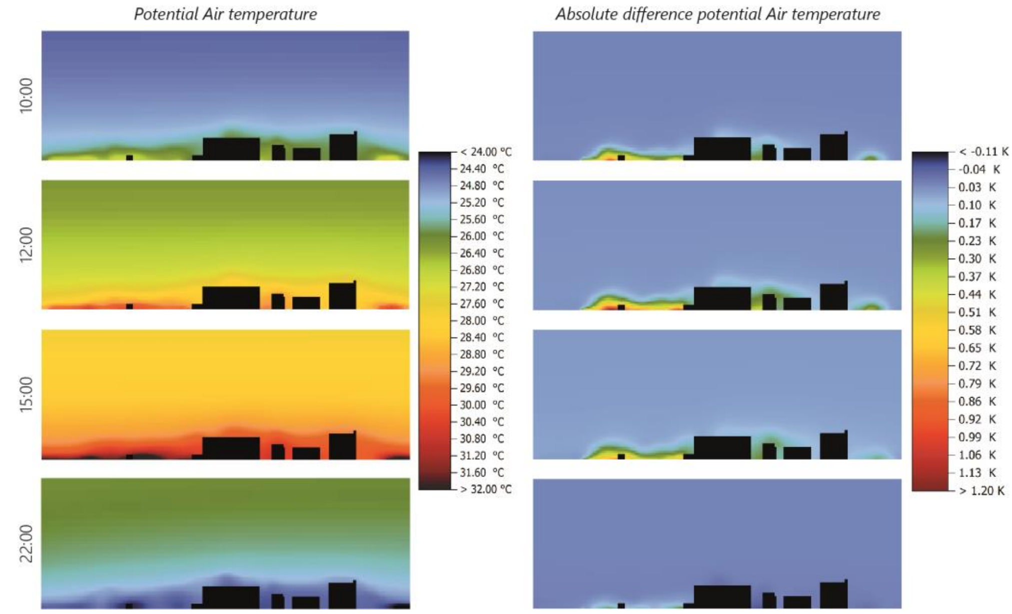

Figure 13. Potential T_{air} in the AS; absolute difference ΔT_{air} between AS and CPS.

6.3. Universal Thermal Climate Index

To quantify comfort or discomfort in an outdoor environment, several indicators have been developed to define the range of acceptable comfort conditions; these are useful for a comparison between multiple scenarios. The Universal Thermal Climate Index (UTCI) has been adopted for such analyses. The UTCI was developed following the concept of equivalent temperature [120]. A "reference environment" is defined as a condition in which there is a relative humidity of 50% (not exceeding 20 hPa), a wind speed of 0.5 m/s at 10 m above the ground, and a radiant temperature equal to the air temperature, in which the reference person walks at 4 km/h, generating a metabolic rate of 135 W/sqm, about 2.3 MET [121]. This scenario is compared with actual climatic conditions, such as air temperature, wind conditions, average radiant temperature, and humidity, expressed as water vapor pressure or relative humidity. The calculation simulates the phenomena of human heat transfer within the body and to its surface, taking into account the anatomical, thermal, and physiological properties of the human body, i.e., sweat production, shivering, sweating, blood flow, and average skin and face temperature [122]. UTCI measurements represent temperature distinctly from physical measurements in different locations and at different moments of the year [123]. It has been shown that in the largest part of the globe, the UTCI has higher values than the measured temperature due to the fact that our physiological system reacts to thermal conditions as warmer than the actual air temperature due to the combination of intense solar radiation and humid air. On the other hand, at higher latitudes, the UTCI has much lower values due to weak solar radiation and the presence of windier and more cloudy days [123]. The UTCI is expressed in terms of a rating scale consisting of ten different stress levels, representative of the load caused by the physiological and thermoregulatory responses of the human body in responding to actual environmental conditions (Figure 14).

UTCI [°C] range	Above +46°	+38° to +46°	+32° to +38°	+26° to +32°	+9° to +26°	+9° to 0°	0° to -13°	-13° to -27°	-27° to -40°	Below -40°
Stress Category	Extreme heat stress	Very strong heat stress	Strong heat stress	Moderate heat stress	No thermal stress	Slight cold stress	Moderate cold stress	Strong cold stress	Very strong cold stress	Extreme cold stress

Figure 14. UTCI classification.

ENVI-met software was used for the simulations of this index in the study area. Through the BIO-met additional module, it is possible to obtain data for the different analysis scenarios. In the actual scenario conditions, the UTCI index is very high in the morning; temperatures between 24.0 and 33.0 °C were measured at 8:00 a.m. at 1.40 m above the ground. This results in a moderate heat stress category classification. At 3:00 p.m., at the same height, temperatures rise in the range of 32.0 to 40.0 °C, resulting in strong heat stress for people. Shaded areas, i.e., below trees and on squares shaded by buildings, are cooler and are evaluated as moderate heat stress conditions. Strong heat stress conditions are perceived steadily until 6:00 p.m., the time when the reduction in temperatures begins, and at 7:00 p.m., a moderate heat stress level is reached.

The difference in UTCI between AS and CPS is greater when atmospheric temperatures are lowered. The temperature differences result mainly from the dependency of the UTCI on air temperature, mean radiant temperature, solar elevation angle, and solar/surface heat radiation. The introduction of cool pavements has a minor effect, not changing the UTCI thermal stress level compared to actual conditions and not changing the thermal stress category classification (Figure 15).

Porous concrete pedestrian areas, grassy areas, and parking lots with driveway lawns maintain lower UTCI temperatures due to the evaporation of some moisture content present in the surfaces, in the presence of very low albedo. The UTCI gradient is more pronounced during nighttime hours despite the absence of reflection and radiation phenomena. It is assumed that this may be due to the low wind speed, which reduces the movement of heat away from areas where it has accumulated, or to low SVF conditions, where the built-up area holds back the emitted latent energy during the nighttime hours. During the middle hours of the day, thermal stress conditions were slightly worsened due to the increased exposure of pedestrians to shortwave radiation reflected from sidewalks and walls, which also led to higher average radiant temperatures. Analyzing previous studies, the possibility of a worsening of thermal comfort with the application of reflective pavement has been observed, also leading to potential glare problems under certain conditions [30,119]. In conclusion, the thermal stress for users during nighttime hours appears to be zero, but over the central daytime hours, the UTCI temperatures indicate a very high thermal stress, which could be aggravated by reflective pavements when directly exposed to sunlight. However, this could generate a moderate benefit if shade canopies were provided in outdoor areas, which could amplify the benefits of cool pavements on human thermal conditions. In fact, the greatest thermal comfort is recorded in shaded areas, decreasing the thermal stress from the heat by two levels on the UTCI thermal scale.

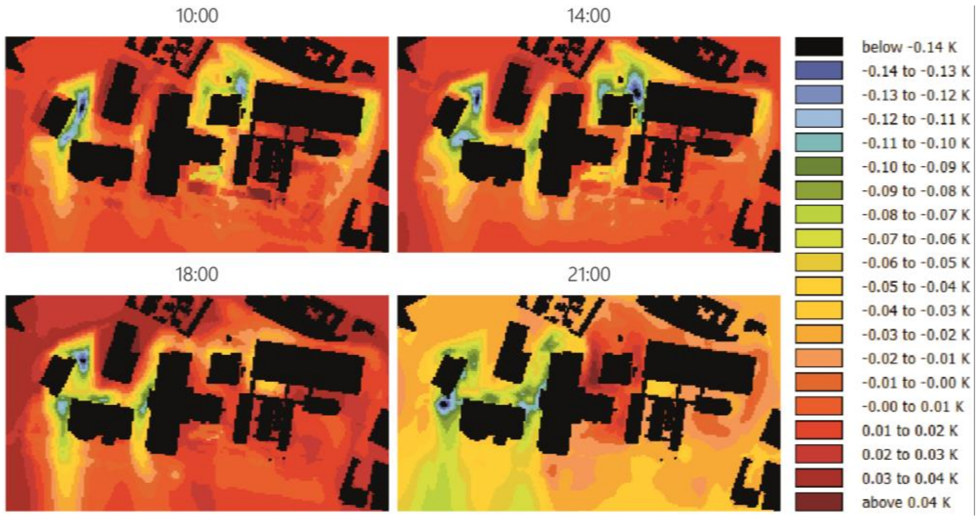

Figure 15. UTCI absolute difference (ΔUTCI) between AS and CPS.

7. Final Considerations and Future Works

The causes and the consequences of the UHI phenomenon include impacts on human health and thermal comfort, increased energy consumption for cooling, air pollution, and deterioration of surface water quality [124]. For this reason, the research work focused on identifying a methodology for energy upgrading of urban neighborhoods that could be applicable on a large scale and replicable in other contexts. The replacement of conventional pavements with cool materials generated a decrease in potential air temperature values at different elevations. Pavement surfaces were cooler by almost up to 9.0 °C in the central hours, giving rise to reductions in atmospheric temperature at the pedestrian level of 0.6 to 1.2 °C, while at 15 m elevation, slightly above the canopy, the reduction was 0.2–0.4 °C in the central daylight hours. Thus, the analyses highlight the benefit of upgrading outdoor pavements with cool materials. In addition, urban heat island considerations show how cool pavements can be used as an urban mitigation instrument.

Evaluating the effectiveness of cold pavements on people's comfort conditions, a slight aggravation of human thermal conditions was found in the middle hours of the day, from +0.1 to +0.8 °C in the UTCI index due to the rise of average radiant temperature, which is due to the increased reflection of pavement materials. The prevailing necessity during the summer season is to mitigate the hot weather, so the integration of shade canopies in outdoor areas is proposed to reduce the heat stress from a very high to moderate level. The introduction of these elements allows the indirect exposure to solar radiation of the surfaces, or parts of them, limiting in this way the absorption of heat and the associated processes. Cool pavements in a neighborhood context provides summer benefits while maintaining the material properties of the building exterior envelope, although it depends on conditions such as SVF, presence of vegetation, and type of building materials. The study demonstrates the effectiveness of urban surface interventions and how they are responsive to neighborhood energy upgrading needs while showing resilience to the ongoing climate alterations.

Future additional developments and applications of the methodology in urban districts may lead to near-zero energy cities. The future developments of the study will focus on expanding the analysis at three different scales:

- Building scale: specifically, to be able to quantify the impact of changing pavement surfaces on indoor thermal comfort conditions and building energy consumption for cooling, the indoor air temperature surfaces at points distant from the external envelope should be analyzed.
- District scale: it might be interesting to carry out simulations to evaluate not only the effectiveness of other regeneration solutions but to analyze the effects of combining cool pavements with other technologies.
- Urban scale: by extending the scale of interventions, it may be useful to expand the study of the impacts that regeneration interventions have within a wider domain, such as whole parts of cities [112].

Managing renewable sources at the neighborhood level would allow lower costs, a sharing of installation and maintenance burdens, and a sharing of the energy benefits gained. A neighborhood-scale project would also provide the advantages of promoting attractiveness in economic terms and increasing user consciousness of energy and environmental issues. In the context described, other future developments can be directed toward the identification of the interference between mitigation systems and the installed PV panels. This is fundamental to assessing the effects that new installations may have in the existing context by evaluating the degree of overall benefit on surface and air temperature trends. In this regard, deeper experimental investigations on the PV roofs and an extensive study of the parameters to be assigned to the material are suggested in order to allow the ENVI-met software to correctly simulate the presence of the panels.

Reflecting on the results obtained, it is also important to establish the accuracy of the input data used during the simulations. This represents a very important issue, since all results used for design assumptions are based on these data. It would be useful to be able to explore this issue further by evaluating the differences in the simulations using both climatic and material data from the literature and data collected in the case study.

An additional focus should also be placed on evaluating the energy production and consumption of buildings in order to determine how self-sustaining these buildings could be and to verify the return over time in economic terms, estimating the overall costs of the interventions, and evaluating the life cycle processes of the proposed interventions.

Author Contributions: Conceptualization, M.G. and R.P.; methodology, M.G. and R.P.; software, M.G.; validation, M.G.; formal analysis, M.G.; investigation, M.G.; resources, M.G.; data curation, M.G.; writing—original draft preparation, M.G.; writing—review and editing, M.G. and R.P.; visualization, M.G.; supervision, R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Strakhova, K. The Modern World Process of Urbanization. 2023. Available online: https://www.researchgate.net/publication/367282566 (accessed on 15 December 2022).
2. Commissione Europea. *Superfici Impermeabili, Costi Nascosti. Alla Ricerca di Alternative All'occupazione e All'impermeabilizzazione dei Suoli*; Commissione Europea: Lussemburgo, 2013. [CrossRef]
3. UN Department of Economic and Social Affairs (UN DESA). 68% of the World Population Projected to Live in Urban Areas by 2050. Available online: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed on 10 January 2023).
4. UNDESA—Population Division. *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*; UNDESA—Population Division: New York, NY, USA, 2019.

5. British Petroleum. *Statistical Review of World Energy*, 71st ed.; British Petroleum: London, UK, 2022. Available online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed on 15 December 2022).
6. Huang, X.; Hao, L.; Sun, G.; Yang, Z.; Li, W.; Chen, D. Urbanization Aggravates Effects of Global Warming on Local Atmospheric Drying. *Geophys. Res. Lett.* **2022**, *49*, e2021GL095709. [CrossRef]
7. Wilke, A.B.B.; Beier, J.C.; Benelli, G. Complexity of the relationship between global warming and urbanization—An obscure future for predicting increases in vector-borne infectious diseases. *Curr. Opin. Insect Sci.* **2019**, *35*, 1–9. [CrossRef] [PubMed]
8. Helbling, M.; Meierrieks, D. Global warming and urbanization. *J. Popul. Econ.* **2022**, 1–37. [CrossRef]
9. Georgiadis, T. CAMBIAMENTI CLIMATICI ED EFFETTI SULLE CITTÀ—REBUS: REnovation of Public Buildings and Urban Spaces. 2018. Available online: https://issuu.com/laboratoriorebus/docs/rebus_03_georgiadis (accessed on 20 December 2022).
10. Doherty, M.; Klima, K.; Hellmann, J.J. Climate change in the urban environment: Advancing, measuring and achieving resiliency. *Environ. Sci. Policy* **2016**, *66*, 310–313. [CrossRef]
11. Carter, J.G.; Cavan, G.; Connelly, A.; Guy, S.; Handley, J.; Kazmierczak, A. Climate change and the city: Building capacity for urban adaptation. *Prog. Plan.* **2015**, *95*, 1–66. [CrossRef]
12. Wang, C.; Wang, Z.-H. Projecting population growth as a dynamic measure of regional urban warming. *Sustain. Cities Soc.* **2017**, *32*, 357–365. [CrossRef]
13. Santamouris, M.; Kolokotsa, D. *Urban Climate Mitigation Techniques*; Routledge: London, UK, 2016; Volume 1.
14. Pörtner, H.O.; Roberts, D.C.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V. *Climate Change 2022: Impacts, Adapataion and Vulnerability Summary for Policymakers. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2022.
15. World Meteorological Organization (WMO) and the Copernicus Climate Change Service. State of the Climate in Europe 2021. 2022. Available online: https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate/Europe (accessed on 17 December 2022).
16. Noor, T.; Nazeer, I.; Attique, Z.; Shahzad, M.; Baqi, A. Global temperature variations since pre industrial era. *Int. J. Innov. Sci. Technol.* **2021**, *3*, 67–74. [CrossRef]
17. NOAA National Centers for Environmental Information. State of the Climate: Global Climate Report for Annual 2022. 2022. Available online: https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202113 (accessed on 10 January 2023).
18. Consiglio Nazionale della Green Economy. Rapporto: Verso la neutralità climatica delle Green City. *Approcci, Indirizzi, Strategie, Azioni, X Edizione Degli Stati Generali.* 2021. Available online: https://www.statigenerali.org/documenti/documenti-2021/ (accessed on 15 December 2022).
19. World Economic Forum (WEF). Net Zero Carbon Cities: An Integrated Approach. 2021. Available online: https://www.weforum.org/reports/net-zero-carbon-cities-an-integrated-approach/ (accessed on 20 December 2022).
20. Croce, S.; Novelli, A.; Vettorato, D. Visualizzazione di parametri morfologici e ambientali a supporto della pianificazione urbana. In Proceedings of the XXIII Conferenza Nazionale ASITA, Trieste, Italy, 12–14 November 2019; Available online: https://www.researchgate.net/publication/337258740 (accessed on 10 January 2023).
21. Ambrosini, D.; Galli, G.; Mancini, B.; Nardi, I.; Sfarra, S. Evaluating mitigation effects of urban heat islands in a historical small center with the ENVI-Met® climate model. *Sustainability* **2014**, *6*, 7013–7029. [CrossRef]
22. Andreucci, M.B.; Cupelloni, L.; Tucci, F. Simulations beyond the building, identifying climate adaptation scale jumping potentials to district and city level. Research by design for the city of Monterotondo (Italy). In *Proceedings of Building Simulation 2021: 17th Conference of IBPSA.*; KU Leuven: Leuven, Belgium; 2022. [CrossRef]
23. Faragallah, R.N.; Ragheb, R.A. Evaluation of thermal comfort and urban heat island through cool paving materials using ENVI-Met. *Ain Shams Eng. J.* **2021**, *13*, 101609. [CrossRef]
24. Gerundo, C. *L'adattamento delle città ai cambiamenti climatici*; Fedoa Press—Federico II University Press: Napoli, Italy, 2018.
25. Kyriakodis, G.-E.; Santamouris, M. Using reflective pavements to mitigate urban heat island in warm climates—Results from a large scale urban mitigation project. *Urban Clim.* **2018**, *24*, 326–339. [CrossRef]
26. Mahdavi, A.; Kiesel, K.; Vuckovic, M. Methodologies for UHI analysis: Urban heat Island phenomenon and related mitigation measures in central Europe. In *Counteracting Urban Heat Island Effects in a Global Climate Change Scenario*; Springer International Publishing: Berlin/Heidelberg, Germany, 2016; pp. 71–91. [CrossRef]
27. Dessì, V. *Progettare il comfort urbano. Soluzione per un'integrazione tra società e territorio*; Sistemi Editoriali: Napoli, Italy, 2008.
28. U.S. Environmental Protection Agencys Office of Atmospheric Programs. Cool Pavements. Reducing Urban Heat Islands: Compendium of Strategies; 2012. Available online: https://www.epa.gov/heat-islands/heat-island-compendium (accessed on 10 January 2023).
29. Oke, T.R.; Mills, G.; Christen, A.; Voogt, J. *Urban Climates*; Cambridge University Press: Cambridge, UK, 2017.
30. Mizwar, I.K.; Napiah, M.; Sutanto, M.H. Thermal properties of cool asphalt concrete containing phase change material. In *IOP Conference Series: Materials Science and Engineering*; Institute of Physics Publishing: Bristol, UK, 2019; Volume 527, p. 012049. [CrossRef]
31. Li, H.; Harvey, J.T.; Holland, T.J.; Kayhanian, M. Corrigendum: The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management. *Environ. Res. Lett.* **2013**, *8*, 049501. [CrossRef]
32. Levermore, G.; Parkinson, J.; Lee, K.; Laycock, P.; Lindley, S. The increasing trend of the urban heat island intensity. *Urban Clim.* **2018**, *24*, 360–368. [CrossRef]

33. Mirzaei, P.A. Recent challenges in modeling of urban heat island. *Sustain. Cities Soc.* **2015**, *19*, 200–206. [CrossRef]
34. White, P.; Golden, J.S.; Biligiri, K.P.; Kaloush, K. Modeling climate change impacts of pavement production and construction. *Resour. Conserv. Recycl.* **2010**, *54*, 776–782. [CrossRef]
35. Ikechukwu, E.E. The Effects of Road and Other Pavement Materials on Urban Heat Island (A Case Study of Port Harcourt City). *J. Environ. Prot.* **2015**, *06*, 328–340. [CrossRef]
36. Kappou, S.; Souliotis, M.; Papaefthimiou, S.; Panaras, G.; Paravantis, J.A.; Michalena, E.; Hills, J.M.; Vouros, A.P.; Ntymenou, A.; Mihalakakou, G. Cool Pavements: State of the Art and New Technologies. *Sustainability* **2022**, *14*, 5159. [CrossRef]
37. Fujimoto, A.; Tokunaga, R.; Kiriishi, M.; Kawabata, Y.; Takahashi, N.; Ishida, T.; Fukuhara, T. A road surface freezing model using heat, water and salt balance and its validation by field experiments. *Cold Reg. Sci. Technol.* **2014**, *106–107*, 1–10. [CrossRef]
38. Qin, Y.; Zhang, X.; Tan, K.; Wang, J. A review on the influencing factors of pavement surface temperature. *Environ. Sci. Pollut. Res.* **2022**, *29*, 67659–67674. [CrossRef]
39. Santamouris, M. Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. *Renew. Sustain. Energy Rev.* **2013**, *26*, 224–240. [CrossRef]
40. Doulos, L.; Santamouris, M.; Livada, I. Passive cooling of outdoor urban spaces. The role of materials. *Sol. Energy* **2004**, *77*, 231–249. [CrossRef]
41. Qin, Y.; Hiller, J.E. Understanding pavement-surface energy balance and its implications on cool pavement development. *Energy Build.* **2014**, *85*, 389–399. [CrossRef]
42. Wang, Z.; Xie, Y.; Mu, M.; Feng, L.; Xie, N.; Cui, N. Materials to Mitigate the Urban Heat Island Effect for Cool Pavement: A Brief Review. *Buildings* **2022**, *12*, 1221. [CrossRef]
43. Santamouris, M. Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **2012**, *103*, 682–703. [CrossRef]
44. Berardi, U. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy Build.* **2016**, *121*, 217–229. [CrossRef]
45. Smith, K.R.; Roebber, P.J. Green Roof Mitigation Potential for a Proxy Future Climate Scenario in Chicago, Illinois. *J. Appl. Meteorol. Clim.* **2011**, *50*, 507–522. [CrossRef]
46. Savio, P.; Rosenzweig, C.; Sokecki, W.D.; Slosberg, R.B. *Mitigating New York City's Heat Island with Urban Forestry, Living Roof, and Light Surfaces*; NewYork City Regional Heat Island Initiative: Albany, NY, USA, 2006.
47. Chen, H.; Ooka, R.; Huang, H.; Tsuchiya, T. Study on mitigation measures for outdoor thermal environment on present urban blocks in Tokyo using coupled simulation. *Build. Environ.* **2009**, *44*, 2290–2299. [CrossRef]
48. Cirrincione, L.; Marvuglia, A.; Scaccianoce, G. Assessing the effectiveness of green roofs in enhancing the energy and indoor comfort resilience of urban buildings to climate change: Methodology proposal and application. *Build. Environ.* **2021**, *205*, 108198. [CrossRef]
49. Del Serrone, G.; Peluso, P.; Moretti, L. Evaluation of Microclimate Benefits Due to Cool Pavements and Green Infrastructures on Urban Heat Islands. *Atmosphere* **2022**, *13*, 1586. [CrossRef]
50. Musco, F.; Fregolent, L. *Pianificazione Urbanistica e Clima Urbano: Manuale per la Riduzione dei Fenomeni di isola di Calore Urbano, Regione Veneto*; Il Poligrafo: Padova, Italy, 2014.
51. Lai, D.; Liu, W.; Gan, T.; Liu, K.; Chen, Q. A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces. *Sci. Total. Environ.* **2019**, *661*, 337–353. [CrossRef]
52. EU SCIENCE HUB. Data Sources and Calculation Methods. Available online: https://ec.europa.eu/jrc/en/PVGIS (accessed on 17 January 2023).
53. CEI 82-25:2022. Guida Alla Progettazione, Realizzazione e Gestione di Sistemi di Generazione Fotovoltaica. p. 10. Available online: https://mycatalogo.ceinorme.it/cei/item/0000018783/ (accessed on 20 January 2023).
54. PVGIS—Photovoltaic Geographical Information System. Available online: https://re.jrc.ec.europa.eu/pvg_tools/en/ (accessed on 10 January 2023).
55. Mungule, M.; Iyer, K.K.R. A Review on Role of Pavement Materials on Urban Heat Island Effects. In *Sustainable Cities and Resilience, Lecture Notes in Civil Engineering*; Springer: Singapore, 2022; pp. 229–237. [CrossRef]
56. Santamouris, M.; Xirafi, F.; Gaitani, N.; Spanou, A.; Saliari, M.; Vassilakopoulou, K. Improving the Microclimate in a Dense Urban Area Using Experimental and Theoretical Techniques—The Case of Marousi, Athens. *Int. J. Vent.* **2012**, *11*, 1–16. [CrossRef]
57. American Concrete Pavement Association (ACPA). Albedo: A Measure of Pavement Surface Reflectance. *Concrete Pavement Research & Technology, Old Orchard Rd.* 2002. Available online: https://trid.trb.org/view/920184 (accessed on 18 January 2023).
58. Santamouris, M.; Synnefa, A.; Karlessi, T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Sol. Energy* **2011**, *85*, 3085–3102. [CrossRef]
59. Gaitani, N.; Mihalakakou, G.; Santamouris, M. On the use of bioclimatic architecture principles in order to improve thermal comfort conditions in outdoor spaces. *Build. Environ.* **2007**, *42*, 317–324. [CrossRef]
60. Chen, J.; Zhou, Z.; Wu, J.; Hou, S.; Liu, M. Field and laboratory measurement of albedo and heat transfer for pavement materials. *Constr. Build. Mater.* **2019**, *202*, 46–57. [CrossRef]
61. *ASTM E1980-11R19*; Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces. ASTM International: West Conshohocken, PA, USA, 2019. [CrossRef]

62. Akbari, H.; Levinson, R.; Rosenfeld, A.; Elliot, M. Global Cooling: Policies to Cool the World and Offset Global Warming from CO_2 Using Reflective Roofs and Pavements. *J. Heat Isl. Inst. Int.* **2012**, *7*, 1–10.
63. Qin, Y. A review on the development of cool pavements to mitigate urban heat island effect. *Renew. Sustain. Energy Rev.* **2015**, *52*, 445–459. [CrossRef]
64. Moretti, L.; Di Mascio, P.; Fusco, C. Porous Concrete for Pedestrian Pavements. *Water* **2019**, *11*, 2105. [CrossRef]
65. Tsoka, S.; Theodosiou, T.; Tsikaloudaki, K.; Flourentzou, F. Modeling the performance of cool pavements and the effect of their aging on outdoor surface and air temperatures. *Sustain. Cities Soc.* **2018**, *42*, 276–288. [CrossRef]
66. Chen, Y.; Li, Z.; Ding, S.; Yang, X.; Guo, T. Research on heat reflective coating technology of asphalt pavement. *Int. J. Pavement Eng.* **2021**, 1–10. [CrossRef]
67. Li, Z.; Guo, T.; Chen, Y.; Wang, C.; Chen, Q.; Ding, S.; Chen, Q.; Chen, H. Preparation and Properties of New Thermal Reflective Coating for Asphalt Pavement. *Materials* **2022**, *15*, 8087. [CrossRef]
68. Zhu, S.; Mai, X. A review of using reflective pavement materials as mitigation tactics to counter the effects of urban heat island. *Adv. Compos. Hybrid Mater.* **2019**, *2*, 381–388. [CrossRef]
69. Ferrari, A.; Kubilay, A.; Derome, D.; Carmeliet, J. The use of permeable and reflective pavements as a potential strategy for urban heat island mitigation. *Urban Clim.* **2019**, *31*, 100534. [CrossRef]
70. Liu, Q.; Varamini, S.; Tighe, S. Field Evaluation of Red-Coloured Hot Mix Asphalt Pavements for Bus Rapid Transit Lanes in Ontario, Canada. *Coatings* **2017**, *7*, 58. [CrossRef]
71. Wang, J.; Meng, Q.; Zhang, L.; Zhang, Y.; He, B.-J.; Zheng, S.; Santamouris, M. Impacts of the water absorption capability on the evaporative cooling effect of pervious paving materials. *Build. Environ.* **2019**, *151*, 187–197. [CrossRef]
72. Cheela, V.R.S.; John, M.; Biswas, W.; Sarker, P. Combating Urban Heat Island Effect—A Review of Reflective Pavements and Tree Shading Strategies. *Buildings* **2021**, *11*, 93. [CrossRef]
73. Nichols Consulting Engineers—NCE. *Pavement Management Program: Final Report*; Nichols Consulting Engineers—NCE: Blue Lake, CA, USA, 2012.
74. Tran, N.; Powell, B.; Marks, H.; West, R.; Kvasnak, A. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. *Transp. Res. Rec.* **2009**, *2098*, 124–130. [CrossRef]
75. Texas Department of Transportation. Texas Pavement Manual. 2021. Available online: http://onlinemanuals.txdot.gov/txdotmanuals/pdm/index.htm (accessed on 20 January 2023).
76. Krispel, S.; Peyerl, M.; Maier, G.; Weihs, P. Reduction of urban heat islands with whitetopping. *Bauphysik* **2017**, *39*, 33–40. [CrossRef]
77. Xie, J.; Zhou, Z. Numerical Analysis on the Optimization of Evaporative Cooling Performance for Permeable Pavements. *Sustainability* **2022**, *14*, 4915. [CrossRef]
78. Manteghi, G.; Mostofa, T. Evaporative Pavements as an Urban Heat Island (UHI) Mitigation Strategy: A Review. *Int. Trans. J. Eng Manag. Appl. Sci. Technol.* **2019**, *11*, 1–15.
79. Tan, K.; Qin, Y.; Du, T.; Li, L.; Zhang, L.; Wang, J. Biochar from waste biomass as hygroscopic filler for pervious concrete to improve evaporative cooling performance. *Constr. Build. Mater.* **2021**, *287*, 123078. [CrossRef]
80. Nakayama, T.; Fujita, T. Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. *Landsc. Urban Plan.* **2010**, *96*, 57–67. [CrossRef]
81. Elizondo-Martínez, E.-J.; Andrés-Valeri, V.-C.; Juli-Gándara, L.; Rodríguez-Hernández, J. Multifunctional Porous Concrete Urban Pavements for a More Sustainable and Resilient Future. *Proceedings* **2018**, *2*, 1453. [CrossRef]
82. Noviandini, Z.P.; Dewi, O.C.; Laksitoadi, B.; Widyarta, M.N. The Effect of Permeable Pavement on Pedestrian Walkway for Human Comfort. In *IOP Conference Series: Earth and Environmental Science*; Institute of Physics Publishing: Bristol, UK, 2020. [CrossRef]
83. Mohajerani, A.; Bakaric, J.; Jeffrey-Bailey, T. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *J. Environ. Manag.* **2017**, *197*, 522–538. [CrossRef] [PubMed]
84. Gao, L.; Wang, Z.; Xie, J.; Liu, Y.; Jia, S. Simulation of the Cooling Effect of Porous Asphalt Pavement with Different Air Voids. *Appl. Sci.* **2019**, *9*, 3659. [CrossRef]
85. Li, H.; Harvey, J.; Ge, Z. Experimental investigation on evaporation rate for enhancing evaporative cooling effect of permeable pavement materials. *Constr. Build. Mater.* **2014**, *65*, 367–375. [CrossRef]
86. Rymer, B.; Donavan, P.R. Determining End Limits of Quieter Pavement Projects. *Transp. Res. Rec. J. Transp. Res. Board* **2011**, *2233*, 145–151. [CrossRef]
87. Bao, T.; Liu, Z.L.; Zhang, X.; He, Y. A drainable water-retaining paver block for runoff reduction and evaporation cooling. *J. Clean. Prod.* **2019**, *228*, 418–424. [CrossRef]
88. Santamouris, M.; Gaitani, N.; Spanou, A.; Saliari, M.; Giannopoulou, K.; Vasilakopoulou, K.; Kardomateas, T. Using cool paving materials to improve microclimate of urban areas—Design realization and results of the flisvos project. *Build. Environ.* **2012**, *53*, 128–136. [CrossRef]
89. He, B.-J.; Wang, J.; Liu, H.; Ulpiani, G. Localized synergies between heat waves and urban heat islands: Implications on human thermal comfort and urban heat management. *Environ. Res.* **2020**, *193*, 110584. [CrossRef]
90. Taleghani, M.; Berardi, U. The effect of pavement characteristics on pedestrians' thermal comfort in Toronto. *Urban Clim.* **2018**, *24*, 449–459. [CrossRef]

91. Shimazaki, Y.; Aoki, M.; Nitta, J.; Okajima, H.; Yoshida, A. Experimental Determination of Pedestrian Thermal Comfort on Water-Retaining Pavement for UHI Adaptation Strategy. *Atmosphere* **2021**, *12*, 127. [CrossRef]
92. Kántor, N.; Unger, J. The most problematic variable in the course of human-biometeorological comfort assessment—The mean radiant temperature. *Open Geosci.* **2011**, *3*, 90–100. [CrossRef]
93. ISTAT. Population Data by Municipality. Available online: https://demo.istat.it/app/?i=P02&l=it (accessed on 10 February 2023).
94. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef] [PubMed]
95. Sistema Nazionale per la Protezione dell'Ambiente (SNPA). Rapporto—Consumo di suolo, Dinamiche Territoriali e Servizi Ecosistemici. Edizione 2022. 2022. Available online: https://www.isprambiente.gov.it/it/attivita/suolo-e-territorio/suolo/il-consumo-di-suolo/i-dati-sul-consumo-di-suolo (accessed on 25 February 2023).
96. Sistema Nazionale per la Protezione dell'Ambiente (SNPA). Il Consumo di Suolo in Italia. Trasformazioni in atto e attività di monitoraggio—Edizione 2022. Available online: https://webgis.arpa.piemonte.it/agportal/apps/MapSeries/index.html?appid=a69317f87a5745a0b556526579755e37 (accessed on 10 February 2023).
97. ISPRA e SNPA. Schede Regionali. Consumo di Suolo, Dinamiche Territoriali e Servizi Ecosistemici. Report di sistema SNPA | 32 2022. Available online: https://www.snpambiente.it/2022/07/26/consumo-di-suolo-dinamiche-territoriali-e-servizi-ecosistemici-edizione-2022/ (accessed on 20 February 2023).
98. Regione Veneto. Contenimento del Consumo di Suolo. 2022. Available online: https://www.regione.veneto.it/web/ambiente-e-territorio/contenimento-consumo-di-suolo#:~:text=14%2F2017%2C%20della%20quantit%C3%A0%20massima,4%20della%20legge%20regionale%20n (accessed on 20 February 2023).
99. Lobaccaro, G.; De Ridder, K.; Acero, J.A.; Hooyberghs, H.; Lauwaet, D.; Maiheu, B.; Sharma, R.; Govehovitch, B. Applications of Models and Tools for Mesoscale and Microscale Thermal Analysis in Mid-Latitude Climate Regions—A Review. *Sustainability* **2021**, *13*, 12385. [CrossRef]
100. Noro, M.; Lazzarin, R. Urban heat island in Padua, Italy: Simulation analysis and mitigation strategies. *Urban Clim.* **2015**, *14*, 187–196. [CrossRef]
101. Busato, F.; Lazzarin, R.; Noro, M. Three years of study of the Urban Heat Island in Padua: Experimental results. *Sustain. Cities Soc.* **2014**, *10*, 251–258. [CrossRef]
102. Noro, M.; Busato, F.; Lazzarin, R.M. UHI effect in the city of Padua: Simulations and mitigation strategies using the Rayman and Envimet models. *Geogr. Pol.* **2014**, *87*, 517–530. [CrossRef]
103. Zhang, L.; Yuan, C. Multi-scale climate-sensitive planning framework to mitigate urban heat island effect: A case study in Singapore. *Urban Clim.* **2023**, *49*, 101451. [CrossRef]
104. Naboni, E.; Havinga, L.C. *Regenerative Design in Digital Practice: A Handbook for the Built Environment*; Eurac Research: Bolzano, Italy, 2019.
105. Epw Map—Ladybug. Available online: https://www.ladybug.tools/epwmap/ (accessed on 15 December 2022).
106. Climate.OneBuilding.Org. Available online: https://climate.onebuilding.org/ (accessed on 15 December 2022).
107. Oikolab. Available online: https://oikolab.com/ (accessed on 15 December 2022).
108. Shiny Weather Data. Available online: https://www.shinyweatherdata.com/ (accessed on 15 December 2022).
109. ARPAV. Dati Meteorologici Orari. Available online: https://www.ambienteveneto.it/datiorari/ (accessed on 15 December 2022).
110. ENVI-met. Available online: https://www.envi-met.com/it/ (accessed on 15 December 2022).
111. Crank, P.J.; Sailor, D.J.; Ban-Weiss, G.; Taleghani, M. Evaluating the ENVI-met microscale model for suitability in analysis of targeted urban heat mitigation strategies. *Urban Clim.* **2018**, *26*, 188–197. [CrossRef]
112. Croce, S.; D'agnolo, E.; Caini, M.; Paparella, R. The Use of Cool Pavements for the Regeneration of Industrial Districts. *Sustainability* **2021**, *13*, 6322. [CrossRef]
113. Yang, X.; Zhao, L.; Bruse, M.; Meng, Q. Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces. *Build. Environ.* **2013**, *60*, 93–104. [CrossRef]
114. Gros, A.; Bozonnet, E.; Inard, C. Cool materials impact at district scale—Coupling building energy and microclimate models. *Sustain. Cities Soc.* **2014**, *13*, 254–266. [CrossRef]
115. Tsoka, S.; Tsikaloudaki, A.; Theodosiou, T. Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications—A review. *Sustain. Cities Soc.* **2018**, *43*, 55–76. [CrossRef]
116. Lobaccaro, G.; Croce, S.; Vettorato, D.; Carlucci, S. A holistic approach to assess the exploitation of renewable energy sources for design interventions in the early design phases. *Energy Build.* **2018**, *175*, 235–256. [CrossRef]
117. Tsoka, S.; Tsikaloudaki, K.; Theodosiou, T.; Bikas, D. Urban Warming and Cities' Microclimates: Investigation Methods and Mitigation Strategies—A Review. *Energies* **2020**, *13*, 1414. [CrossRef]
118. Wang, J.; Santamouris, M.; Meng, Q.; He, B.-J.; Zhang, L.; Zhang, Y. Predicting the solar evaporative cooling performance of pervious materials based on hygrothermal properties. *Sol. Energy* **2019**, *191*, 311–322. [CrossRef]
119. Yi, Y.; Jiang, Y.; Li, Q.; Deng, C.; Ji, X.; Xue, J. Development of Super Road Heat-Reflective Coating and Its Field Application. *Coatings* **2019**, *9*, 802. [CrossRef]
120. Bröde, P.; Jendritzky, G.; Fiala, D.; Havenith, G. The Universal Thermal Climate Index UTCI in Operational Use. In Proceedings of the Conference: Adapting to Change: New Thinking on Comfort Cumberland Lodge, Windsor, UK, 9–11 April 2010; Available online: http://nceub.org.uk (accessed on 21 April 2023).

121. Jendritzky, G.; Havenith, G.; Weihs, P.; Batchvarova, E. Towards a Universal Thermal Climate Index UTCI for Assessing the Thermal Environment of the Human Being; Final Report COST Action 730; 2009. Available online: https://www.cost.eu/actions/730/ (accessed on 17 March 2023).
122. Di Napoli, C.; Pappenberger, F.; Cloke, H.L. Assessing heat-related health risk in Europe via the Universal Thermal Climate Index (UTCI). *Int. J. Biometeorol.* **2018**, *62*, 1155–1165. [CrossRef]
123. UTCI. Available online: https://utci.lobelia.earth/what-is-utci (accessed on 17 March 2023).
124. Vujovic, S.; Haddad, B.; Karaky, H.; Sebaibi, N.; Boutouil, M. Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements. *Civileng* **2021**, *2*, 459–484. [CrossRef]