Using textile canopy shadings to decrease street solar loads

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ABSTRACT: One of the main design goals of bioclimatic urbanism in locations suffering from excessive heat is providing shade. In the Mediterranean region, a common strategy to achieve this goal is the use of textile shading devices over the street. This work aims to evaluate the potential of these 'sun sails' in decreasing street solar loads. To this end, we analyse an actual street in Cordoba, a city with extreme summer conditions, using climate-based simulations. We compare the distribution of solar loads over the urban canyon surfaces with and without sun sails under several scenarios of street and tissue reflectance. Results show that the use of sun sails, especially if high-mounted, is an effective strategy to limit street solar loads with simultaneous benefits for pedestrians and building comfort. In absolute terms, the outcomes of sun sails are similar in streets with dark or light-coloured façades, and better than whitening interventions. The effectiveness of these devices not only depends on the openness of the tissue but also on its colour.
KEYWORDS: Sun sails, Shading, Urban cooling, Heat mitigation, Mediterranean region.

1. INTRODUCTION

Cities with temperate and hot climates are already home for the majority of humans on Earth and will concentrate the population growth of the next few decades. In these areas, the excessive heat poses a seasonal or all year long comfort problem, which will worsen as the climate change progresses, due to global warming and the increase in extreme heat events. Therefore, one of the main challenges of sustainable urban planning worldwide consists of implementing strategies to cool the city.

Under excessive warm conditions, limiting the solar loads received by urban surfaces constitutes a major design goal. Shading has demonstrated to be an effective strategy in this sense, regardless of the way to generate it [1]. At the urban scale, literature has mainly focused on the positive effect of self-shading urban morphologies [5] and shade trees [6], while the attention paid to urban shading devices has been far more limited [2].

Textile canopy shadings may constitute an interesting choice when dealing with some design constraints, such as water shortage or the need for removable protections. In Mediterranean cities, typically affected by these limitations, the use of street sun sails is common (Fig. 1). Up to date, studies have mainly assessed the benefits of this kind of device on pedestrian comfort relying on point analyses [2-3]. More spatialized analyses covering the global street scale are essential, though, for a comprehensive evaluation of sun sails effects. In this vein, shadows cast by sun sails may also affect buildings, helping to limit their overheating, and hence, their cooling energy consumption [11].

Figure 1: Urban sun sails in Sierpes St (Sevilla, 1918) and Gondomar St (Cordoba, 2018).

2. OBJECTIVE

The present work aims to assess the effectiveness of textile canopy shadings in limiting the solar loads absorbed by the street surfaces. Specifically, the goal of this paper is to answer three questions:

- What is the most effective urban intervention: adding urban shading devices or whitening the street?
- Are sun sails equally effective in dark and light-coloured urban environments?
- How does the sun sail colour affect its cooling potential?

To provide realistic insights on the subject, we analyse an existing street in Cordoba, a city with extreme summer conditions. We simulate the solar loads absorbed by façades and the pavement, comparing results with and without sun sails for the complete warm season under different scenarios.

3. METHOD

The present study relies on computer simulations over a 3D mock-up of an actual street. To complete these simulations, we followed three steps.

First, we created a 3D model of the investigated urban environment. Using CAD tools, we generated two versions of this urban model: with and without sun sails. To create buildings, we extruded the 2D footprints from cadastral sources, using the individual building heights retrieved from Google Earth Pro. Sun sail pieces were modelled as two offset surfaces, extremely close to one another, meshed in the same way, with variable tilt and elevation.

Second, we assigned the optical properties to the surfaces comprised in the model. In the most general case, materials can transmit (directly and diffusely), reflect (directly and diffusely) and absorb the impinging solar energy. Coefficients τ_r, τ_d, ρ_r, ρ_d and α express, respectively, the ratio between these options ($\tau_r+\tau_d+\rho_r+\rho_d+\alpha = 1$). For this work, we assume that ground and façade surfaces are opaque perfect diffusers ($\tau_r=\tau_d=\rho_r=0$), verifying then Equation (1):

$$\rho_d + \alpha = 1 \qquad (1)$$

Regarding sun sails, we consider them as open wave tissues that partially block the incident radiation. According to Kotey's experimental measurements [7], this kind of tissues transmits radiation both directly (τ_r) and diffusely (τ_d), while the radiation blocked is whether absorbed and/or reflected backwards purely diffusely ρ_d (ρ_r=0). This work models the optical behavior of sun sails tissues accordingly, as expressed in Equation (2):

$$\tau_r + \tau_d + \rho_d + \alpha = 1 \qquad (2)$$

For this study, we assume that the value of the diffuse transmission (τ_d) and reflection (ρ_d) is constant regardless of the incident angle θ, being dependent on the tissue color. Conversely, the tissue direct transmission (τ_r) is angular-dependent feature of the tissue. Its maximum value happens at a normal incidence ($\vartheta=0°$) and corresponds to the openness factor of the tissue ($A_0=\tau_{r0}$). As the incidence angle increases, τ_r gradually diminishes to zero at $\vartheta>65°$ [7].

Third, we proceed to the calculation of the solar loads absorbed by surfaces in the model. To this end, we use the algorithm detailed in [10], based on radiosity method [8]. This technique requires the meshing of the complete urban scene: sky and built surfaces. In this study, we use a fine mesh (<0.5m^2) for the surfaces of interest (façades, sun sails and the ground) and a coarser one for the rest of the scene (>4m^2). We subdivided the sky into a 5000-element mesh following the equal-area partition proposed by [4]. To calculate the radiance of each sky patch, we used the Perez All-Weather model [9], using as inputs the climatic data of the selected location (**.epw* file), and the position of the Sun at each time step. Another prerequisite of the radiosity method is the computation of the *view factors* (F_{ij}) between all the pairs of elements *i-j* in the scene. In this paper, we chose instead to use *'extended view factors' (F_{ij}*)*. This technique allows for accounting not only diffuse radiation exchanges (ρ_d, τ_d) but also the specular ones (ρ_r, τ_r). Thanks to this approach, we can perform accurate computations of the radiative exchanges in the complete urban scene (not view dependent), taking into account in detail all the optical properties of the sun sails (τ_r, τ_d, ρ_d, α).

Once fulfilled the basic prerequisites of the Radiosiy method, we calculate the irradiance (E_i) received by any patch *i* of the scene. To this end, we need to solve the system of linear equations under the form of Equation (3). The first term of this expression accounts for the radiation from the sky vault, the second and third terms, the reflected and transmitted parts from the built environment, respectively.

$$E_i = \sum_j \left(F^*_{ij} M_j + F^*_{ij} \rho_{d,j} E_j + F^*_{ij} \tau_{d,j'} E_{j'} \right) \forall \text{ patch } i \qquad (3)$$

where E_{i} / E_j - irradiances on patch *i / j* (Wm^{-2});
F^*_{ij} - extended view factor from patch *i* to *j;*
M_j - exitance of the patch *j* (Wm^{-2});
$\rho_{d,j}$ – diffuse reflectance of the patch *j*;
$\tau_{d,j'}$ – diffuse transmittance of the patch *j'*.

**Patches j and j' represent a pair of identical patches in the two offset surfaces of sun sails.*

Finally, we compute solar loads (A_i), that is, the fraction of the incident solar radiation that ends up being absorbed by each street surface. To do this, we multiply the irradiance of each surface by their total solar absorptance, following Equation (4).

$$A_i = \alpha_i E_i \qquad (4)$$

where A_i - solar load of patch *i* (Wm^{-2});
E_i - irradiance on patch *i* (Wm^2);
α_j – absorptance of the patch *i*.

4. CASE STUDY

4.1 Site description

Cordoba is a historical city located in the South of Spain (37°53'N). It presents a Mediterranean climate with mild winters and a warm and dry season running from May to September (Fig. 2). During this period, the average high exceeds 30°C, and heatwaves and air temperature peaks over 40°C are recurrent.

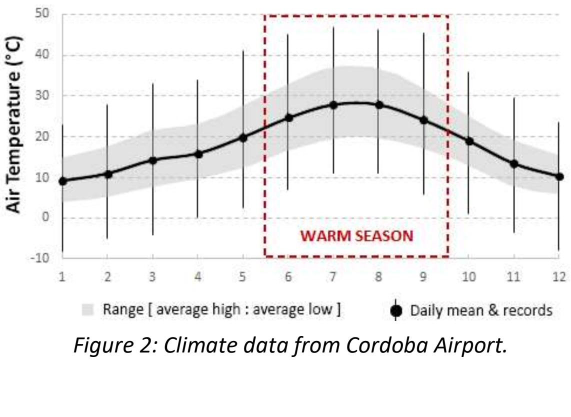

Figure 2: Climate data from Cordoba Airport.

To mitigate these extreme conditions, every year, the city council and a local commerce association promote the installation of textile canopy shadings over several commercial streets of the city centre. This work focuses on one of them: *Gondomar* St. This street is a deep urban canyon (W/H=0.6), bounded by North and South facing façades (Fig. 3a).

Gondomar St is mainly composed of high reflective façades (white, beige, yellow), as shown in Fig. 1. Occasionally, some dark façades appear, typically made of bare brick, a common cladding in the city. The street ground is a low reflectance surface made of a dark grey granite paving.

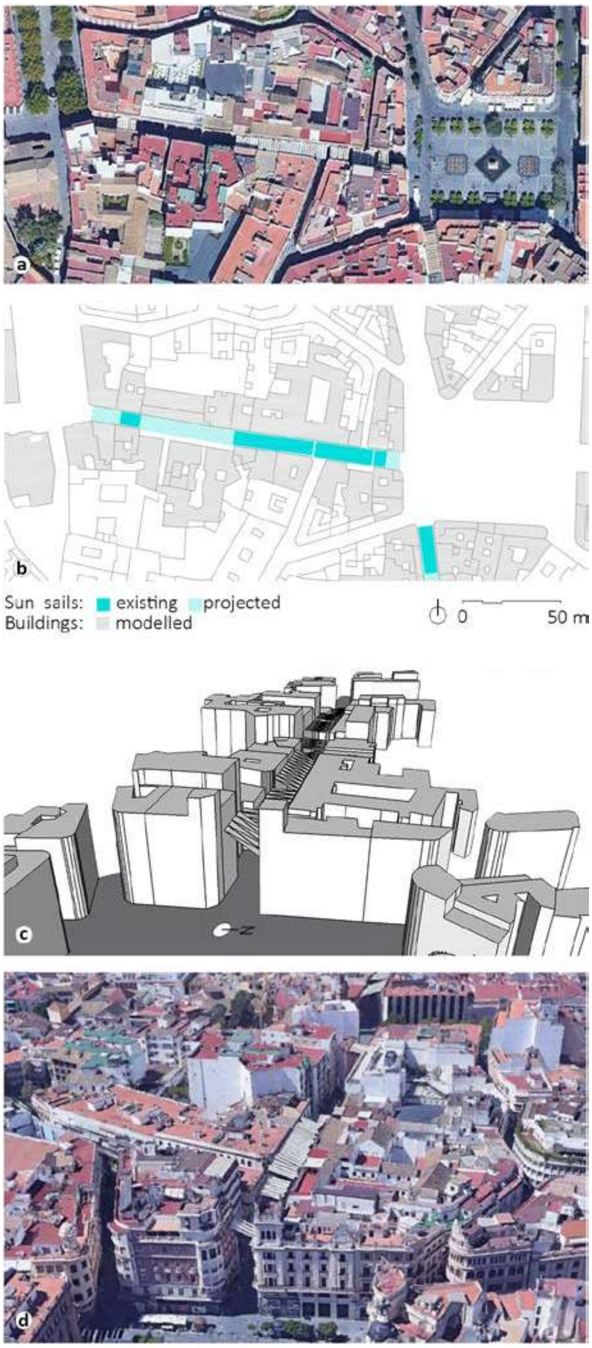

Figure 3: Plans (up) and aerial views (down) of Gondomar St (source: Google Earth Pro) and its 3D model.

The sun sails installed in this street consist of white triangle-shaped pieces of micro-perforated PVC tissue. Individual pieces are fixed to the upper part of façades through metallic tensors, leaving gaps between them to reduce wind-drag effects and air stagnation. Due to the difference in height among opposing buildings, the tilt of sun sails varies along the street, creating additional gaps (Fig. 3d).

Until now, the shading devices installed in *Gondomar* St only shelter the street partially (Fig. 3b). The city council is currently studying the possibility of an extension project to cover the street along its entire length for the next years.

4.2 Simulation model and scenarios

Following *Section 3*, we created two geometrical models of *Gondomar* St: one without sun sails, another with them. The latter model included not only the existing sun sails but also the projected ones, as shown in Fig. 3c.

To address the design-related questions posed in the present work, we analysed the street solar loads under six different scenarios (Fig. 4).

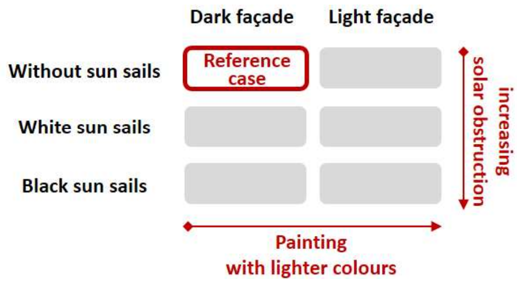

Figure 4: Case scenarios studied through simulations.

Based on the features of this urban area, we defined two idealistic scenarios regarding the façade reflectance: dark and light-coloured. For both cases, we run simulations between 15 May and 15 September without sun sails, and with two types of them: black and white. Table 1 summarises the optical properties considered for each scenario. Notice that ground and roof properties, as well as the tissue openness, were the same in all the simulations.

Table 1: Optical properties of urban surfaces and sun sail tissues at normal incidence (θ = 0°).

Model surface	τ_r	τ_d	ρ_d	α
Dark façade	0	0	0.30	0.70
Light façade	0	0	0.70	0.30
Ground	0	0	0.10	0.90
Roof	0	0	0.40	0.60
White sun sail[1]	0.18	0.12	0.62	0.08
Black sun sail[2]	0.18	0	0.08	0.74

Tissue with an openness factor of A_0 = 18%, made of white fibers (ρ=0.90) [1] *or black fibers (ρ=0.10)* [2]

5. RESULTS

This section presents the simulation results of the solar loads absorbed by street surfaces for all the investigated scenarios. The order of graphs in Figs. 5 and 6 follows the scheme in Fig. 3. This makes it possible to compare the impact of whitening façades and increasing solar protection at a glance (by reading from left-to-right or top-to-bottom, respectively).

5.1 Distribution of solar loads over façades

Fig. 5 presents the distribution of solar loads over the façades of the investigated street. Results show that the south façade of a dark street with no sun sails has the highest solar gains. In contrast, the north façade of a light-coloured street with black sun sails presents the lowest solar gains.

In the absence of sun sails, north and south-facing façades present differentiated behaviours. The south façade absorbs higher solar loads than the north one, and with a more uniform distribution. Differences between orientations decrease when façades are lighter due to the multiple reflections.

When sheltered by sun sails, both façades present a similar distribution of solar loads, characterized by two differentiated zones: below and above the shading devices. Façade areas below the sun sails absorb significantly less solar radiation than those above it, regardless of the façade and sun sail colour. These two parameters affect, though, their effectiveness as a heat mitigation strategy.

For the same openness factor, black tissues have lower global transmittance and reflectance than white ones. Therefore, the tissue colour affects the absorption of solar radiation of surfaces both below and above sun sails. In both cases and for both façades, solar loads are lower when using black tissues instead of the white ones. In fact, façade solar loads above white sun sails exceed those without sun sails at all due to an increase in reflected radiation.

The results also indicate that the effectiveness of sun sails varies depending on the reflectance of the street. The reduction in solar loads due to sun sails on the façades is more evident the darker they are, especially on the south-facing one.

5.2 Distribution of solar loads over the pavement

Fig. 6 depicts the solar loads absorbed by the pavement of the investigated street for the different scenarios assessed. Solar loads over the pavement are maximum in the street with no solar protection and white façades, due to the multiple inter-reflections between these surfaces. Conversely, the dark street sheltered by black sun sails presents the lowest solar loads over the pavement.

The installation of sun sails reduces significantly the solar radiation absorbed by the ground, regardless of the façade and sun sail colour. This

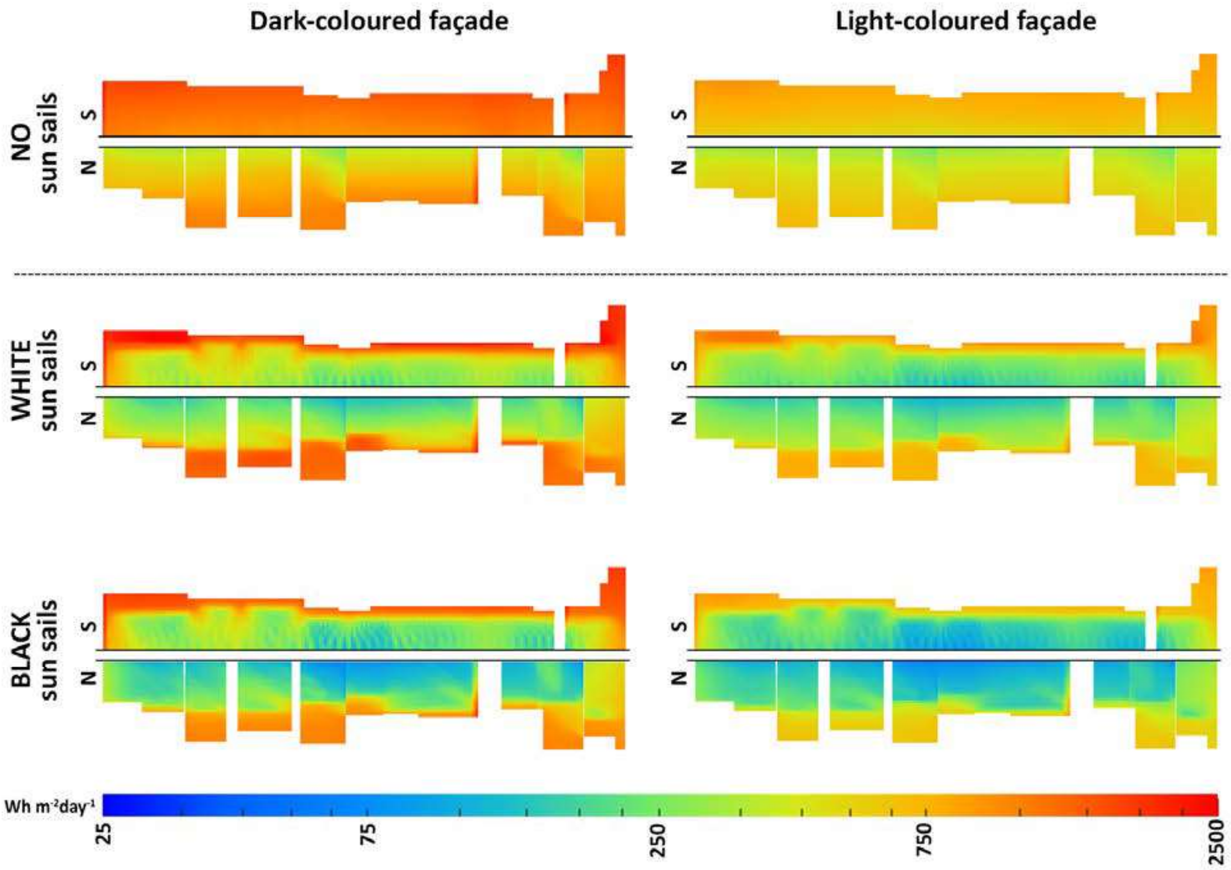

Figure 5: Solar loads absorbed by street surfaces with and without sun sails (Wh m^{-2}day^{-1}, from 15/05 to 15/09).

decrease is especially noticeable on the area close to the base of the building facing south, that is, the pavement area receiving direct solar radiation.

5.3 The global effect of sun sails on solar street loads

Since the use of sun sails affects the solar gains of façades and pavement simultaneously, it has a global impact on the street scale. To discuss this aspect, we introduce the concept of *street solar loads*, as the sum of the solar loads (MWh/season) accumulated by the ground and façade surfaces bounding the studied street during the investigated period. In this sense, Fig. 7 compares the effect of whitening the façades or installing sun sails on the *street solar loads* of the street with dark façades (base scenario). Results show that, regardless of their colour, the use of sun sails is the best alternative to reduce street solar loads. Though painting and installing sun sails have a similar impact over the façade solar loads, the former intervention increases ground solar gains (+20%) while the latter reduces them (up to -65%).

Fig. 8 compares the impact of sun sails on the solar loads of streets with a different reflectance. Results show that, in absolute terms, the reduction in solar loads due to the installation of sun sails is similar for streets with light and dark façades, being only slightly higher in the latter environment. The reason is that sun sails avoid radiation from penetrating into the canyon and being absorbed by surfaces whether directly (dark façades) or after multiple reflections (light façades).

These results also demonstrate that the colour of sun sail plays a secondary - but not negligible - role in the global effectiveness of these devices. The use of black sun sails instead of the white ones helps to reduce street solar loads between 8-12%. This means that roughly 20% of the total decrease in streets solar loads due to the presence of sun sails depends on their colour.

6. DISCUSSION

Results in this work indicate that the darker the sun sails, the more effective they are in reducing solar gains over the street surfaces. However, black tissues absorb more solar radiation than the white ones, therefore overheating to a greater extent and emitting more longwave radiation towards buildings and pedestrians. This counter effect diminishes the effectiveness of black sun sails somehow.

The assessment of the impact of sun sails on the longwave exchanges between the street surfaces and users is beyond the scope of this paper since it would require thermal simulations. However, a complete evaluation of the cooling potential of this kind of urban shading devices should take into account this aspect.

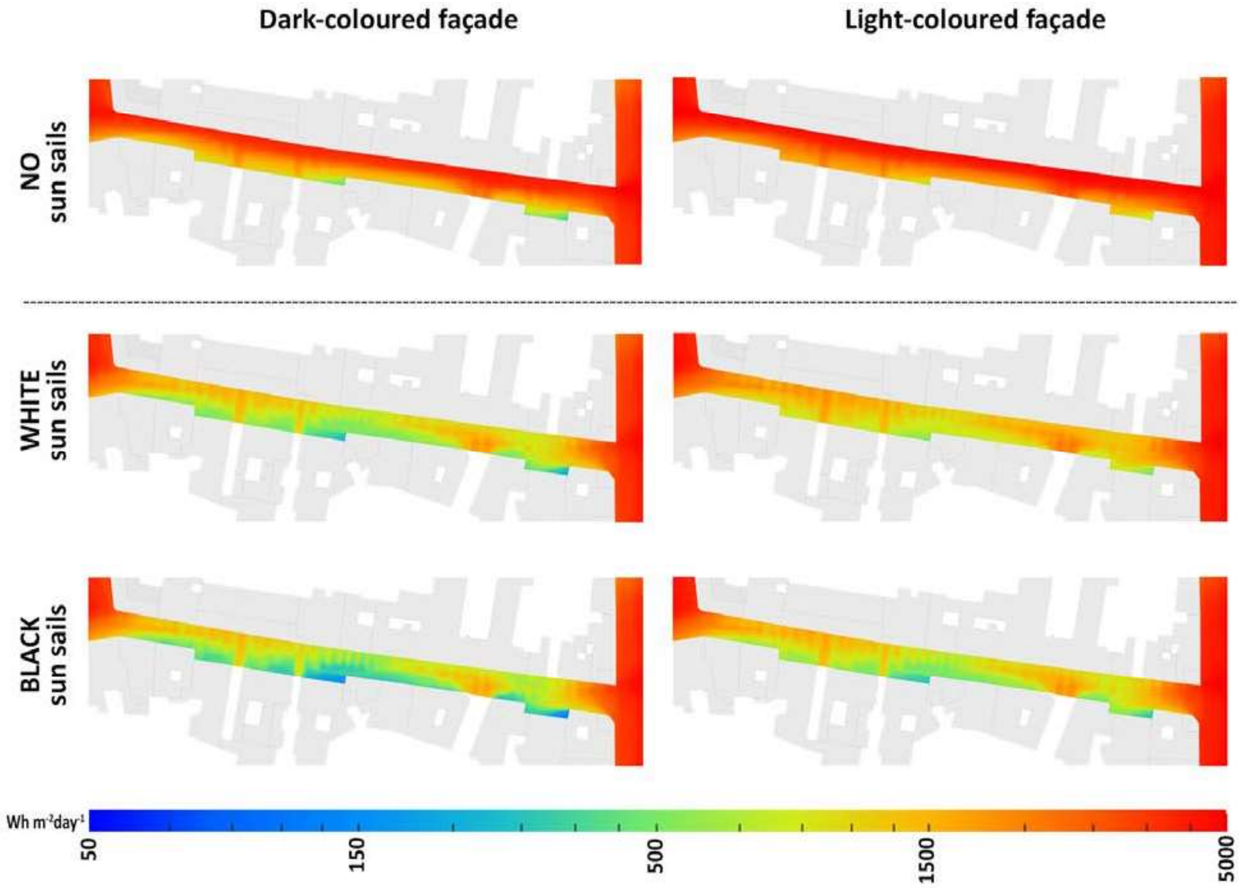

Figure 6: Solar loads absorbed by street surfaces with and without sun sails (Wh m^{-2}day^{-1}, from 15/05 to 15/09).

The use of sun sails will decrease wind speeds within the street, a key aspect for indoor and indoor comfort. Further investigations in this matter are needed.

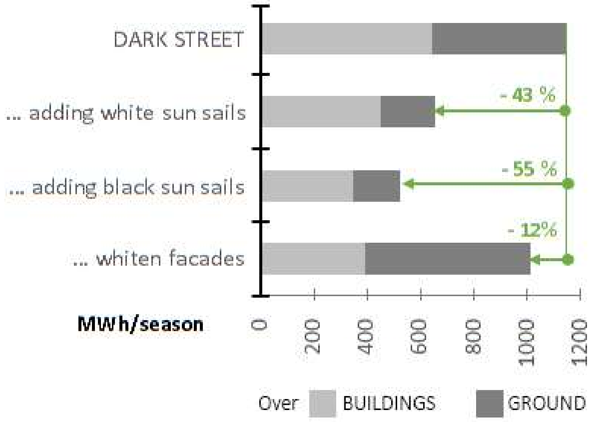

Figure 7: Impact of painting or installing sun sails on solar loads of the 'dark street'.

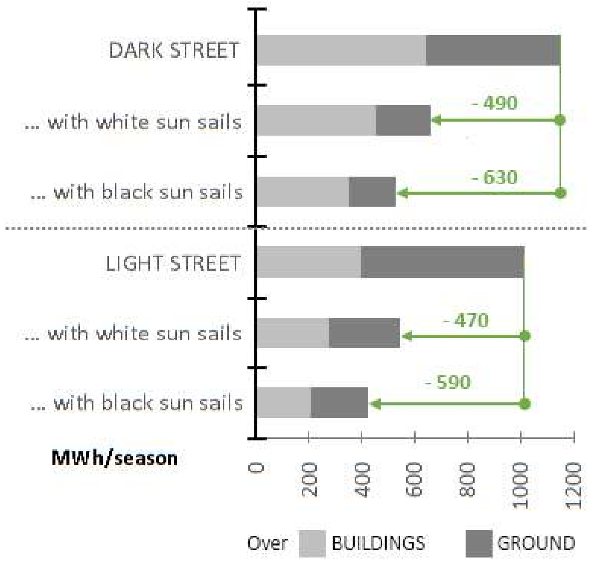

Figure 8: Impact of adding sun sails on the solar loads depending on façade reflectance.

7. CONCLUSIONS

This paper assessed the impact of urban sun sails over the solar loads of façades and ground, as critical parameters for cooling energy consumption and pedestrian comfort. Based on the results of our simulations, we conclude that:

- Installing sun sails is a highly effective way to reduce street solar loads, with decreases between 43-64%. Suns sails are more effective than whitening façades because they limit not only the solar gains over façades but also over the ground.
- At the local scale, shading is more effective, the darker a surface is. However, at a street level, sun sails are almost equally effective in environments with dark or light-coloured façades, making them an exportable heat mitigation strategy.
- The sun sail colour affects its cooling potential in a not negligible way (± 20%). Darker tissues have a better performance than the lighter ones, due to their reduced transmittance and reflectance. Regardless of the tissue colour, high-mounted sun sails are always desirable, but this is especially important with light-coloured tissues.

Urban interventions may have opposing effects on building and street users. Therefore, it is crucial to take into account both aspects when assessing their suitability. The main potential of sun sails is their simultaneous benefits for outdoor and indoor summer comfort, without affecting the street appearance or winter solar gains. Additionally, sun sails balance solar loads between buildings, helping to "democratise" urban cooling needs.

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