How Microclimate Mitigation Affects Building Thermal-Energy Performance in Residential Zero Energy Italian Settlements

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Abstract

A key research effort has been dedicated toward zero energy buildings in the last decades. Recent interest is currently switching its focus from single-building scale to the inter-building scale, by enlarging the thermal-energy balance up to the settlement level, with the purpose to optimize the whole district energy efficiency and its environmental sustainability. This scale enlargement up to the district size leads to further optimization opportunities that must be considered when performing building thermal-energy dynamic simulations. In this view, buildings within net Zero-Energy Settlements (nZES) can improve their performance thanks to outdoor microclimate improvement techniques that could succeed in mitigating both winter thermal losses and summer overheating risks. In this work, microclimate modeling and building dynamic simulation tools are integrated to assess the impact of varying microclimate conditions on the building energy performance at a settlement level. The case study is performed on a residential district in Italy. In particular, microclimate simulations are carried out to predict the mitigation potential of specific strategies applied at settlement scale, i.e. cool materials, greenery, and their combination. Therefore, starting from the results of the microclimate optimization, new microclimate boundary conditions are generated to be used within the dynamic simulation environment. The final aim is to quantify the impact of such optimized microclimate boundary conditions on the buildings energy performance.

The results from the microclimate simulations, supported by the European funded Horizon 2020 project ZERO-PLUS, highlighted how microclimate can play a key role in affecting outdoor thermal comfort conditions. Moreover, the dynamic simulations carried out by using the results from a microclimate optimization as input weather files, always show a decrease on the final energy needs of the building in the nZES. The highest and non-negligible reduction is reached in the final cooling need of the optimized scenario by coupling both cool and green optimization strategies, i.e. about 12 % of the initial value.

1. Introduction

The local urban microclimate has recently become a fundamental issue for designers and urban planners (Corrado et al., 2015). This is due to the fact that local microclimate phenomena have a strong impact on buildings performance at urban scale, therefore climatic considerations must be necessarily taken into account in urban design (Grobman et al., 2016). Different approaches are currently available to estimate the local microclimate and evaluate its effect on the built environment, i.e. numerical simulations and experimental monitoring campaigns (Carlon et al., 2016; Salata et al., 2016; Atzeri et al., 2016). In fact, local different boundary conditions, i.e. streets geometry (Jihad et al., 2016), vegetation (Dimoudi et al., 2003), and building materials (Kaloniti et al., 2016), can considerable modify the local microclimate in terms of air temperature, relative humidity, ventilation, and air quality (Maiheu et al., 2010) by affecting indoor and outdoor thermal comfort conditions at an inter-building scale, in addition to energy consumption (Ballarini et al., 2014). In (Nicol et al., 2015) the microclimate in Hong Kong was mapped to estimate the influence of urban morphology. In fact, it has become very urgent to develop

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reliable modeling approaches to couple the microclimate evaluation with dynamic building simulation tools for predicting buildings thermal-energy behavior. Nakaohkubo et al. (2007) implemented a tool combining a heat balance simulation for urban surfaces by using GIS for input data, and a simple simulation algorithm to predict the surface temperature distribution of urban blocks. Such a tool was able to predict the impact of building shape, materials, and tree shade on the local thermal environment. Moreover, in Peng et al. (2012) the combination of outdoor and indoor environmental simulation was performed to support the design of sustainable urban dwellings, by bridging three simulation platforms, i.e. Envi-met for urban settlement simulations, Ecotect for building simulation, and U-Campus for combined indoor-outdoor 3D visualization modeling of urban precincts. Many approaches have been used to determine how local urban microclimate can influence the building performance. Sanchez de la Flor et al. (2006) implemented an analytical methodology to assess building performance under modified outdoor conditions. They proved that building energy consumption is strongly correlated to climate factors, and therefore improvements in urban microclimate have direct and indirect consequences on energy savings. Moreover, De la Flor et al. (2004) proposed a computational model able to quantify the modification of the climatic variables in an urban context and to assess how they affect the thermal performance of urban buildings. They highlighted the evident interaction between such two systems, able to modify their mutual energy balances. This proved that the coupling of urban models and building thermal performance simulations is useful to understand the consequences on heating/cooling requirements and even on outdoor thermal comfort. Similarly, Liu et al. (2016) investigated the effects of outdoor air temperature, air humidity, global temperature and wind speed on outdoor thermal sensation. The results revealed that outdoor microclimate parameters play important roles on outdoor thermal sensation. Gros et al. (2016) coupled building energy simulations and microclimate simulations to assess the impact of urban morphology and density, urban landscaping, and buildings and soil thermal properties on solar irradiance, wind flows, air temperature, and energy demand. Solar irradiance reduction up to 7 % and of wind speed reduction up to 80 % were detected in different districts. This work deals with the simulation of the microclimate of a case study residential net Zero-Energy Settlement (nZES), which includes four nearly Zero-Energy houses (EPISCOPE, 2012). The aim of such simulation was to evaluate the mitigation capability of different strategies applied at settlement-scale, represented by (i) the implementation of cool coatings on building roofs and outdoor pavements, (ii) the conscious greenery design and optimization, and (iii) the combination of both these solutions. Microclimate simulation outputs were used as input of building dynamic thermal-energy simulation in the form of .epw weather files. Therefore, the optimized microclimate weather files were used as boundary conditions of the case study nZES. Finally, the impact of mitigated microclimate conditions on buildings energy performance was evaluated.

2. Materials and Methods

Firstly, the microclimate simulation was carried out. Four different scenarios were elaborated, i.e. the "Reference (Ref)" scenario, corresponding to the realistic configuration of the settlement according to the architectural design, and three "mitigation" scenarios, where innovative optimization solutions were applied at district scale to counteract local climate phenomena. Such three mitigation scenarios consist of:

- "Green" scenario: increase of vegetation percentage;
- "Cool" scenario: increase of solar reflectance (R_{solar}) of built surfaces, i.e. roof and pavement;
- "Combined (Comb)" scenario: combination of both the above-described solutions.

The aim of the microclimate simulations was to (i) optimize the local microclimate of the settlement and (ii) produce new weather files to be used in the dynamic simulations to see the impact of the improved local microclimate on the buildings' energy performance.

Secondly, the microclimate simulation outputs were used to generate new optimized weather files to be used in the dynamic simulation of the energy performance of the buildings of the nZES.

Therefore, the applied methodology globally consisted of the following steps:

- Microclimate simulation and analysis of the (i) reference and (ii) mitigation scenarios;
- Generation of new optimized weather files;
- Dynamic energy simulation of the case study buildings with the (i) original TMY weather file and (ii) different mitigated microclimate boundary conditions deriving from the microclimate simulations previously fulfilled.

2.1 Description of the Case Study

The case study district (nZES) is situated in Rimini (Italy) and is constituted by four single-family houses. Such villas, referred to in the text as nZES buildings (i.e. buildings in the net Zero-Energy settlement), are nearly Zero-Energy buildings. In fact, single buildings present high-energy performance (EPISCOPE, 2012), while in the district a net zero energy balance is achieved thanks to the inclusion of energy efficient technologies at settlement level.

In the "Reference" settlement microclimate model (Ambrosini et al., 2014), the following inputs were defined:

- Ground: the "Loamy soil" was selected to represent natural ground, while "asphalt road" was used to represent the street cover. The "pavement concrete" was used for the surrounding built surfaces.
- Buildings: traditional building technologies from the current regulation were used.
- Vegetation: it was modelled consistently with the vegetation percentage and position of the real site.

Fig. 1 shows the geographical location of buildings. The thermo-physical properties of the materials are summarized in Table 1 (Ref).

the nZES buildings dynamic energy model was elaborated in order to evaluate the energy benefits deriving from the microclimate mitigation strategies by using (i) the original TMY weather file and (ii) the optimized weather boundary conditions derived by the microclimate simulation output.

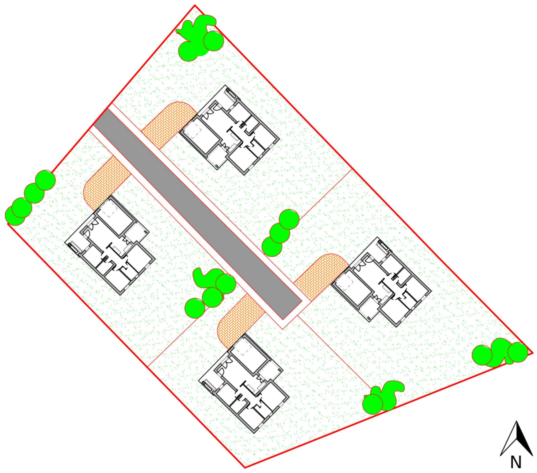

Fig. 1 – Plan view of the Italian case study settlement

2.2 Microclimate Simulation of the "Reference" Scenario

The simulations of the outdoor microclimate conditions were carried out by using ENVI-met. The input climate data used for the simulations were provided by Meteoblue (2016) which enables the inclusion of detailed topography, ground cover (e.g. forest, fields, rock, and water) and surface cover (e.g. snow and water). The model was implemented by considering a 1-m unit grid dimension.

2.3 Microclimate Simulation of the Optimization Scenarios

Additional optimization scenarios were simulated for the settlement to (i) improve the local microclimate conditions, (ii) evaluate the most performing mitigation solution, and (iii) provide new weather files able to consider the microclimate improvement to be used in the dynamic energy simulation for assessing the role of microclimate mitigation on buildings energy performance. Three mitigation configurations were proposed. The first mitigation strategy consisted in the increase of the vegetation percentage according to the different landscape constraints of the settlement. In particular, deciduous trees (South-West) and hedges (North-East) were introduced in addition to the draining pavement for the asphalt road. The introduction of such elements was aimed at (i) protecting the buildings from direct sun irradiation in summer and let it seep out in winter, and (ii) protecting them from the Northern cold winds while keeping an external boundary which could easily be over crossed by the wind in summer.

The second mitigation strategy consisted of (i) the increase of the solar reflectance of roof tiles and external walls, and (ii) the implementation of cool paving materials, e.g. with natural cool gravels (Castaldo et al., 2015). Moreover, highly reflective asphalt was used for the roads. Table 1 shows the solar reflectance values of all the surface materials, before and after the implementation of the mitigation strategies. The last mitigation strategy consisted in the simultaneous combination of the two above-mentioned solutions.

Table 1 – Solar reflectance values [%] for each material in the different modeled scenarios

Material	Ref	Cool	Green	Comb
Asphalt road	20	60	20	60
Concrete paving	40	40	-	40
Gravel paving	-	80	-	80
Flat tiles	15	58	15	58
Pitched clay tiles	30	77	30	77
External walls plaster	40	71	-	71

2.4 Dynamic Energy Simulation

The simulation of the case study nZES (net Zero-Energy Settlement) was carried out using the DesignBuilder-EnergyPlus tool in thermostatically controlled conditions (EERE, 2014). All four buildings within the settlement, characterized by similar characteristics in terms of construction technologies, HVAC systems, occupancy schedule, etc., were modelled together and their energy performance was separately simulated. In particular, the following technologies are implemented in the buildings: XPS insulation, cool materials as roof and wall external coating, low-e double glazing PVC windows, LED lighting system, high efficiency air-to-water heat pump as HVAC system, mechanical ventilation with heat recovery, photovoltaic panels with storage, building integrated wind turbine system, and smart energy systems control. The nZES building components main technical characteristics are reported in Table 2. Since the results from the dynamic simulations showed a maximum 3 % energy performance difference among buildings, the simulation outputs related to one single building (referenced in the text as nZES standard building) are here reported. The comparative energy performance analysis between the reference nZES building scenario, characterized by original typical weather dataset (TMY), and the optimized scenarios, i.e. considering the optimized microclimates generated by means of the previous numerical analyses, was carried out in terms of annual energy consumption. The considered set-point temperatures were equal to 20 °C and 26 °C for heating and cooling, respectively.

Table 2 – General technical characteristics of the case study building

nZES building characteristics	
Flat roof U-value [W/m²K]	0.15
Flat roof R_{solar} [%]	58
Pitched roof U-value [W/m²K]	0.16
Pitched roof R_{solar} [%]	77
External wall U-value [W/m²K]	0.18
External wall R_{solar} [%]	71
Ground floor U-value [W/m²K]	0.22
Windows U-value [W/m²K]	1.50
Heating system COP	4.1
Cooling system EER	3.8

3. Results and Discussion

3.1 Microclimate Simulations of the “Reference” Scenario

This section shows the results of the “Reference” scenario microclimate simulations both in summer and winter conditions. Such simulations are aimed at evaluating the optimization potential of the selected mitigation strategies in terms of outdoor thermal comfort, and consequently their impact on the building energy performance.

The data were extracted at pedestrian height (0.9 m above the ground). The results were post-processed in terms of dry bulb temperature (°C), relative humidity (%), mean radiant temperature (°C), and wind speed (m/s). The air temperature ranged between 21 °C and 36 °C. Moreover, a maximum temperature of 35.4 °C and a minimum temperature of 32.5 °C were detected. As for the relative humidity, this varied between a 27.6 % and 33.2 %. The mean radiant temperature fluctuated between 49 °C and 73.6 °C. Finally, the wind speed ranged between zero and 1.57 m/s. Fig. 2–3 show the spatial distribution of the air temperature in different hours of the day, in summer and winter conditions, respectively. As for the wind speed in the Green scenario, the presence of the hedge does not allow the air circulation at 0.9 m and has the effect of reducing the wind velocity in the proximity of the buildings. This generates a reduction of the convective mixing in the whole settlement. In winter, a globally lower mitigation effect is registered, with no penalties.

3.2 Microclimate Simulations of the Optimized Scenarios

This section describes the results of the 24 h simulations of the optimized mitigation scenarios in summer (Fig. 4).

In summer conditions, a good mitigation of the outdoor air temperatures (i.e. up to -1.5 °C) was detected by comparing the Green and Ref scenario. A lower mitigation effect but more effective at night was registered by implementing the cool strategies. Finally, a non-negligible air temperature reduction was found out by comparing the Comb and Ref configuration, especially around the two buildings in the northern part of the settlement. The increase in relative humidity is more significant in the Green and Comb scenarios compared to the Cool one. This is motivated by the presence of the 5 m high trees. On the contrary, no microclimate mitigation effect is registered in close proximity of the 2-m high hedge.

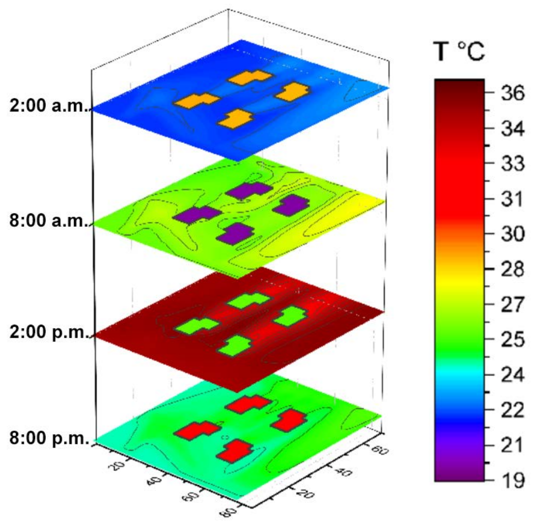

Fig. 2 – Summer air temperature map at different times of the day

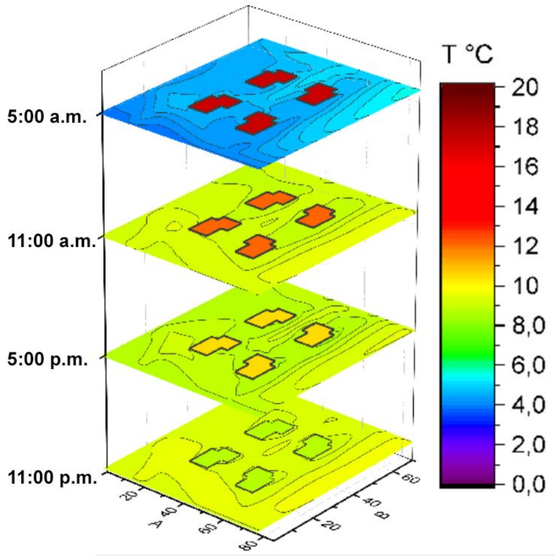

Fig. 3 – Winter air temperature map at different times of the day

As for the mean radiant temperature, a reduction of about 20 °C is detected in the Green configuration due to the shading effect of vegetation to the incoming solar radiation. On the contrary, the mean radiant temperature slightly increases due to the presence of the reflective gravel on the paving surfaces. Additionally, there is a slight mean radiant temperature increase and reduction up to 10 m of height in the Cool and Combined configuration, respectively.

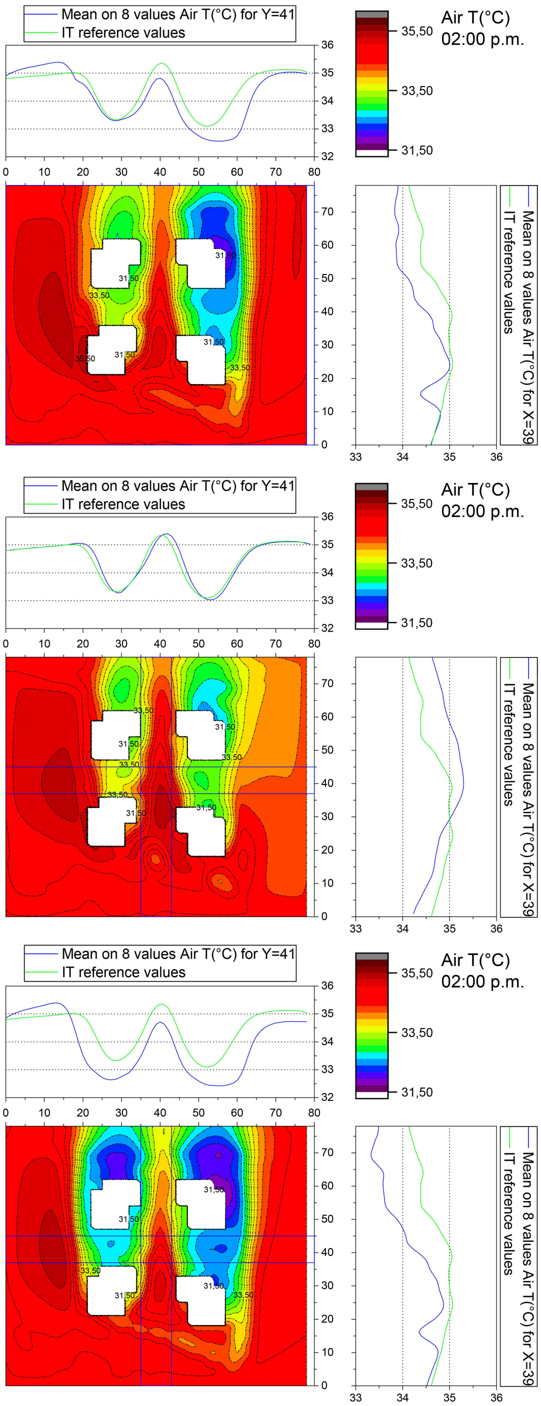

Fig. 4 – Summer air temperature distribution in the Green, Cool, and Combined scenarios

3.3 Assessment of the nZES Building Energy Performance

This section shows the results of the annual energy dynamic simulation of the nZES standard building in the four different scenarios considered, i.e. reference (nZES), mitigated Green, Cool, and Comb. Buildings were simulated under thermostatically controlled conditions to assess the achievable energy saving corresponding to local microclimate boundary conditions variation.

Table 3 – Annual energy consumption, production, and Primary Energy requirement (E_P) for nZES standard building

Building in the *nZES*	Energy [kWh/m²/y]	E_P [kWh/m²/y]
Heating	45.0	108.9
Cooling	0.8	1.9
DHW	3.8	9.2
Regulatory Energy	49.6	120.0
Lighting	12.5	30.3
Equipment	15.4	37.3
Total Energy	77.5	187.6
Wind Generated Energy	23.7	-
Solar Generated Energy	46.2	-
Total Generated Energy	69.9	-

Table 3 reports the results of the analysis under thermostatically controlled conditions, in terms of final annual energy consumption of the nZES standard building. The final energy consumption is defined as the sum of regulatory energy, i.e. heating, cooling, and domestic hot water (DHW), and the additional energy consumption for appliances, i.e. lighting and equipment. Such two energy contributions are separated since the regulatory energy is the only one affected by the microclimate mitigation strategies applied to the nZES. Moreover, Table 4 shows the difference in terms of building regulatory, heating, and cooling energy among the three optimized scenarios and the nZES reference scenario. As expected, the results show that the greater effect of the implementation of both cool materials and greenery in the outdoor areas of the settlement is detected in summer. In fact, all the optimized scenarios present a lower cooling energy need compared to the reference nZES scenario, which is maximized in the Combined scenario with a final 11.8 % cooling need reduction. Therefore, the combination of the application of cool materials and greenery in the outdoor areas of the settlement optimizes both outdoor microclimate conditions and building energy performance in summer. Moreover, in the optimized scenarios the energy need for heating is reduced though slightly, i.e. up to 2.5 %. Therefore, the optimized scenarios present a lower total energy need with respect to the reference nZES scenario, with up to a 4 % regulatory energy consumption reduction in the Comb scenario.

Table 4 – Energy requirements variation in the three optimized scenarios with respect to the reference nZES scenario

		Cool	Green	Comb
Heating	ΔE [kWh/m²/y]	-0.37	-0.24	-0.18
	% decrease	-2.48	-1.62	-1.21
Cooling	ΔE [kWh/m²/y]	-0.09	-0.34	-0.90
	% decrease	-1.22	**-4.42**	**-11.83**
Regulatory	ΔE [kWh/m²/y]	-0.46	-0.58	-1.08
	% decrease	-1.76	-2.20	**-4.09**

4. Conclusions and Future Developments

In the present work, 3D Computational Fluid Dynamics and building energy simulation tools were coupled in order to investigate the mitigation potential of specific strategies applied at settlement level, and to quantify their effect on buildings' energy need. The purpose was to develop outdoor mitigation strategies to improve the outdoor microclimate conditions perceived by pedestrians, and to reduce the buildings' energy needs. To this aim, preliminary microclimate simulations stressing the effect of selected mitigation strategies, i.e. implementation of cool coatings on buildings roofs and outdoor pavements, greenery, and their combination were carried out. Therefore, building upon the results of such microclimate simulations, new optimized weather files were generated and used as boundary conditions for the dynamic simulation of the nZES buildings energy performance. Finally, the comparison between the energy performance of the nZES standard building carried out by using (i) the original typical weather dataset (TMY) and (ii) different optimized weather files was performed. Microclimate analysis allowed a preliminary assessment of the outdoor thermal comfort conditions at settlement scale. Results showed how the different proposed mitigation strategies lead to an improvement of the outdoor thermal comfort. The selected mitigation strategies also produce non-negligible reductions on the final energy need of the nZES building, mostly affecting regulatory energy consumption. A maximum of 4 % energy saving was reached in the Combined scenario.

In conclusion, this work demonstrated that properly selected microclimate mitigation strategies applied at district scale, aside from improving the local outdoor thermal comfort, can also produce non-negligible effects on the thermal energy performance of buildings. Future developments of this work will concern the comparison between the effect of the microclimate mitigation strategies and the occupants' behavior on the final energy consumption and indoor comfort of the nZES buildings.

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