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Abstract. Urban greening has great ecological, social and economic benefits for the built environment. It also has significant impacts on the microclimate and urban energy balance. In this study, we quantify the impacts of urban greening on the ground surface temperatures and the microclimate (e.g. the air temperature and the wind speed variation) as well as the cooling demand at the European scale. Specific archetypes for seventeen European cities are generated based on each city's geometrical and statistical data. Additionally, several greening scenarios are proposed. The results show the positive effects of urban greening on mitigating rising ambient air temperatures, decreasing annual average ground-surface temperatures, and reducing the cooling demand, mostly in South European cities.

1. Introduction

With rising urbanization, the urban heat island (UHI) effect, i.e. the phenomenon that urban atmospheres are warmer than the surrounding rural or non-urbanized areas [1], is increasing. In this regard, manmade (anthropologic) land-cover changes [2] and substitution of vegetation by built and artificial surfaces play a vital role, as they increase heat storage within the urban canopy and contribute to the UHI. More specifically, artificial surfaces such as asphalt, concrete, and pavement materials absorb significant heat, which leads to an air temperature rise through the heat convection process [4]. With increasing temperatures, energy consumption increases and air quality degenerates [5]. Consequently, the management of the microclimate becomes primordial. Several factors affect the microclimate, including the city structure, the surface materials used in the built environment, the availability of urban vegetation, precipitation, and heat generation [6]. Incorporation of cool materials that possess high solar reflectance and infrared emittance properties and maintain lower surface temperatures in the urban environment [7] as well as the integration of urban green spaces (urban greening) such as parks, open spaces, gardens, green walls or roofs, are advanced ways to mitigate the rising UHI intensities and the rising energy demands [8]. While there are a few studies that explore the impacts of urban greening at the neighborhood and urban scale, there has to date hardly been any study exploring the impact of urban greening on the energy demand and the microclimate at the regional scale. In this study, a methodological approach is proposed to quantify these impacts for seventeen European cities.

2. Methodology

The following European metropolitan areas are considered in this study in order to assess the impact of urban greening, or grass ground covering, on the energy demand and the microclimate using an archetype approach. These include Athens, Madrid, Rome, Paris, Brussels, Bern, Prague, Vienna, Budapest, Warsaw, Amsterdam, Berlin, Dublin, London, Copenhagen, Oslo and Stockholm. Towards the above objective, the methodology presented in Figure 1 is adopted, which is explained in detail in this section.

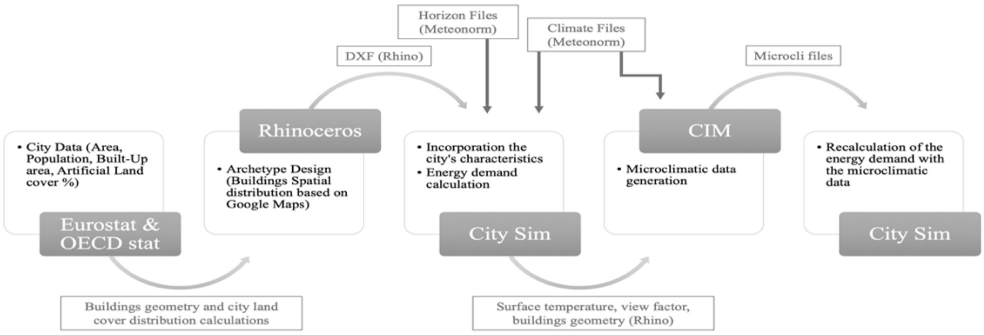

Figure 1. Representative block flow diagram of the methodology followed in this study

2.1. Archetype generation

First, data such as total surface area, population size, built area percentage, artificial or greening land-cover percentages are retrieved for each metropolitan region from the Eurostat [9] and Organization for Economic Co-operation and Development (OECD) databases [10]. Based on this information, the total surface area required by the population in a typical city is calculated based on the SIA 2024 standards [11]. Each metropolitan area considers the densely populated city center or urban core, as well as the surrounding territories and urban areas. Knowing the percentage of built area in each city, and assuming that the ground floor area of each building in the archetype occupies 5% of the total ground area, the number of buildings in each of the archetypes is determined. Also, the greening and artificial land cover percentages in the archetype model are the same as those in the database, and greening is represented by grass ground covering. Following that, specific archetypes, representative of each of the metropolitan areas, are generated by using Rhinoceros (3D computer graphics application software). A standard urban archetype configuration is assumed for all the metropolitan areas, however, the building's emplacement in each archetype is based upon the assessment of each metropolitan area's actual urban configuration. For this task, the aerial view is retrieved from Google Maps, and the direction of urban development starting from the city center is assessed. Following that, the archetype is generated assuming that the buildings of the urban core are represented by a central building, and the adjacent buildings are characteristic of the main urban development areas. As an assumption, the buildings in the model are placed equidistantly to each other and to the artificial areas, to minimize microclimate and energy demand variations. For example, urban development can be seen towards the North, North-East, North-West, West, and South-East directions (Fig. 2, a). Accordingly, the archetype is developed in order to capture the actual city configuration as shown in Fig. 2 (b). Finally, the archetypes generated are imported in the form of a DXF file into CitySim Pro, an urban energy simulation software (Fig. 2 (c)). The horizon and climatic data of each metropolitan area are retrieved from the Meteonorm database. These are imported into CitySim [12], in the form of .hor and .cli file. An XML file is generated, where all the technical and geometric properties can be accessed and specified.

2.2. Buildings specifications and ground scenarios simulation

Buildings are assumed to be Multi Family Houses (MFH) and their typologies as well as their thermal characteristics are modified for each city, according to those of a previous work [13,14] based on TABULA database [15]. The effective number of occupants in each MFH is calculated, as well as their daily schedule [16,17]. To obtain the net energy demand through CitySim, the heat emitted by lighting and electrical appliances is accounted for [16]. Two ground surface material covering scenarios are considered in this study: One asphalt and one greening namely, "All Asphalt" and "Green" for the greening [18]. Details on the modeling of greenery are available in [18], and the Penman-Montheith method, which is the most commonly used and recommended method by the Food and Agriculture Organization of the United Nations (FAO), is applied for the computation of the evapotranspiration [18].

Figure 2. (a) Identification of the main urban development directions starting from the urban core (metropolitan area of Amsterdam) (b) Placement of a central building characteristic of the buildings of the urban centre, and of five adjacent buildings representative of the buildings in each direction of the urban development areas (given that Amsterdam is 30% built [9]), (c) Archetype imported into CitySim in the form of a DXF file.

2.3. Energy demand simulations and microclimatic data generation

For each metropolitan region, two XML files are generated which corresponds to each ground scenario that is used to compute the demand. The ground surface temperatures and view factors are computed by using CitySim. Afterwards, the air temperature, wind speed, and wind direction (obtained from Meteonorm), and the buildings geometry in the archetype are imported into the Canopy Interface Model (CIM) [19] to generate the microclimatic conditions.

3. Results and Discussion

3.1. Impact of greening on the ground surface temperatures

The impact of ground covering on the ground surfaces temperatures for each assessed city is presented in Fig. 3. The green color shading (Fig.3) represents the different greening land-cover percentage in each of the metropolitan areas.

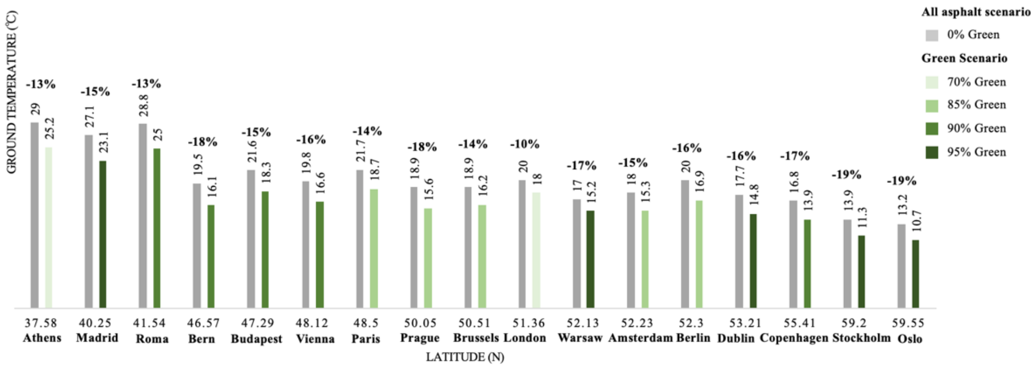

Figure 3. Average annual ground surface temperatures, under the influence of the urban microclimate

When the majority of asphalt surfaces are replaced with grass (going from an "All Asphalt" to a "Green" scenario), lower annual average ground surface temperatures can be observed as presented in Fig. 3. The decrease in annual average ground surface temperatures can be explained by the evapotranspiration of the grass and the reflective properties of the ground surface materials. Due to the evapotranspiration, the grass presents a lower temperature than the artificial surfaces [20] even when it is exposed directly to solar irradiation. The percentages decrease obtained depends on the ratio of greening available in each city, upon the built area. Considering Oslo or Stockholm, which in the maximum greening scenario are 95% green and only 5% built, the highest percentages of decrease (equal to 19%) are observed. Whereas the lowest percentage of decrease, about 10%, is observed for London, which is densely built (30% built) and 70% green. Considering Southern cities of interest with significant cooling demands, such as Athens, Madrid and Rome, the absolute decreases in annual average ground surfaces temperature are respectively equal to 4.2°C, 4°C and 3.8°C. As the cooling potential of grass is more pronounced during the summer and under greater solar irradiance, the highest differences are also observed. For these three cities, the differences are respectively equal to 5°C, 6°C and 6.2°C in July, as compared to 2.3°C, 2°C and 1.6°C in January.

The simulation model is validated by comparing the buildings' heating demands obtained (considering the urban climate) in Tabula database [15]. The difference between the model and the Tabula measured data equals 9%, which presents a good agreement between the two.

3.2. Impact of greening on the microclimate

The annual average ambient air temperatures and wind speeds for each city, as provided by Meteonorm (blue bars) and those computed by CIM (green and grey bars, considering each ground covering scenario), are shown in Fig. 4.

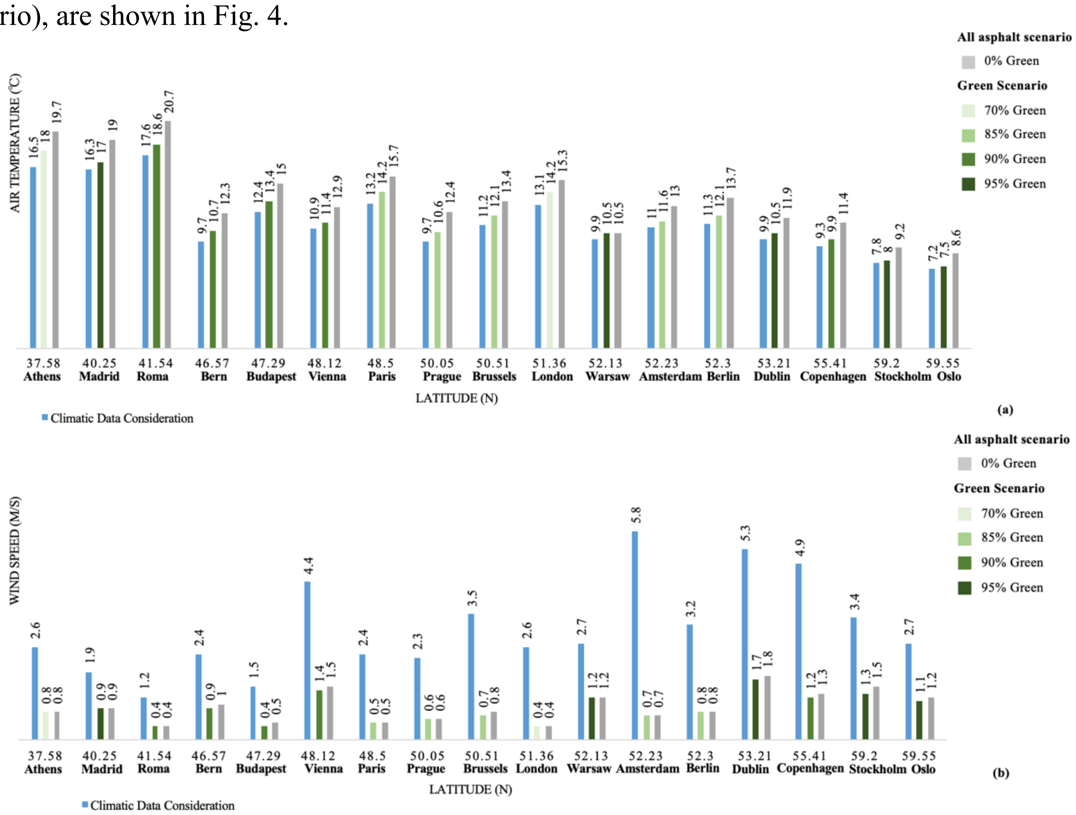

Figure 4. Annual average air temperatures (a) and annual average wind speeds (b), as provided by Meteonorm (blue bars-climatic data consideration) and as computed by CIM (microclimatic data).

As a percentage of greening is introduced, ambient air temperatures decrease above the ground surfaces and within the urban canopy. These decreases directly reflect the impact of ground covering on the air temperature in the microclimate environment, and the cooling potential of grass. Absolute decreases in annual average air temperatures observed when comparing the values obtained under a "Green" scenario to those obtained under an "All Asphalt" scenario are equal to 1.7°C (9% decrease), 2°C (10% decrease) and 2.1°C (10% decrease) respectively for Athens, Madrid and Rome. More specifically, the highest monthly average decreases in air temperatures correlate with the highest monthly average decreases in ground surface temperatures. For Athens, Madrid and Rome, the air temperature decreases during July are respectively equal to 2.6°C, 3.3°C, 3.7, while those observed during January are equal to 0.8°C, 0.7°C, and 0.7°C. The different values obtained for these three cities are explained by the percentage of greening available (70%, 95% and 90% respectively for Athens, Madrid and Rome), the percentage of built area, and the height of buildings modeled.

The impact of greening on the urban microclimate is also more noticeable for the most southern cities, namely the three previously mentioned cities, as these present warmer climates, longer and sunnier days annually (high solar radiation) as compared to cities situated more to the North. The highest decreases in absolute annual average air temperature are observed for the mentioned three cities, as compared to the lowest ones of 1.2ºC and 1.1ºC observed for Oslo and Stockholm.

Increases in air temperatures observed when comparing those provided by CIM (microclimatic scenario) to those retrieved from Meteonorm (climatic scenario). This can be explained partly by the fact that CIM considers the influence of buildings present and surface temperatures in the urban environment when calculating the high resolution vertical profiles of the meteorological variables. Given that lower wind speeds are calculated by CIM, there is a local trapping of heat inside the canopy layer, which leads to an increase in the air temperature [21]. The height of buildings also influences those calculated values. The annual average wind speeds as provided by Meteonorm and those calculated by CIM for each city are shown in Fig.4b.

3.3. Impact of greening on the energy demands
When CitySim is coupled with CIM, energy demand considering microclimatic conditions is computed. Higher heating demands are observed for all cities when greening is introduced. The annual heating demand percentage increases by 5% for all the cities considered. However, given that the cooling potential of grass is most evident during the summer, by lowering ambient air temperatures, the impact of greening is most prominent on the cooling demands (as shown in Fig. 5).

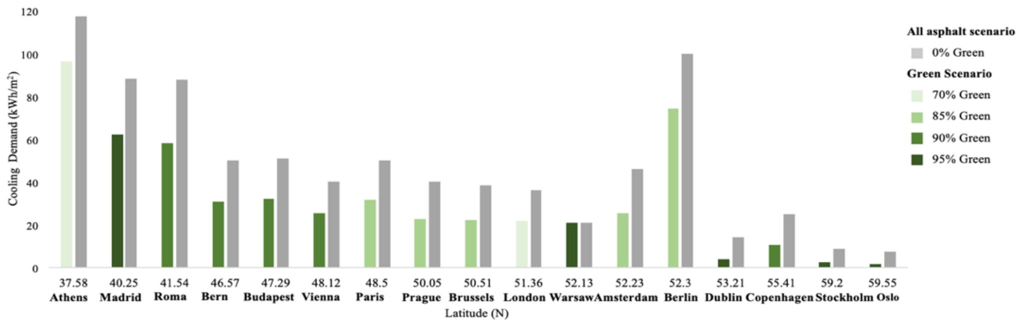

Figure 5. Annual cooling demands computed on CitySim considering microclimatic conditions.

For the most southern European cities such as Athens, Madrid and Rome, the percentages of cooling demand decrease are respectively equal to 18%, 29.6% and 33.5%. These results confirm the positive impact of greening and the influence of land cover greening percentage (among other factors) on reducing cooling demand. For instance, Athens is 70% green whereas as Madrid is 95% green. The results obtained during a typical summer month, such as July, are summarized in Table 1.

Table 1: Impact of greening obtained for the three most southern European cities during July

City	Average ground surface temperature decrease (ºC, %)	Average ambient air temperature decrease (ºC, %)	Cooling demand decrease (kWh/m^2, %)
Athens	5ºC (11%)	2.6ºC (8%)	4.2 kWh/m^2 (14.5%)
Madrid	6ºC (13%)	3.3ºC (11%)	5.4 kWh/m^2 (23.8%)
Rome	6.2ºC (13%)	3.7ºC (11%)	6 kWh/m^2(30%)

4. Conclusion and Recommendations
In this study, the impact of greening and grass ground covering on the urban microclimate and urban energy demands is assessed and quantified. When grass surface is introduced, there is a decrease in

ground surface temperature, given the evapotranspiration and reflective properties of grass. The impact of greening is more obvious for Southern European cities, under high solar radiation, and during summer months and sunny times of the day. The cooling potential of grass is reflected by a cooling of the ambient air above the ground surfaces, as the air temperature decreases. As grass provides cooling effects, when green surfaces are introduced (Scenario "Green") significant decreases in cooling demand, during the summer months, are observed. The percentages of annual average decrease in cooling demand are respectively equal to 18%, 30%, and 34% for Athens, Madrid and Rome. Limitations of this study include the assumption of a certain standard urban archetype configuration. While the impact of greening in decreasing ambient air temperatures and cooling demands is demonstrated (by comparison of two ground covering scenarios), a different archetype configuration will lead to different results. Two main future developments of this study are first, building a more extensively elaborated archetype (including different urban configurations and other types of vegetation) for each metropolitan area of a country, which would bring to a comprehensive analysis at the European level. Second, the optimization of the energy systems for each archetype, in order to provide a comprehensive view of a European energy hub.

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