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Urban microclimate and climate change impact on the thermal performance and ventilation of multi-family residential buildings

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ABSTRACT

Urban settings and climate change both impact on energy use and thermal comfort inside buildings. This paper first presents a study of changes in energy demand in residential buildings considering the overlapping effect of climate change and urban heat island intensity in two European locations; Cadiz (Spain) and London (United Kingdom), representing temperate and hot European climates and moderate and dense urban settings. Future-urban weather files were generated and simulations were run considering energy demand and indoor thermal comfort. In hot climate regions such as the one of Cadiz, future climate will increase the cooling demand and the additional impact of the UHI leads to a further increase of up to +28% of total energy demand compared to the current climate without considering urban effects. Future-urban weather conditions will be detrimental also for buildings in London, where the annual energy demand is predicted to increase by up to the 16% if future climate and urban effects are included. This is due to a higher increase in cooling demand compared to the reduction for the heating need. The paper also presents a method to take into account microclimatic conditions in naturally ventilated buildings, especially the effect of wind variations around the building which impacts natural ventilation rates. Air and surface temperature and wind speeds were studied using ENVImet and the resulting microclimatic conditions were used as inputs to the EnergyPlus Airflow Network model for the calculation of the building ventilation rates. It was found that ventilation rates are reduced (in comparison to meteorological weather files) and this reduction impacts negatively on internal operative temperatures. A thermal comfort analysis was carried out indicating that the selection of a suitable weather file and microclimatic conditions is essential for more accurate predictions of internal thermal comfort and will assist in the sizing of passive and active systems to avoid overheating.

1. Introduction

In thermal simulations studies of buildings, ambient conditions are accounted for by using weather files of the building's location, providing hourly values of typical ambient conditions: temperature, humidity, solar radiation, wind. Weather files are built using historical observational data usually over 30 years; they are based on measurements at meteorological stations usually at airports. Therefore, weather files do not account for characteristics of the urban environment which modifies climatic conditions, especially those of air temperature and wind. In addition, buildings designed and built today, will last for many years. Therefore, future climate projections should be used to predict how our buildings will perform in 30 or 50 years. Using such climate projections can ensure that energy and comfort performance simulations can more realistically predict future performance – avoiding what has been termed 'performance gap', between measured performance and predicted performance.

In addition to climate change, urban environments experience a local increase of air temperature due to the so-called Urban Heat Island (UHI) effect [38,39]. The UHI intensity is defined as the temperature difference between urban areas and their surrounding rural areas. The temperature increase is caused by enhanced absorption and storage of heat in urban areas compared to rural environments due to building density, thermal capacity and optical properties of building and urban materials, lack of vegetation and water and anthropogenic heat generation from vehicles and HVAC systems [13,22,54,39,46,50].

The UHI intensity varies across a city depending on the characteristics of the urban fabric. The temperature increase is higher in the

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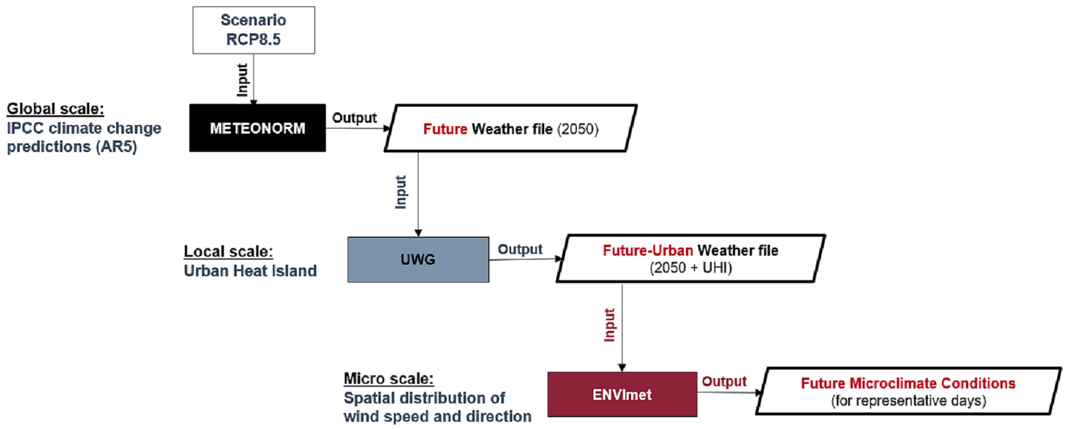

Fig. 1. Method to generate future urban microclimate conditions to perform dynamic thermal simulations.

denser urban areas with tall buildings and narrower canyons, where high amount of vertical surfaces intercept and absorb solar radiation, reduce the infrared exchange with the sky and reduce the wind speed and the convective heat losses [13,45,60,50]. Many studies correlated the UHI intensity with density parameters such as the ratio of building footprint to total urban site, the average building height, the ratio of building height to the street width and the ratio of façade surface to total site [22,54,42,14,50,48,51]. The temperature variability across a city due to the density of urban fabric significantly affects the energy impact of the UHI [20,25]. Furthermore, the UHI intensity is variable with time and season, being stronger in the summer, due to higher solar radiation and absorption by urban structures. For this reason, the negative energy impact in summer normally overcomes the energy saving in winter in hot and temperate climates, resulting in an overall increase of annual energy demand compared to a rural environment [52].

Urban environments also affect wind speed and direction. The roughness of the urban surface decreases the wind speed by 20 to 30% and increases the turbulence intensity by 50 to 100% when moving from the countryside to the city [11], modifying the free stream velocity above the buildings [40]. The reduction of mean wind speed at the pedestrian level is even higher, reaching up to 60% in dense urban areas [43]. The building shape and the geometrical characteristics of its surroundings (i.e. the ratio of the width and the length of the street to the height of the buildings) also impact on the airflow around urban buildings modifying the natural ventilation potential of buildings [31,58]. These micro-scale phenomena have significant impact on the outdoor thermal comfort but also on the building energy performance in urban context [9,10,35,36,47–48]. Therefore, these micro-scale modifications should also be accounted for when performing building performance simulations in the urban context.

The impact of the overlapping effect of global warming and urban microclimate on building thermal performance is therefore important for our understanding on how building will perform now and in the future. Methodologies for generation of future weather files for building simulation exist following IPCC scenarios [15,17,18,26]. Methodologies which include both future weather and urban microclimate are less developed. Extensive research has been carried out on urban climate models and coupling methodologies to include urban microclimate in dynamic thermal simulation (DTS) [2,19,23,28,51,55,59]. However, very few attempts have been reported to generate future weather data that also include urban effects, to investigate the thermal performance and overheating risk of buildings under future urban climate conditions [7,20,29,49].

To fill this gap, we proposed a methodology based on the use of urban climate models (UWG) and detailed microclimate models (ENVImet) for urban microclimate simulation, in order to investigate the overlapping effects of climate change and urban effects on the future performance of urban buildings. The novel contribution of this paper consists in using the future-urban weather file as input to microclimate simulations, to investigate the impact of the buildings' shape and urban context on the air flow and surface temperatures distribution and if these microclimate modifications have negative impacts on the indoor environment.

2. Methodology

The methodology adopted in this study to generate future urban microclimate conditions to perform Dynamic Thermal Simulations

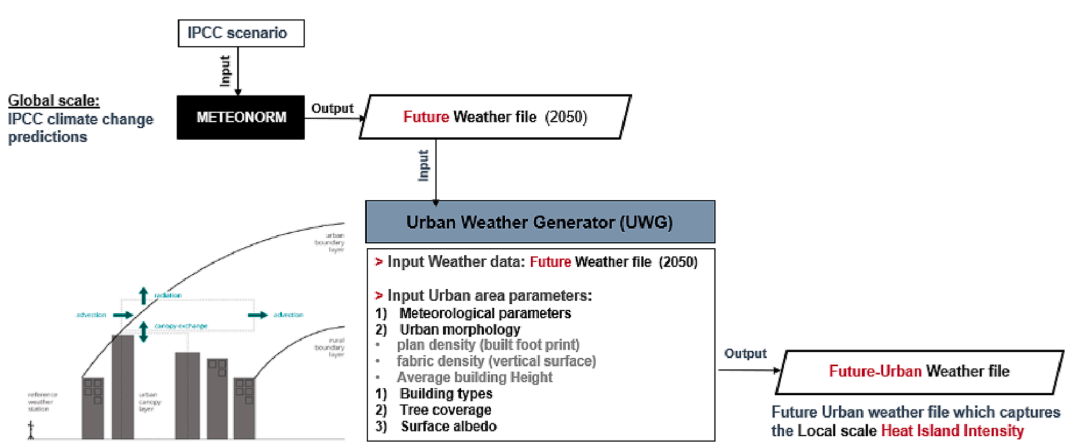

Fig. 2. Procedure to include the UHI effect in future weather files using the Urban Weather Generator.

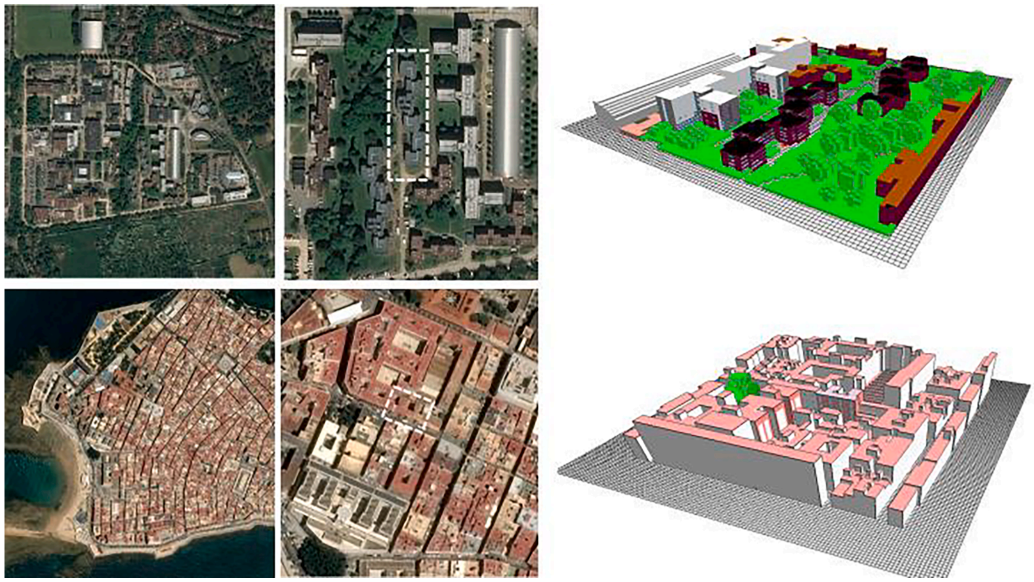

Fig. 3. Aerial view of the London and Cadiz buildings and urban context and corresponding ENVImet models.

(DTS) is reported in Fig. 1. The methodology is demonstrated on two case-study residential buildings, one located in London, UK and the second in Cadiz, Spain. These buildings were demonstration residential buildings of the ReCO2ST project and thus provided data for this study.

METEONORM was used to generate contemporary and future weather files. The contemporary weather files are based on meteorological observations recorded between 1996 and 2015 for solar radiation and 2000 and 2019 for all other parameters for both locations of London and Cadiz. For the future weather files, the 2050 RCP 8.5 of the AR5 scenarios [18] was used to represent a pessimistic scenario which seems likely for the next 30 years.

The future weather files were used as input to the UWG [4,5] to generate future-urban weather files, capturing the local modifications of air temperature determined by an urban area at the local scale [50,48,51].

2.1. Generating future-urban weather files

The Urban Weather Generator (UWG) has been developed to generate urban canyon weather files using rural weather files as input [5,28]. UWG is composed of four modules: a Rural Station Model, a Vertical Diffusion Model, an Urban Boundary Layer model and an Urban Canopy model including a Building Energy Model which allows to account for the impact of buildings on the urban air temperature. The modules are described in detail in the relevant publications by B. Bueno and J. Mao [6]; Bueno, Hidalgo, et al. [4]; Bueno, Norford, et al. [5,28]. The MATLAB version of UWG V4.1 [27]was used for this analysis.

The urban weather file generated by UWG accounts for the heat fluxes from roofs, walls and windows and the road and the anthropogenic heat fluxes due to exfiltration and waste heat from building HVAC systems and traffic. The input weather conditions are given by a "rural" weather file – generally the airport weather file – in the EnergyPlus format (.epw). In this study, the future weather files generated by METEONORM are used as input to UWG calculations to generate future-urban weather files that capture the local UHI intensity of the urban areas where the buildings are located. This is shown diagrammatically in Fig. 2.

The urban area in UWG is described through a set of parameters representative of key urban fabric characteristics that affect UHI intensity, namely: urban morphology parameters, building typology mix, vegetation coverage, anthropogenic heat from traffic and albedo, thermal capacity and emissivity of urban materials. Among these, the most relevant are the urban morphology parameters [5,28,34,50].

In UWG, urban morphology is described using three parameters:

- Building density: ratio of the building footprints area to the urban site area
- Vertical to Horizontal Ratio: ratio of the building facades area to the urban site area
- Average building height: average height of building normalised by building footprint

These are used to calculate the average width and height of the urban canyon for the computation of the external surface temperatures of walls, roads and roofs based on the incoming, absorbed and reflected radiation by urban surfaces.

Also the meteorology parameters have been found to have a huge impact on the accuracy of the urban temperature estimation compared to observations [28]. For this reason, the UWG models are calibrated with measured urban air temperatures in order to find the best fit of the meteorological parameters for each location.

UWG generates urban weather files with morphed air temperature and relative humidity values based on the hourly UHI intensity of the urban area, keeping the other variables to the same value as in the input weather file.

2.2. Generating future urban microclimate conditions

The air circulation around buildings is another climate modification affecting building energy performance in dense urban areas. A methodology to account for this effect has been recently proposed [51], bringing together the power law profile used in the British Standard on ventilation for buildings (British Standards [3] and the empirical models of wind speed in urban canyons developed for the URBVENT project [11]. This methodology can be used to calculate hourly urban wind speed values from undisturbed wind speed values by following the algorithm reported in [51]depending on the geometry and orientation of the urban canyon and the velocity and direction of the undisturbed wind speed.

However, these simplified models do not account for the impact of the actual three-dimensional geometry of the building and its surrounding obstacles on the air flow around the building. In this study, ENVImet was used to perform microclimate simulations to investigate the impact of the demo buildings' shape and urban context on the air

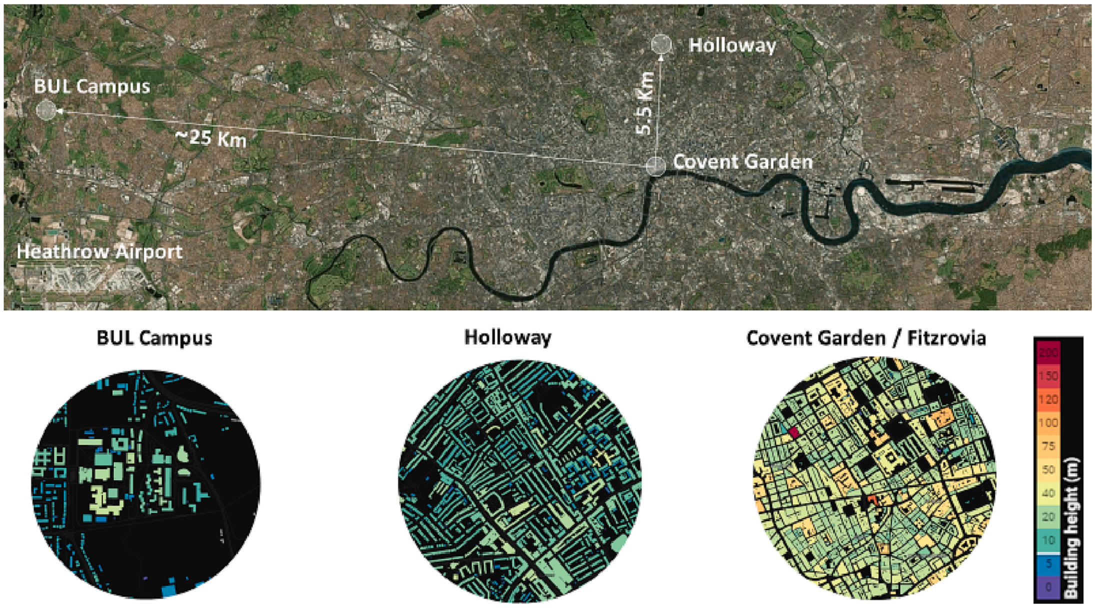

Fig. 4. Urban fabric characteristics of different areas across Greater London. The Holloway area is taken as reference for the estimation of the UHI intensity in a typical residential area of London.

flow and surface temperatures and if these microclimate modifications have negative impacts on the indoor environment.

ENVImet is a microclimate simulator for urban areas with high spatial and temporal resolution. The model has been further developed in the last years [16]. The last release V4.4.4 allows to run simulations in "full forcing" mode, namely using local hourly values of air temperature, relative humidity, wind speed and direction as input inflow boundary conditions to the three-dimensional CFD atmospheric model, increasing significantly the model accuracy [47].

The ENVImet simulations were performed for two case-studies, using as input the air temperature, relative humidity, wind speed and direction of the hottest week of the future weather files generated by METENORM. The ENVImet models for Cadiz and London are reported in Fig. 3, Fig. 14 and Fig. 19.

The outputs of the microclimate simulations provided the spatial and temporal distribution of wind speed and directions at the building facades and the surface temperatures of surrounding buildings. These were used as boundary conditions to the EnergyPlus models of the two buildings, to investigate their impact on the indoor thermal environment. The ENVImet simulations were run for 108 h so as to have hourly outputs for 4 days, discarding the first 12 h buffer time.

2.3. Linkage between ENVImet outputs and EnergyPlus

The outputs of the ENVImet microclimate simulations were used as input values to the Air Flow Network (AFN) models in EnergyPlus for the calculation of the wind pressure and the ventilation rates of the two buildings. This entailed a different approach compared to the standard approach using standard pressure coefficients derived from nearly weather stations which does not account for microclimate around the building. The approach is outlined below.

The EnergyPlus AFN model calculation of the wind pressure (p_w) at each opening is based on Bernoulli's equation (1)

$$p_w = c_p \rho \frac{V_{ref}^2}{2} < \infty \tag{1}$$

where c_p are the wind pressure coefficients and V_{ref}^2 is the local wind speed at the building height calculated with the power law profile, considering the roughness of the weather station site and the building site and the height above ground level [56]. In this study, the pressure coefficients values for each façade have been set based on the AIVC TN44 tables for low-rise buildings surrounded by obstructions equal to the height of the building [40]. The main weakness of this procedure consists in the calculation of the local wind speed based on the power law profile, which is not valid within the urban canopy layer where the presence of large obstacles (buildings, trees) significantly modifies the airflow around buildings. The inaccuracy of the ventilation potential due to this approximation can be relevant, since the wind speed elevated to the second power is the major determinant of the wind pressure calculation.

In this study, the standard approach using the undisturbed wind speed and the pressure coefficients is compared to another approach using the hourly values of wind speed and direction at each facade derived from ENVImet simulations. This approach is similar to previous literature where wind pressure outputs from CFD modelling has been used to calculate wind pressure coefficient on building façades [8,33]. ENVImet does not provide wind pressure outputs, but do provide wind speed at the different cells of the building facades. Therefore, such values can be used to calculate the wind pressure at each opening.

The "Outdoor:nodes" objects in EnergyPlus were used to set the hourly wind speed and direction values calculated by ENVImet as input values to the external nodes of the AFN model for the calculation of the wind pressure. Using this approach, the wind pressure at each AFN external node is calculated as follows:

$$p_w = \pm \rho \frac{V_{CFD}^2}{2} \tag{2}$$

where V_{CFD}^2 is the hourly wind speed in front of the building façade calculated by ENVImet and $\pm$ is the direction of the pressure determined by the relative angle of the wind stream on the facade, considering a positive pressure (inward acting) on the windward facades and a negative one (outward acting) on the leeward surfaces.

In the case of Cadiz, additionally the impact of the surface temperature of the wall opposite to the studied building was investigated. The building in Cadiz is located in a narrow canyon, facing another building of similar height. Some studies highlighted that the actual temperature of surrounding urban elements may affect the thermal performance of urban buildings, by decreasing the heat losses though long-wave exchange with the environment [19,41,51]. For this reason, the impact of

Table 1
Urban Weather Generator Simulation Parameters.

Urban Area		Cadiz - City Centre	London - Holloway area
Meteorological Parameters	**Unit**	**Value**	**Value**
Urban Boundary Layer Height - Day	m	500	1000
Urban Boundary Layer Height - Night	m	50	50
Inversion Height	m	100	50
RSM Temperature Reference Height	m	2	5
RSM Wind Reference Height	m	10	10
Circulation Coefficient	–	1.2	1.2
UCM-UBL Exchange Coefficient	–	0.2	0.3
Day Threshold (for UBL night/day)	W/m^2	350	250
Night Threshold (for UBL night/day)	W/m^2	50	50
Minimum wind velocity	m/s	1	0.5
Rural Average Obstacle Height	m	0.1	0.1
Urban Fabric Characteristics	**Unit**	**Value**	**Value**
Average Building Height	m	14.4	8.6
Fraction of waste heat into canyon	–	0.5	0
Building Density	–	0.56	0.33
Vertical to Horizontal Ratio	–	1.6	0.72
Urban Area Characteristic Length	m	1000	1000
Max Dx	m	250	250
Road Albedo	–	0.21	0.21
Pavement Thickness	m	0.5	0.5
Sensible Anthropogenic Heat (Peak)	W/m^2	8	8
Latent Anthropogenic Heat (Peak)	W/m^2	2	2
Vegetation Parameters	**Unit**	**Value**	**Value**
Urban Area Veg Coverage	–	0	0.17
Urban Area Tree Coverage	–	0.05	0.15
Veg Start Month	–	4	4
Veg End Month	–	10	10
Vegetation Albedo	–	0.25	0.25
Latent Fraction of Grass	–	0.5	0.5
Latent Fraction of Tree	–	0.5	0.5
Rural Road Vegetation Coverage	–	0.5	0.5

the actual temperature of the wall facing the studied building was also investigated. To do so, the hourly surface temperatures calculated by ENVImet have been assigned to the shading surface in front of the main façade of the Cadiz building. This was done by using the new "Surrounding surface" objects of EnergyPlus V9.3.0 and assigning the corresponding view factors to the external surfaces of the main façade of the building. A conceptual illustration of the link between the ENVImet outputs and the EnergyPlus models is reported in Figure and Figure. It must be clarified that also UWG calculates the temperature of the urban canyon surfaces (road, walls and roofs). The calculation is based on the radiant fluxes in the bidimensional, averaged-oriented urban canyon representative of the urban area. This is a simplified approach widely accepted in urban heat island studies to estimate the average urban canyon air temperature. Conversely, the urban canyon model is not sufficiently accurate for surface temperatures estimations, as they show a high variability depending on the actual three-dimensional urban geometry. For this reason, we performed this last set of EnergyPlus simulations using the UWG values as input air temperatures and the ENVImet values just for the surface temperature of the facing building, for a more accurate calculation of the infrared radiation exchange.

3. Results and discussion

3.1. Future weather and impact of urban environments

3.1.1. UHI intensity in representative locations

The building in Cadiz is located in a very dense urban texture and in a climate region with high solar radiation and summer air temperatures, where the UHI intensity has the highest negative impact, increasing the already high cooling energy demand. The Cadiz city centre consists of a small peninsula surrounded by the sea, enabling high ventilation and cooling ability for the built environment as compared to the same urban texture located in more interior locations.

The UHI intensity in London and its impact on building energy performance has been extensively documented [12,20,21,57]. However, the building in London is located in the Campus of Brunel University, in a semi-urban area close to the Heathrow airport where the urban effect is very weak compared to more inner areas. Therefore, another assumption was made for the London building, considering that it was located in a typical residential area of London closer to the city centre (Holloway), where the UHI intensity has been measured [22,47]. The location and the characteristics of the urban fabric in the Holloway area compared to the Brunel area and the city centre are compared in Fig. 4.

The London UWG model was calibrated by comparing the simulated urban temperatures to hourly air temperature measured in the reference urban location in London [47–48]. However, we could not identify a study for Cadiz but we found a study for Sevilla (Romero [44] which has similar urban fabric characteristics. Therefore, we are confident that the UWG output would apply to the urban characteristics of the second case study in Cadiz.

The settings of the UWG models are reported in Table 1.

The comparison between the UWG calculations and the measured urban temperatures was carried out for three summer months. The mean daily cycle of air temperature in June, July and August in the urban

Table 2
Measured and simulated (UWG) monthly UHI intensity in Sevilla and London.

Month	SEVILLA Mean Monthly UHI		CADIZ Mean Monthly UHI	LONDON Mean Monthly UHI	
	Measured	UWG	UWG	Measured	UWG
June	2.4 °C	2.4 °C	1.6 °C	0.7 °C	0.7 °C
July	2.2 °C	2.7 °C	1.8 °C	0.6 °C	0.8 °C
August	2.5 °C	2.9 °C	1.7 °C	0.8 °C	0.7 °C

The calibrated UWG models (London and Cadiz using Seville as a substitute for calibration reasons only) were thus used to generate future-urban weather files for London and Cadiz. The overlapping effect of climate change and UHI intensity on the monthly mean air temperatures in the two locations are reported in Fig. 5 for Cadiz and Fig. 6 for London.

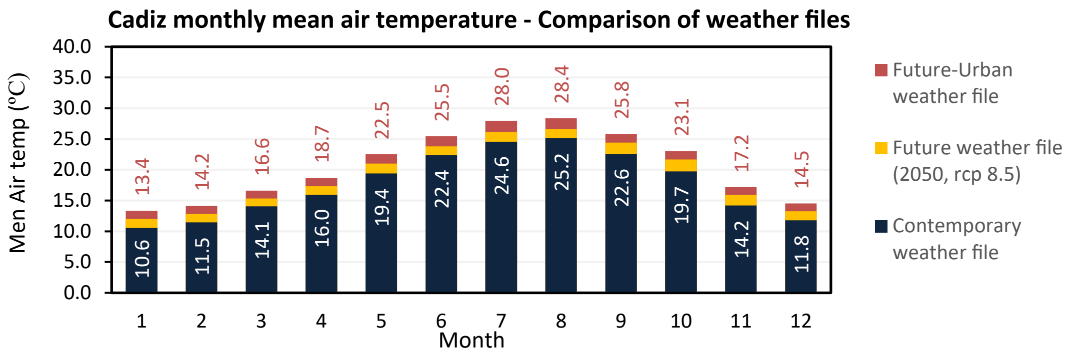

Fig. 5. Monthly mean air temperatures of the current, future and future-urban weather files generated for Cadiz.

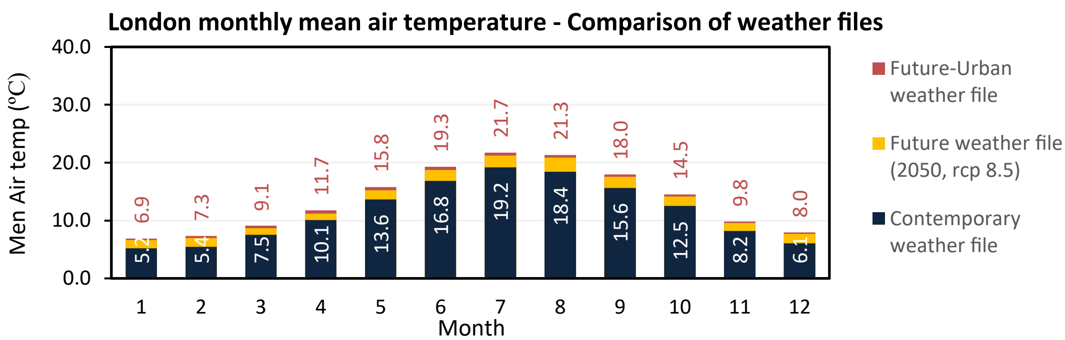

Fig. 6. Monthly mean air temperatures of the current, future and future-urban weather files generated for London.

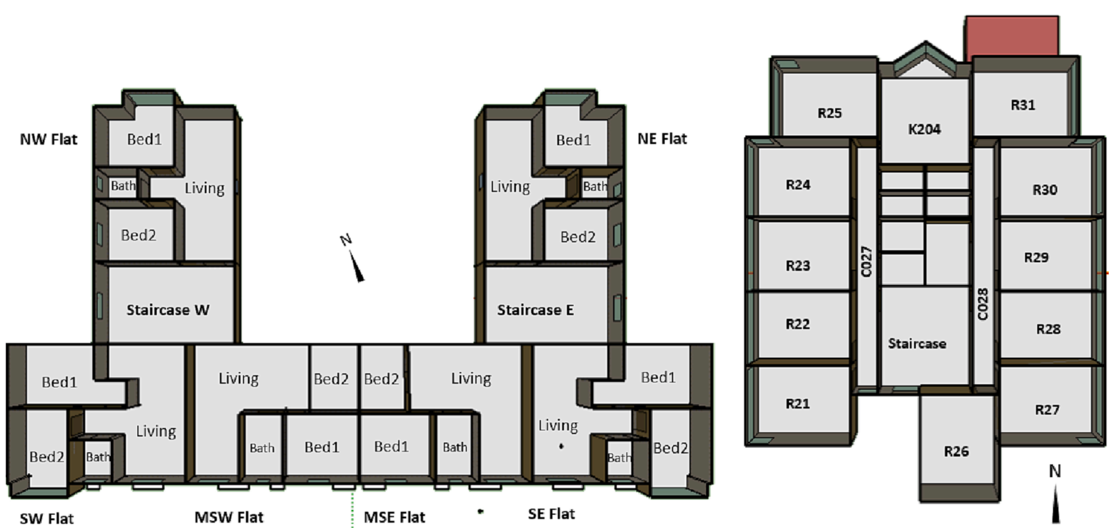

Fig. 7. EnergyPlus models of the typical floor of the demo building in Cadiz (left) and London (right).

locations of London and Sevilla as measured and simulated with UWG was compared showing good agreement. The mean monthly UHI intensity as computed by UWG and measured at the urban locations is reported in Table 2. The results indicate a smaller UHI intensity in Cadiz compared to Sevilla. This is reasonable considering the influence of the ocean on Cadiz's climate, leading to higher wind speed and reduced temperature range compared to Sevilla.

In Cadiz, the monthly mean UHI intensity ranges between a minimum of 1.3 °C in March and November to a mean maximum of 1.8 °C in July. This is similar in magnitude for locations near to Atlantic ocean [1]. The maximum combined effect of climate change and UHI effect is predicted for July, reaching a mean monthly air temperature of 28.0 °C, namely + 3.4 °C compared to the current weather file for Cadiz. This is the result of a 1.6 °C temperature increase due to climate change and additional 1.8 °C increase due to UHI intensity.

In London, the monthly UHI intensity is lower, ranging between a minimum of 0.3 °C in the winter months to a maximum monthly intensity of 0.6 °C in June. Also in London, the maximum combined effect of climate change and UHI effect is predicted for the summer months. In August, the mean monthly air temperature reaches 21.3 °C, which is 2.9 °C higher compared to the mean monthly value from the contemporary weather file for Heathrow. The temperature increase is mainly due to climate change (+2.4 °C) and to a lesser extent to the UHI intensity (+0.5 °C).

Table 3
Settings for the ideal heating and cooling systems used in the simulations.

London		
Ideal Heating system		
Set point	**Schedule**	**Availability**
20 °C	05:00—19:00	Jan - April & Oct-Dec
15 °C	00:00—05:00 & 19:00—23:00	
Ideal Cooling system		
Set point	**Schedule**	**Availability**
25 °C	always on	May-Sep
Cadiz		
Ideal Heating system		
Set point	**Schedule**	**Availability**
20 °C	05:00—19:00	Jan - March & Nov-Dec
15 °C	00:00—05:00 & 19:00—23:00	
Ideal Cooling system		
Set point	**Schedule**	**Availability**
27 °C	always on	Apr - Oct

3.1.2. *Impact of future urban weather on buildings performance*

The impact of future-urban weather files on the building energy demand and the indoor environmental quality have been both assessed. Baseline dynamic thermal models were developed for the Cadiz and the London buildings which are representative of the typical floor of each building. The geometry and thermal zoning of the two models is reported in Fig. 7. The typical floor of the London building consists of 11 bedrooms and communal areas while the typical floor of the Cadiz building is divided into 6 two-bedroom flats.

The baseline DTS models have fabric thermal performance as in the actual buildings. The external wall and glazing U-Values used in the simulations are 1.93 and 2.7 W/m^2•K for London and 1.19 and 5.89 W/m^2•K for Cadiz. The ceiling and floor surfaces are assumed to be adiabatic. The Air Flow Network (AFN) model of EnergyPlus was used to simulate the ventilation rate due to wind pressure, windows opening, and multi-zone airflows linkage. A detailed description of the internal gains and occupancy schedules for these buildings can be found in (Foda and Kolokotroni, 2020). In addition, some controls were applied for shading, ventilation, and heating/cooling system to predict energy demand:

- The shading systems are external shutters in the Cadiz model and internal blinds in the London model. These are assumed to be on if the solar radiation on the windows is higher than 150 W/m^2 to avoid overheating due to an excess of solar gains.
- The ventilation rate is controlled at the zone level assuming that windows are open if the indoor temperature is higher than 23 °C and higher than the outdoor temperature. The minimum air change per hour for indoor air quality in winter are achieved through infiltration.
- Ideal heating and cooling systems were added in the bedrooms and living rooms of both models to estimate the change in the buildings energy demand under different climate boundary conditions. The set points and schedules are reported in Table 3.

The cooling and heating demand of the two buildings was simulated using EnergyPlus and the following weather files:

1) Contemporary weather files
2) Future weather files (2050, RCP 8.5)
3) Future-Urban weather files (including the UHI effect)

3.1.3. *Impact on cooling, heating and annual energy demand*

The results confirm a strong impact of both the future and urban weather conditions on the heating and cooling demands of the two buildings.

The results for Cadiz are illustrated in Table 4 and Fig. 8. As expected, in the hot climate of Cadiz, a further increase of temperature due to climate change and UHI effect is very detrimental on the building

Table 4
Impact of climate change and urban effects on the energy demand of the demo building in Cadiz.

CADIZ	Annual building energy demand per unit of floor area (kWh/m^2)					
	Heating Energy	Δ Heating	Cooling Energy	Δ Cooling	Annual Energy demand	Δ annual energy demand
Contemporary weather file	10.2		18.4		28.7	
Future weather file (2050)	6.7	−34%	25.3	+37%	32.0	+12%
Future-Urban weather file (2050)	4.2	−59%	32.4	+76%	36.7	+28%

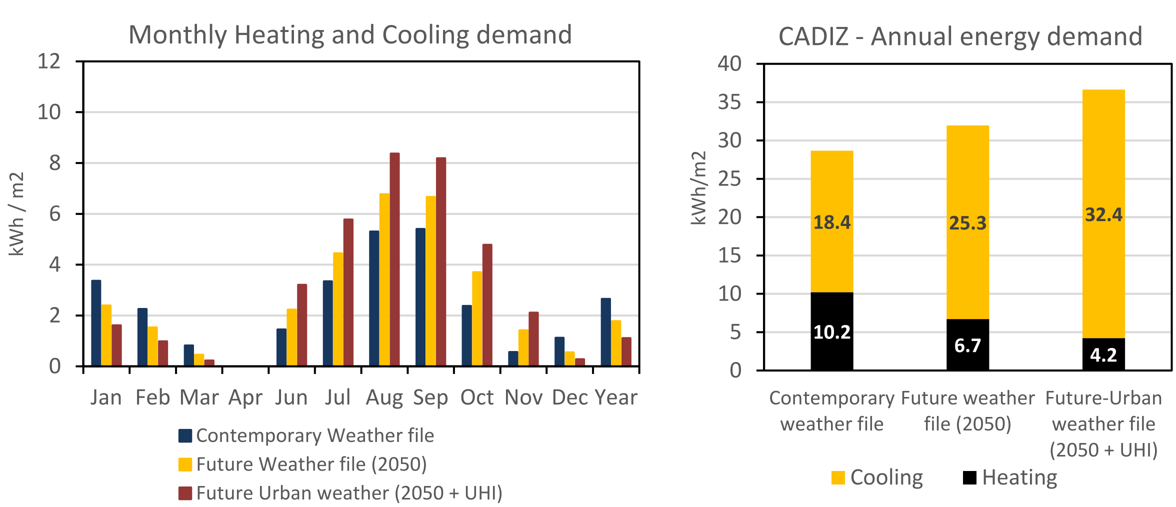

Fig. 8. Impact of climate change and urban effects on the energy demand of the demo building in Cadiz.

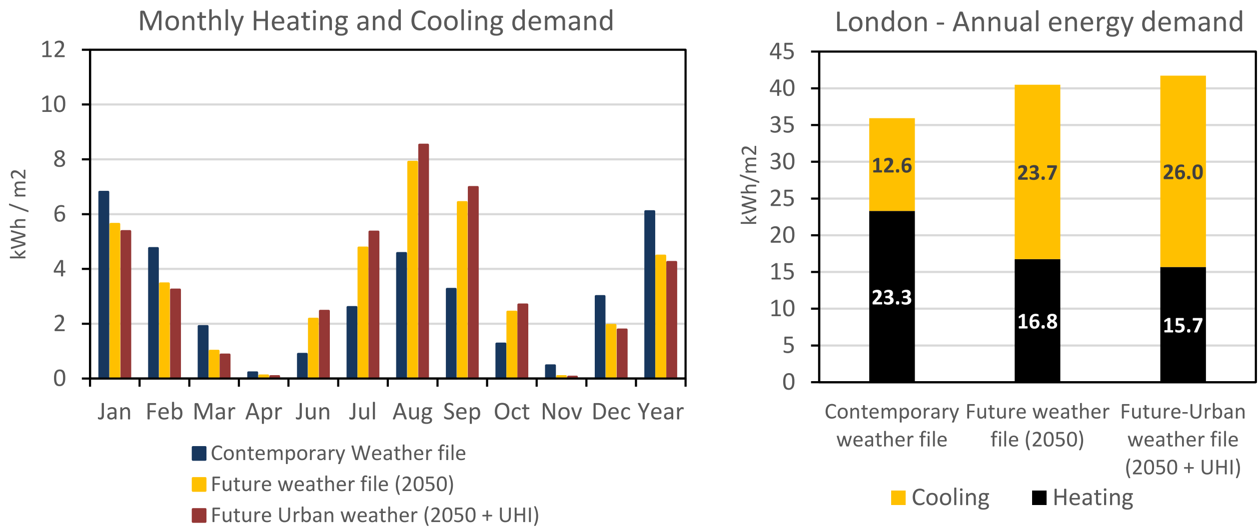

Fig. 9. Impact of climate change and urban effects on the energy demand of the demo building in London.

Table 5
Impact of climate change and urban effects on the energy demand of the demo building in London.

LONDON	Annual building energy demand per unit of floor area (kWh/m^2)					
	Heating Energy	Δ Heating	Cooling Energy	Δ Cooling	Annual Energy demand	Δ annual energy demand
Current weather file	23.3		12.6		35.9	
Future weather file (2050)	16.8	−28%	23.7	+88%	40.5	+13%
Future Urban weather file (2050)	15.7	−33%	26.0	+106%	41.7	+16%

energy demand. Under future climate, the cooling demand increases by 37% compared to the current situation; the additional impact of the UHI leads to a further increase of the cooling demand up to + 76% compared to the current climate without considering urban effects. The increase of air temperature has a beneficial impact on the heating demand, but this does not balance the additional cooling need. As a result, the annual energy demand is projected to increase by 12% due to climate change, while the increase reaches the 28 % of the current energy demand if also the UHI effect is included in the future climate projections. This also means that the energy consumption of buildings in this climate zone in the future will be very reliant on cooling more than heating needs.

The results for London are reported in Fig. 9 and Table 5. These show that the annual energy demand will also increase in London under future-urban weather conditions, due to a higher increase in cooling demand compared to the reduction of the heating demand. The annual energy demand increases by 13% in 2050 due to climate change; the increase is up to the 16% if also urban effects are included. Moreover, urban and climate change effects will modify the relative share for cooling and heating of the annual energy demand. The demo building in the present weather conditions and neglecting the UHI intensity uses the 65% of the annual energy demand for heating and the 35% for cooling, while in future-urban weather conditions the share will be 38% for heating and 62% for cooling. These results confirm the high risk of overheating and increase of energy consumption due to air conditioning posed by climate change for buildings in London, especially in central urban areas [20,24,30].

The impact of UHI and climate change on energy demand are as expected and in similar range reported in literature [53] for heating dominated climates.

3.1.4. *Impact on indoor thermal comfort*

A further set of simulations was performed for the buildings

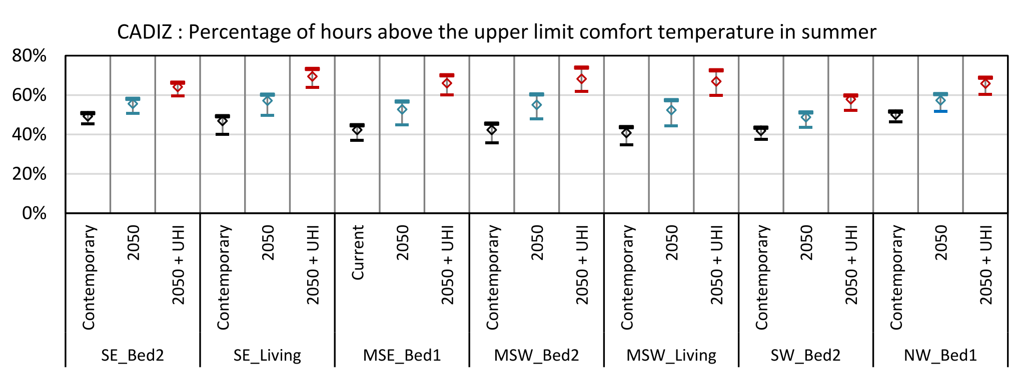

Fig. 10. Adaptive temperatures for Cadiz and percentage of hours that different rooms are above the upper temperature limit over the summer season under varying climate conditions. The average values are calculated over the three months June to August, the minimum and maximum values correspond to the monthly mean of June and July respectively (the coolest and hottest months of the season).

Table 6
Adaptive comfort temperature range for Cadiz under varying climate conditions.

CADIZ	Contemporary	Future 2050	Future 2050 + UHI
Adaptive Optimal Temperature (°C)	26.8	27.3	27.8
Adaptive Temperature - Lower limit - Category II (°C)	22.8	23.3	23.8
Adaptive Temperature - Upper limit - Category II (°C)	29.8	30.3	30.8

assuming free running mode (i.e. without HVAC systems) to assess the impact of climate change and urban context on the percentage of hours that the indoor operative temperatures are above the thermal comfort limits. To this aim, the adaptive thermal comfort limits have been calculated according to the European standard EN 16798-1 as a function of the running mean of the outdoor temperature (BSI, 2019, [37]). The upper and lower temperature limits were set as ±3 °C of the optimal temperature, corresponding to the Category II of expectation defined in the EN 16798-1.

The simulations were run for the three months, from June to August.

The results for Cadiz are presented in Fig. 10, showing the percentage of time that the operative temperature of representative rooms is above the upper limit of the adaptive comfort range (Table 6). The rooms reported in the graphs show that the building has a significant overheating issue under all considered weather conditions. Obviously, climate change and UHI effects worsen the indoor thermal environment increasing the overheating hours. The highest relative increase in overheating hours is experienced by the bedrooms and living rooms of the MSE and MSW flats (floor plan is reported in Figure), where climate change and UHI intensity determine an increase of discomfort hours by 24–26% compared to the results for the current, non-urban weather file. In these rooms, the operative temperature is predicted to be above 30.8 °C for up to the 74% of the time in July, the hottest month. The MSE and MSW flats are the most affected by the raise in outdoor temperature probably due to their orientation (the main façade is oriented south-west) and to the central position within the building, decreasing their ability to dissipate excess heat through the envelope. The impact of UHI in increasing the percentage of discomfort hours is very clear in all the rooms, confirming the necessity to include the UHI intensity in the input weather files when performing building energy simulation in current and future conditions in hot climate regions.

The results for representative rooms of the London building are reported in Fig. 11 and Table 7. Overheating is an issue also for the demo building in London and climate change and UHI effect make it much more critical compared to the current weather conditions. In July, the hottest month, the operative temperature of the rooms is above the upper limit of 28.7 °C for the 53–75% of the time under future-urban weather conditions. The overheating issue is most certainly determined by high internal gains due to occupancy (11 students) and use of cooking and electrical appliances and by geometrical factors such as a very compact floor plan with low ceiling single-sided rooms that limit the cooling potential of natural ventilation.

3.2. *Results of microclimate analysis*

3.2.1. *Microclimate analysis: Wind speed and direction at the demo building sites*

The microclimate simulations confirmed the relevant role played by the 3D urban morphology on wind speed and direction around the studied buildings. The results for the dominant wind directions are reported in Fig. 12 and Fig. 13 for London and Cadiz, respectively. It should be noted that these results are for sample summer days which correspond to the days simulated using ENVImet. In the case of London, the wind speed at the building facades is affected by the surrounding buildings and trees and by the shape of the building itself. In Cadiz, the wind flow in the main street is significantly reduced by the dense urban fabric and its orientation with respect to the dominant wind direction (South-West), despite the proximity to the sea. The simulations also showed that the wind speed in the courtyard is very low for any wind speed and direction.

3.2.2. *Impact of microclimate conditions on indoor thermal comfort*

The simulation results showed that the site-specific wind speed and surface temperatures have a clear impact on the indoor thermal operative temperatures and air change per hour of the two buildings. The wind speed at the openings of representative flats of the Cadiz model as calculated by ENVImet and by EnergyPlus are compared in Fig. 15. The

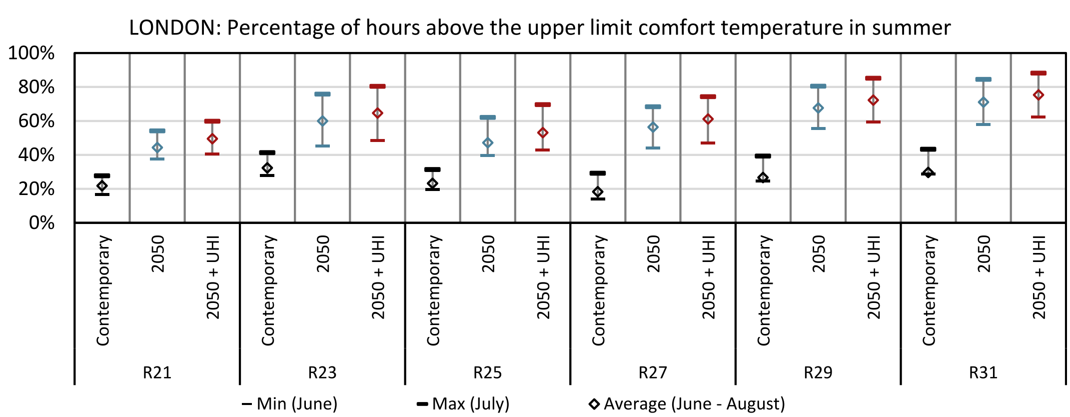

Fig. 11. Adaptive temperatures for London and percentage of hours that different rooms are above the upper temperature limit over the summer season under varying climate conditions. The average values are calculated over the three months June to August, the minimum amd maximum values correspond to the monthly mean of June and July respectively (the coolest and hottest months of the season).

Table 7
Adaptive comfort temperature range for London under varying climate conditions.

LONDON	Contemporary	Future 2050	Future 2050 + UHI
Adaptive Optimal Temperature (°C)	24.8	25.5	25.7
Adaptive Temperature - Lower limit - Category II (°C)	20.8	21.5	21.7
Adaptive Temperature - Upper limit - Category II (°C)	27.8	28.5	28.7

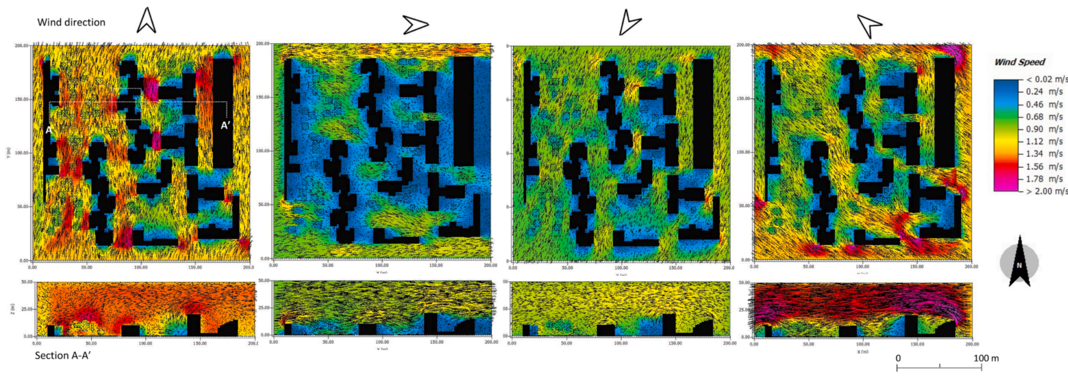

Fig. 12. ENVImet results of the airflow around the building in London for different dominant wind directions. The horizontal maps represent the wind speed distribution at 4.5 m above ground level, corresponding to the height of the studied floor. Below each horizontal map, the vertical distribution of wind speed is reported.

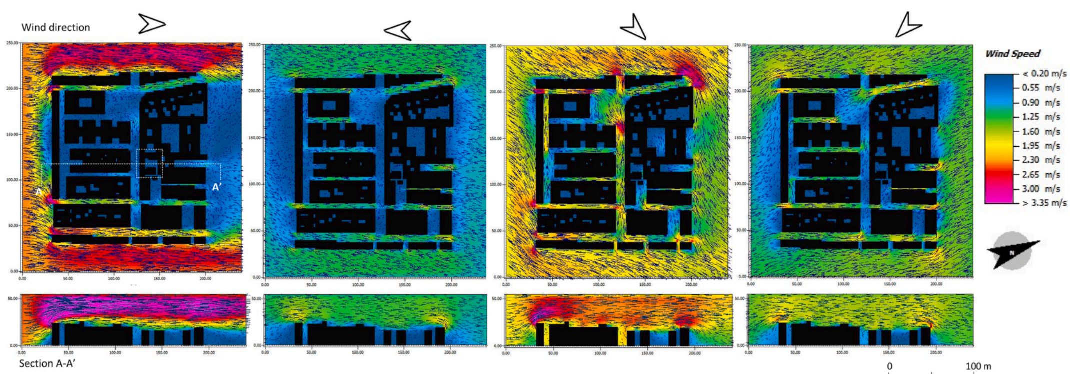

Fig. 13. ENVImet results of the airflow around the building in Cadiz for different dominant wind directions. The horizontal maps represent the wind speed distribution at 4.5 m above ground level, corresponding to the height of the studied floor. Below each horizontal map, the vertical distribution of wind speed around the building is reported.

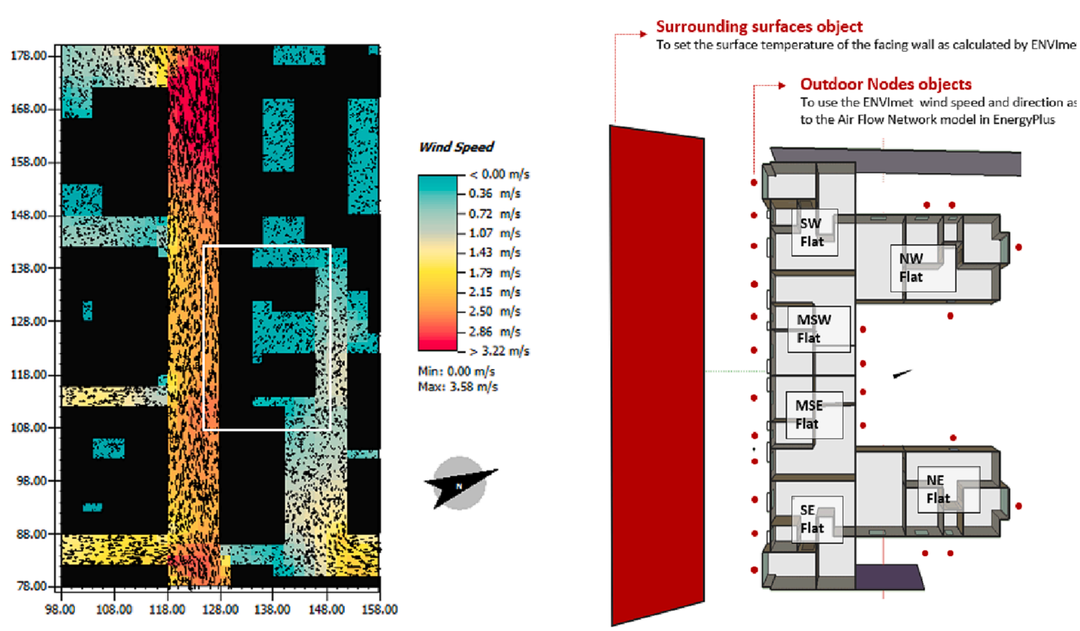

Fig. 14. ENVImet outputs and use of outdoor nodes and Surrounding Surface objects in the Cadiz model.

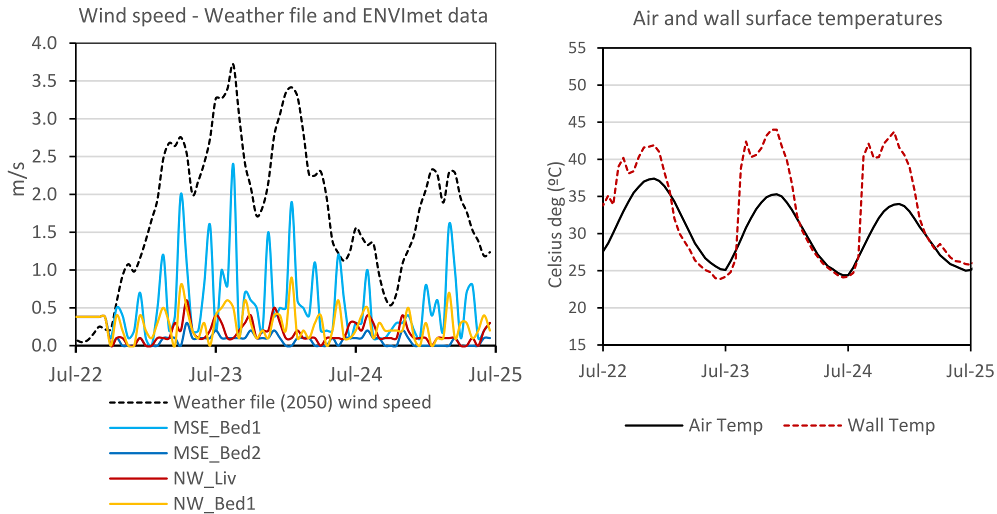

Fig. 15. Difference between the weather file and the ENVImet wind speed data at the height of the windows in representative rooms of the Cadiz model (left) and difference between the air temperature and the surface temperature of the wall opposite to the studied building (right).

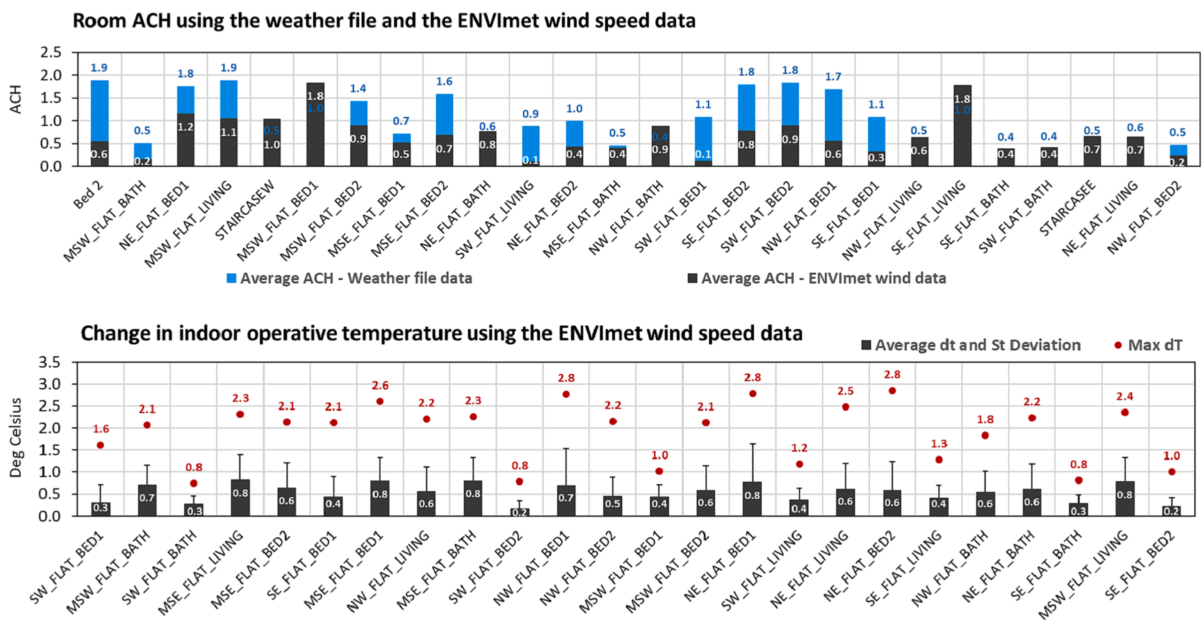

Fig. 16. Top: Comparison of the room ACH calculated using the weather file and ENVImet wind data for the Cadiz building. Bottom: Average and maximum impact of reduced ACH on the room operative temperatures.

wind speed calculated by ENVImet is significantly lower than the one estimated by EnergyPlus for the flats facing the main street (i.e MSE flat) and even more for those facing the courtyard (i.e. NW). Fig. 15 also shows a clear difference between the air temperature and the opposite wall temperature especially during daytime and also during nighttime in the hottest day.

Fig. 16 shows a comparison of the rooms' air change per hour (ACH) as calculated using the standard approach and the weather file data or the ENVImet data. The second graph illustrates the impact of the modified ACHs on the room operative temperatures. The results confirm that the decrease wind speed in urban canyons has an impact on the natural ventilation potential of urban buildings, decreasing the ventilation rates. This is more or less evident depending on the room location and opening characteristics. The biggest reduction is found for the rooms having larger windows and for the rooms of the flats MSW and MSE, located in the middle of the main façade of the building.

The reduced ventilation rates have an impact on the indoor operative temperatures, with an average increase of 0.2 – 0.8 °C across all the rooms and a maximum increase of up to 2.8 °C due to reduced ventilation rates (see Fig. 17).

A further increase in the indoor operative temperatures of the room facing on the main street is determined by the actual surface temperature of the opposite building, as shown in Fig. 18. The hourly values of wind speed, outdoor temperature and indoor operative temperature have been reported in detail for one of the rooms of the building in Fig. 19.

These graphs (Fig. 18) show that the increase of the indoor operative temperature due to the attenuation of wind speed in the urban fabric is more evident on the days with stronger winds (23rd and 24th of July) and it has an impact on both the daytime and the nigh time indoor

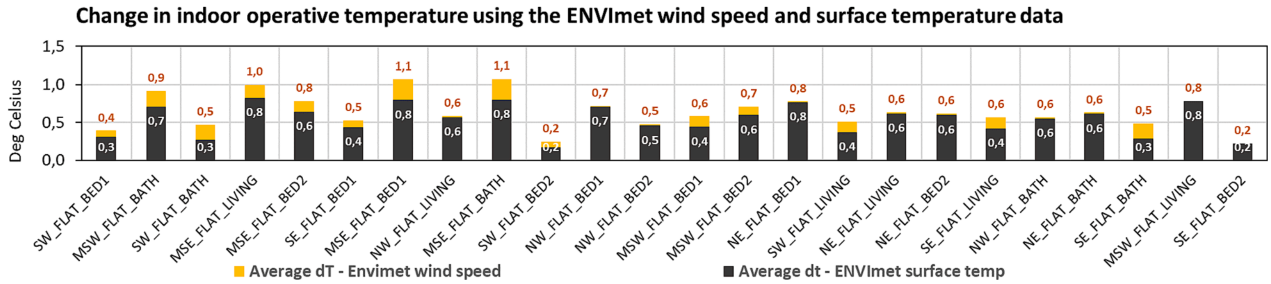

Fig. 17. Increase of the indoor operative temperatures due to the reduced wind speed (grey bars) and surrounding surface temperatures (yellow bars) for the Cadiz demo buildings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

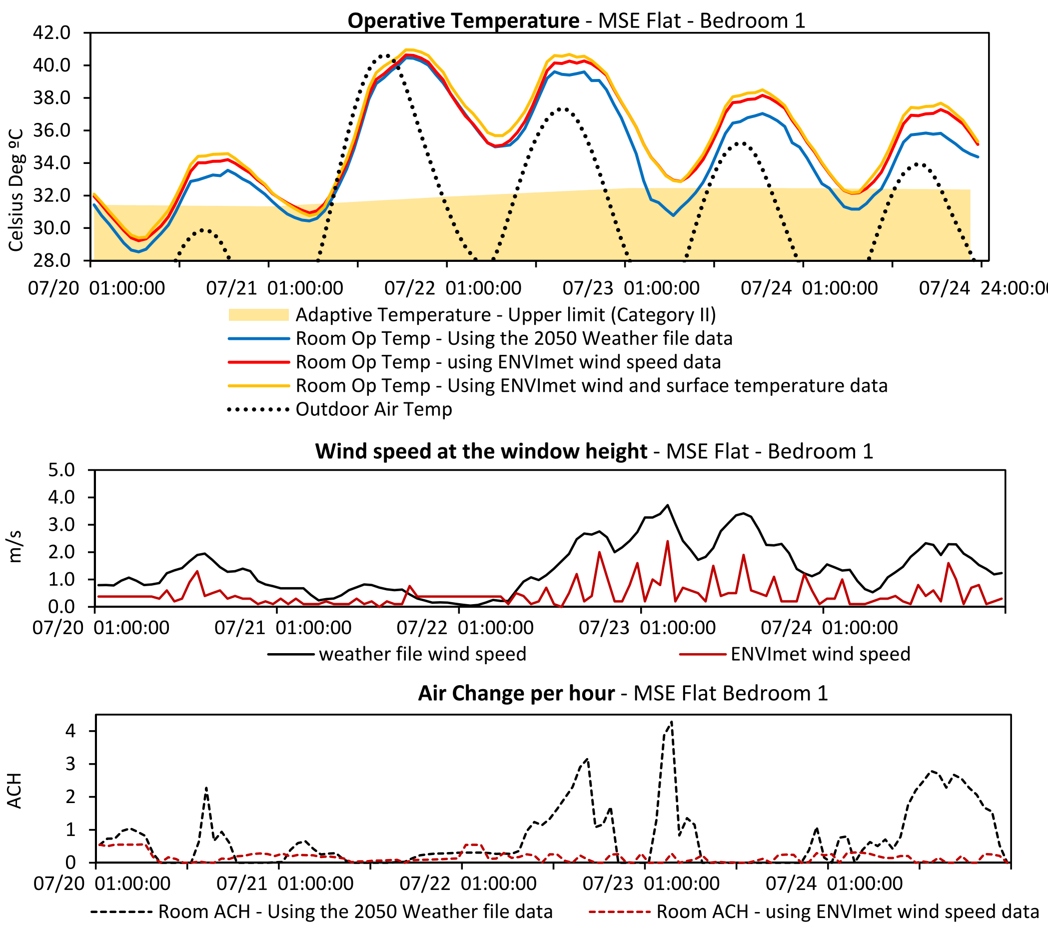

Fig. 18. Hourly values of outdoor temperature, indoor operative temperature, wind speed, and air change per hour under the different boundary conditions for the Bedroom 1 of the flat MSW in the Cadiz demo building.

temperature. Instead, the surface temperature of the facing building has an impact during daytime, increasing the maximum indoor operative temperature.

The modification of wind speed and direction due to the shape of the building and the surrounding obstacles has an impact on the ventilation rates and indoor operative temperatures of the demo building in London. Fig. 20 shows that the wind speed at the building facades is much lower than the estimation done by EnergyPlus using the power law profile. The reduction in wind speed is higher for the rooms on the leeward façade (rooms R27 and R29) than for those on the windward one (rooms R21 and R23).

The reduced wind speed has a clear impact on the ventilation rates of the bedrooms, in particular those on the East facade (R21, R22, R23 and R24), as shown in Fig. 20. Using the ENVImet wind data instead of the weather file data, the ACH of these rooms is reduced by about 35%, from an average of 3.1 to an average of 2 ACH. The other rooms are much less affected by reduced wind speed. In some cases, the ventilation rates increase using the ENVImet data instead of the pressure coefficients and weather files data. This happens for the bedroom R25, which is located on the corner, it is probably due to the beneficial effect of a different wind speed and wind pressure on its window compared to the other windows on the same façade, contributing to create a pressure difference with the other spaces. The reduced ventilation rates of the east-façade rooms also have a significant impact on the indoor operative temperatures of the rooms, which increase of 1.0–1.1 °C on average (Fig. 21). The maximum increase of the operative temperature due to the reduced ventilation reaches up to 3.7 °C.

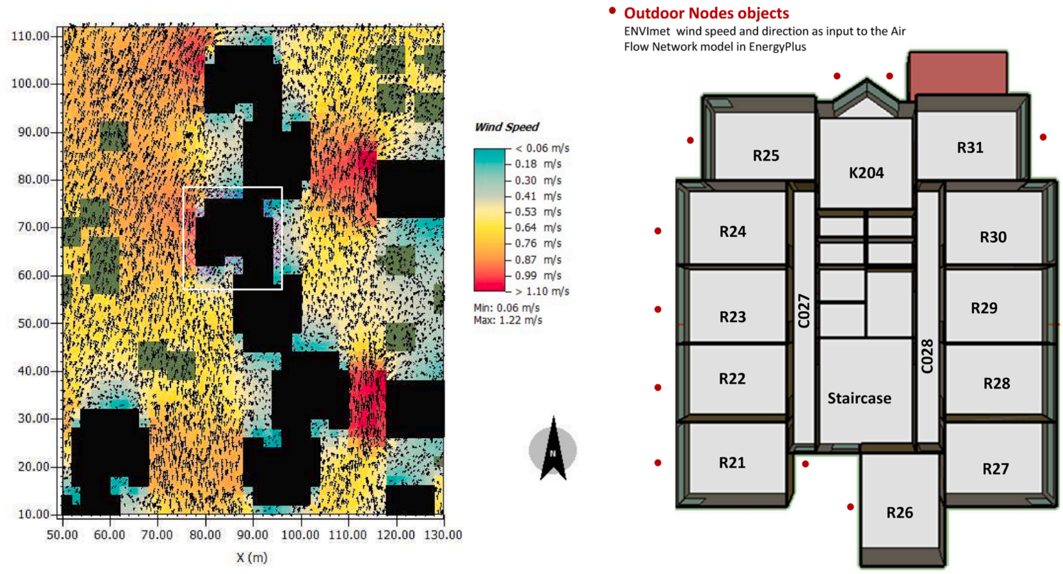

Fig. 19. ENVImet outputs and use of outdoor nodes in the London demo building EnergyPlus model.

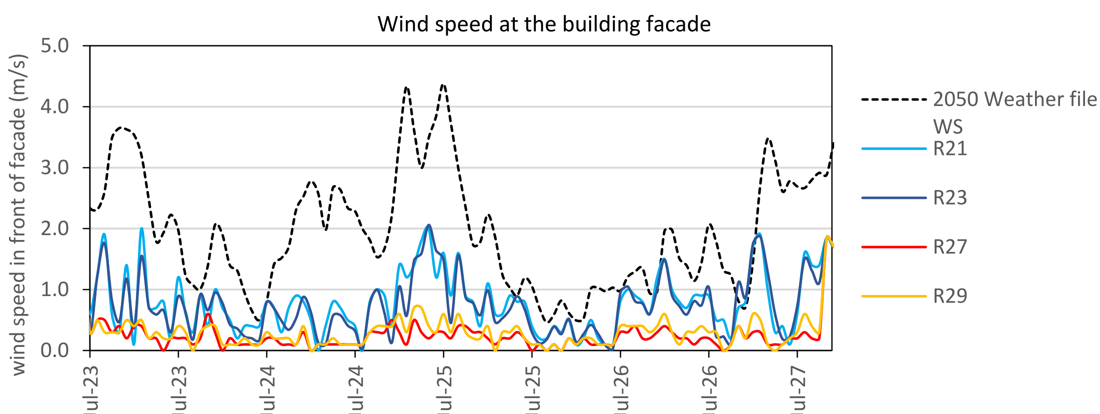

Fig. 20. Difference between the weather file and the ENVImet wind speed data at the height of the windows in representative rooms of the London demo building.

3.3. Limitations of the work

The methods and tools used in this study have some limitations.

The future weather files generated by METENORM are based on stochastic methods to calculate future periods considering the average change in air temperature, precipitation, and global radiation of 10 of the 35 CMIP5 models used in the IPCC report 2015 AR5 [32]. A more detailed prediction of the expected change in the mean and extreme values of all climate variables included in weather files (i.e. air temperature, humidity, wind speed, solar irradiation and atmospheric pressure) can be obtained by dynamic downscaling of global climate projections using regional climate models [26]. Despite that, the proposed methodology is still valid as it can be applied by using more accurate future weather data as input to the UWG and ENVImet models.

Another limitation is that the UWG model cannot fully capture regional and urban scale advective phenomena that also affect urban air temperature and wind velocity and direction around buildings. Such phenomena could be analysed by running mesoscale simulations using the WRF model [19], but at the cost of much higher computational time and complexity of the task. For this reason, mesoscale models are not viable for analysing buildings energy performance for an entire year. Similarly, the methodology proposed in this study to link the ENVImet and EnergyPlus models can be implemented only to analyse a limited number of days, due to the computational cost of the ENVImet simulations. Therefore, it is not suitable to generate wind profiles for an entire year. Nonetheless, it is useful to analyse the ventilation potential of buildings under representative wind speeds and directions for the site of analysis.

4. Conclusions

The paper presented a study of the overlapping effect of climate change and urban context in the prediction of energy use in conditioned buildings and internal thermal comfort in naturally ventilated buildings. The case study residential buildings are located in Cadiz (Spain) and London (United Kingdom), representing temperate and hot European climates and moderate and dense urban settings.

A theoretical analysis was carried out to assess the impact of future-urban weather conditions on the buildings' energy demand and indoor thermal comfort. Urban weather conditions were generated using the UWG tool; its predictions were compared with available measurements of the locations. It was found that in hot climate regions such as the one of Cadiz, future climate will increase the cooling demand by 37% compared to the current situation and the additional impact of the UHI

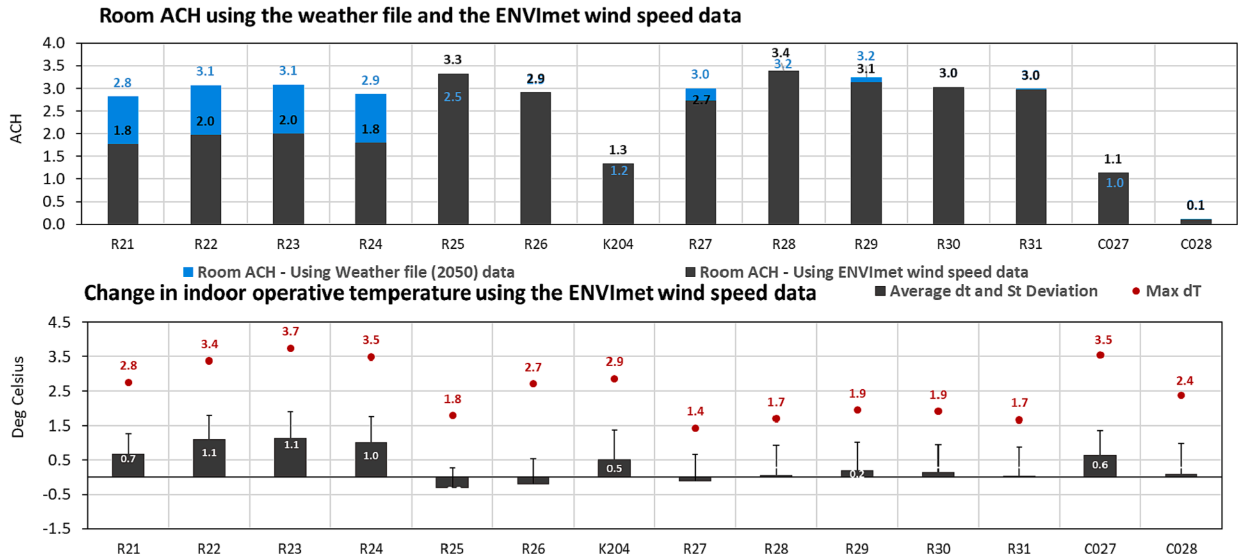

Fig. 21. Top: Comparison of the rooms ACH calculated using the weather file and the ENVImet wind data for the London demo building. Bottom: Average and maximum impact of reduced ACH on the room operative temperatures.

could lead to a further increase of the cooling demand up to +76% compared to the current climate without considering urban effects; the annual heating demand will increase by +28% considering future-urban weather conditions. Future-urban weather conditions will be detrimental also for buildings in London, where the cooling demand can increase by +88% and the additional impact of the UHI could lead to a further increase of the cooling demand up to +106% compared to the current climate without considering urban effects. However annual energy demand is predicted to increase by 13% in 2050 due to climate change and by up to the 16% if also urban effects are included, due to the reduction of heating demand.

In the naturally ventilated residential building in Cadiz, climate change and UHI intensity determine an increase of discomfort hours by 24–26% compared to the results for the current, non-urban weather file. In these rooms (bedroom and living rooms), the operative temperature is predicted to be above 30.8 °C for up to the 74% of the time in July, the hottest month. In the London building overheating is an issue. In July, the hottest month, the operative temperature of the bedrooms is above the upper limit of adaptive thermal comfort for the 53–75% of the time under future-urban weather conditions. It should be noted that this building has a single sided ventilation strategy and high internal heat gains due to occupancy.

A method to consider microclimatic conditions was presented. Air and surface temperature and wind speeds were studied using ENVImet for two case-study buildings in their urban context. The outputs of these microclimate simulations provided the spatial and temporal distribution of wind speed and directions at the building facades and the surface temperatures of surrounding buildings. These were used as boundary conditions to the EnergyPlus models of the two buildings to investigate their impact on achievable natural ventilation rates and the indoor thermal environment. The ENVImet hourly wind speed values were used as input to the Air Flow Network models of EnergyPlus for the calculation of the wind pressure and the ventilation rates of the two buildings. The hourly surface temperatures calculated by ENVImet were assigned to the shading surface in front of the main façade of the case-study building located in Cadiz, to investigate its impact on thermal radiation emission and indoor operative temperatures. This was done by using the "Surrounding surface" objects of EnergyPlus V9.3.0. It was found that ventilation rates are reduced (in comparison to meteorological weather files) and this reduction impacts negatively on internal operative temperatures. The surface temperature of the facing building has a further negative impact during daytime, increasing the maximum indoor operative temperature.

A thermal comfort analysis indicated that the effects of microclimate can lead to significant reductions of natural air flow rate in most cases impacting on operative temperatures which can be up to 3.7 °C in the London case-study (single sided ventilation) and up to 2.8 °C in the Cadiz case study (cross ventilation). This indicates that the presented method on the selection of a suitable weather file and microclimatic conditions is essential for more accurate predictions of internal thermal comfort and will assist in the sizing of passive and active systems to avoid overheating.

5. Authors statement

Both authors have equally contributed to all work reported in this paper.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maria Kolokotroni reports financial support was provided by European Commission.

Data availability

Data will be made available on request.

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