Building and Environment 243 (2023) 110681

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

A climate sensitive design approach to BIPV: Investigating the nexus between solar energy and thermal comfort in cities in Sweden and Cyprus

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ARTICLE INFO

Keywords:
Climate sensitive design
Low emissivity photovoltaics
Thermal comfort
Interstitial urban space
Urban dwellers
Solar systems building integration
Urban morphology
Street level simulations

ABSTRACT

The research performed attempts to answer the question of how building integration of active solar systems may affect the thermal comfort in open areas and the interstitial space between buildings in urban environments. This is done by using computer simulation and in-situ observations at the extreme northern and southern geographies of Europe, namely in Luleå, Sweden and in Limassol, Cyprus. A typical example of the urban grid of each city is chosen and active solar systems are integrated on the facades of buildings, respectively foreach case. The thermal conditions at street level are then simulated, using Envi-MET, before and after systems integration, with the aim of assessing the differences between low and high insolation conditions, using the Physiological Equivalent Temperature (PET) indicator. Subsequently, the thermal conditions in the public space between buildings were once again assessed, with reduced emissivity values for the building integrated PV panels. The results point to the fact that the building integration of PVs lacking low emissivity coatings can have an impact in the thermal comfort of users in the locations specified, especially in the summer, wherein it is shown to be negligible in the southern case study but more significant in the northern one.

1. Introduction

The harmful effects of climate change have brought attention to the building sector's significant contribution to global greenhouse gas emissions - 24% - and primary energy consumption - over 40% - in Europe [1]. This issue first surfaced during the early 1970s, when the first oil crisis occurred [2], leading to a concentrated effort to reduce building energy consumption. Initially, active building systems were targeted to curb the use of fossil fuels for energy production, with the passive approach to bioclimatic architectural composition following in the mid-1970s [3]. Europe's average Global Horizontal Irradiance (GHI) is approximately 1200 kWh/m^2/year [4], and solar energy is recognized as the most promising alternative to reducing reliance on fossil fuels [5–7], at a time when many environmental issues related to fossil fuels extraction and utilization are constantly emerging [8,9].

Increased urbanization may be singled out as one of the factors that has led to the escalation of energy consumption in metropolitan areas, while the interdependence of building massing and the space between buildings and also to the space that surrounds them. Not only are related global energy expenditures more than a third of the total attributable to this condition of building massing proximity, but this has further led to an exacerbation of this condition [10]. Faced with the challenge of mitigating these unwanted conditions on the everyday life of urban dwellers, it is important to quantify such metrics as the comfort of an urban dweller, a challenge which may be partially addressed by pertinent analysis of building façade construction adjacent to these public spaces. In looking at building facades, this study considers a subset of alternative treatments, which are building facades that feature integrated solar systems [11]. This type of concern finds resonance in similar investigations that examine the micro-greenhouse effect, which looks into temperature mitigation of the urban environment. Therein buildings are retrofitted with bio-inspired and retro-reflective façade envelopes [12], given that buildings in urban areas may expect their environmental thermal loading to increase. This is the result of a combination of factors, such as, warmer temperatures due to climatic changes, coupled to an increased frequency of extreme and severe heat events [13].

The investigation in this paper examines the effect on public spaces

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https://doi.org/10.1016/j.buildenv.2023.110681
Received 9 June 2023; Received in revised form 20 July 2023; Accepted 31 July 2023
Available online 2 August 2023
0360-1323/

surrounding buildings in urban areas of architectural design decisions concerning the treatment of building envelopes, specifically the integration of solar systems. These effect on the thermal comfort of urban dwellers of these decisions is tested through simulations, the computational investigation of which is hoped will lead to more informed choices by all stakeholders. In summery then, the research question may be expressed as follows: How does building integration of active solar systems affect the thermal comfort in open areas between buildings in urban environments?

The experiment considers modelling and simulations of these alternative implementations on appropriated locations of building envelopes and on related space conditioning loads. These in turn, are examined in terms of how they may affect the microclimate of interstitial and open spaces in the form of streets, squares and parks surrounding these urban blocks.

The question is related to a broader spectrum of factors affecting user comfort, such as, building massing, paving materiality and planting vegetation. A contention is made that urban dweller comfort at street level is greatly affected and dependent upon these three components and the way in which they affect the regulation of heat resulting from insolation in the diurnal period, and the night-time release of heat during the nocturnal period [14,15].

2. Literature review

In considering how the building integration of active solar systems may affect the thermal comfort in open areas between buildings in urban environments one needs look at this in the context of climate change and at the frequency and the severity of inclement climatic conditions. These may result in extreme and sometimes severe seasonal temperature fluctuations and other factors that will present increasing challenges to the design and construction industry. They also affect urban design considerations of cities, especially with increasing urbanization and of associated effects, which may in turn increases urban energy loads [16–19].

The materiality of building components, such as building shells, roofing elements and paving surfaces and their thermal properties [20–23] may potentially augment both the intensity and the timeframe in which these uncomfortable conditions may persist in an urban area. As such, the materiality of such components plays a significant role on the microclimate of urban settings, with the additional factors of transportation related infrastructure and level and type of vegetation and plantings also contributing to the perception urban thermal comfort [24–26].

Investigations, such as the ones mentioned above, were also augmented by ones that examined so called bio-inspired retro-reflective building envelopes [27,28]. There it was found that the reflected solar radiation and associated heat was reduced with regards to both adjacent building surfaces and to the paved spaces between them, and with the extra benefit of reducing required cooling loads. The implications on building and city design considerations are therefore significant, as over the last fifty years global energy consumption has nearly tripled, exacerbating difficulties in supply, as fossil energy resources are used up on one hand and are found to be in more inaccessible places on the other. This situation has negative consequences on the quality of life and conditions of habitation; on the deterioration of the environment, including a depletion of the ozone layer leading to global warming; and last but not least, on the adverse observed phenomena relating to climate change [29].

2.1. Thermal impact of building envelopes in urban settings

The built environment remains one of the main consumers of energy, in the form of electricity [12,30], with the rate of urbanization constituting an ever-increasing challenge in achieving sustainable goals in the developing world [17,31], where the population shift from rural areas to urban settings is causing pressure on resources from increased demand on goods and services.

Some other researchers have noted that the rising temperatures in the urban cores of metropolitan areas may have been of some benefit to cities in colder climates, but summer conditions have caused challenges with regards to user discomfort and increased demand for cooling [32]. The main culprits in these cases have been compact and heavy construction materials that tend to absorb solar radiation much more readily than natural surfaces. This is exacerbated by the heat flux associated with maintaining acceptable room temperatures by the heating and cooling of buildings [33,34]. Researchers have also noted that by-products of this effect have led to a deterioration of the public health, safety and welfare of citizens, especially those of developing countries [35]. In places such as China the problem is especially dire, since it has replaced the United States as the largest energy consumer in the last decade as a result of an economic boom that has resulted from that country's increased manufacturing capabilities, [36].

A number of measures, stemming from extensive research [37–45], have been suggested and put forth for adoption by the most vulnerable groups, in order to mitigate these negative consequences. These include, increasing the thermal mass in urban areas, increasing the cover of evaporative surfaces by replacing impervious paving with more porous materials or indeed with plantings and vegetation, and also by actively rethinking building-roof and shell-envelope assembly, geometry and materiality and also in reconsidering the adoption of vegetation covers. Despite all of the above, the results often fall below expectations [46]. Consequently, a better understanding of the complexity of these material choices with regards to building shells and their materiality and their subsequent effect on their immediate surroundings – building massing and open spaces – is required. Also, accurately predicting not only building energy performance, but also the microclimatic implications on adjacent associated open and often public areas [46–48], would be a useful and timely endeavour and should lead to further in-depth investigations of building block geometries, massing and materiality.

2.2. Built environment formations

Further investigation and understanding of how built environment formations and climate dynamics are related becomes necessary in the context of considering both the nature of urban surfaces, as well as the governance of the urban energy balance [49,50] in the pursuit of sustainable urban development. Where higher urban temperatures are recorded, this net positive balance is usually the result of several factors: the texture of surfaces in the built environment; the use of low albedo materials and ones of high thermal storage capacity; the reduced incorporation of blue and green components in the urban infrastructure, such as enhancing cooling through the phenomenon of evapotranspiration; and last but not least deteriorating air quality, as a result of pollution from everyday human activity [18,51,52]. In such cases, climate dynamics will exacerbate conditions and they will increase the energy loads of buildings at both ends of the cooling and heating spectrum [51,53]. This in turn would lead to greater energy storage for the conditioning of building spaces, creating further problematic urban environments, resulting from the creation of the warming feedback loop [18,54–56].

In considering the built environment formations and climate dynamics, it is important to bear in mind that shifts in the timing and intensity and in the range of maxima and minima, may be factored in the energy loads required for buildings in such ways as to offset unwanted peak temperatures in a 24-h cycle and according to seasonal requirements. This aspect further complicates the design and construction of building shells and it augments the compromises designers need to address when finding the optimal design proposals in terms of time and budget of construction, long term operational expenses as a result of insulation choices affecting building energy loads, and of course the side effects their choices may have on the viability of the spaces between buildings [57–59].

One the other hand, researchers also note that it is worth considering cooling effects however modest or even negligible these may be [17,60], as the effects of these conditions on open spaces have been recorded in such places as London [61–64]. In that example, longitudinal studies across more intensely urban areas juxtaposed to less dense suburban areas, identified increased warming values in relation to minimum temperatures, while respective maximum temperatures have been shown to decrease, with mean temperatures remaining fairly constant overall [65,66]. Furthermore, these researchers note that in considering historic data from sites in central cities from early in the twentieth century indicate a stabilization of the relative increasing warming trend in recent times.

2.3. Building façade systems

More specifically, it is important to examine a broad range of options and alternatives with regards to the composition of wall facades, as they account for a significant percentage of the building envelope surface area, and they also have an increasing influence on building heat gains. It has been already been noted in research [67,68] that heavyweight building materials and inappropriate paving choices may exacerbate thermal comfort conditions when compared to more lightweight materials, such as sandwich panels and double skinned facades,. This is due to the fact that the former choices tend to absorb and store heat more readily as a result of daylight insolation and these may cause delays in heat dissipation to both the indoor and outdoor environment.

On the other hand, studies of the phenomenon of infrared emissivity in an examination of heavyweight versus lightweight building envelope component choices [69,70] have also noted that the use of lightweight materials such as, gypsum walls, plywood boards and even glass-fibre-reinforced-concrete (GFRC) – properly lined with wool insulation may account for a reduction of interior temperature fluctuations. In yet another study, the research carried out [70,71] indicated that buildings that incorporate high thermal inertia material choices, have a positive effect on the thermal comfort of a building's users at certain times of day, but of questionable benefit to thermal comfort conditions for users in the outdoors, the thermal behaviour of which is partly governed by material choices and façade modifications of a building shells.

Another aspect of the material choice for facades, which has garnered research interest, has been the aspect of reflectivity and its effect on both neighbouring buildings and also in the interstitial open and oftentimes public areas [72–74], with a notable increase in the surface area of these outdoor domains, while reducing the temperature of the interiors under study. Component colours for solid as well as for glazed finishes have also been investigated in similar research contexts [75] and indicate that darker coloration tends to increase heat absorption in the case of building shells – in both facades and roofs. This has also resulted in an increase in exterior ambient temperature, indicating yet again the compromises that may need to be made, and the complexity of the parameters that need to be considered, when examining the implications of material choices and assembly methods of façade systems, to interior and exterior spaces.

While there have been several studies on the impact of building façades on the microclimate of public spaces, there have been relatively fewer on the effect of integrating active solar energy systems into building facades [76]. For example, Freitas et al. [77] studied the impact of photovoltaic (PV) integrated systems on the urban microclimate of a neighbourhood in Lisbon, while Berardi and Graham [78] simulated the microclimate of a neighbourhood in Brampton, Ontario to investigate the trade-offs of large-scale rooftop PV deployment. Both studies found that PV integration had a minor effect on the microclimate.

In the case of building integration of active solar energy systems, different integration proposals and solar collector forms have been developed as part of a concerted effort to improve their solar collection [79–83], with low-emissivity coatings being one main method used to reduce infrared radiation [84]. Other researchers working on the subject [85–87], such as Barone et al. [88] performed an optimization procedure for their collector, and selected an emissivity of 0.24, indicating further that although the literature has examined the low emissivity of solar panel surfaces, its impact on the thermal comfort of public spaces has not been extensively studied, with only a few specific works [89,90] addressing this issue as part of a larger approach.

3. Methodology

The study begins by selecting a typical example of the urban grid in Limassol, Cyprus and Luleå, Sweden.

The next step involves integrating active solar systems on the building facades.

The goal of the study is to compare the thermal conditions in the public space adjacent to the selected building blocks before and after the integration of solar systems to surrounding and adjacent building facades. It should be noted here, that the methodological steps followed for the current research, are illustrated in Fig. 8.

To determine these thermal conditions, the researchers have utilized the Physiological Equivalent Temperature (PET) indicator, which is one of the most popular indices for assessing heat stress in outdoor environments. The Munich Energy Balance Model for Individuals (MEMI) [91] is used to calculate PET, and it has been extensively validated in the literature. Previous research [92] has demonstrated a strong correlation ($r = 0.96$) between PET and the Universal Thermal Climate Index (UTCI) [93], which is one of the most comprehensive indices for assessing heat stress in outdoor areas.

The level of physiological and thermal perception stress is evaluated using PET, as presented in Table 1 [94].

3.1. Locations

3.1.1. Limassol, Cyprus

Limassol, Cyprus is a coastal city located in the southern part of Cyprus and is the second largest urban area in the country. The city features a sparsely built urban layout consisting of a fairly young building stock developed in a "pavilion" style of urban development [97]. The study area selected for this research is situated at the intersections of "Michael Georgalla Str." (East-West axis, marked in yellow on Fig. 1), "Charalambou Mouskou Str." (North-South axis, marked in green on the top-left of Fig. 1), "Dim. Pouliou Str." (North-South axis, marked in green on the top-right of Fig. 1), "9 Iouliou Str." (North-South axis, marked in green on the bottom-left of Fig. 1), and "Oktovriou Str." (North-South axis, marked in green on the bottom-right of Fig. 1). These rights-of-way are 16 m wide and are mainly lined with two-story buildings.

This particular street condition was chosen as the building massing allows for the incorporation of building-integrated active solar systems, while the surrounding buildings are representative of the majority of Limassol's building stock, which consists of small buildings that require

Table 1
Ranges of PET for different grades of thermal perception and physiological stress on humans [94–96].

PET (°C)	Thermal Perception	Physiological Stress
<4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
>41.1	Very Hot	Extreme heat stress

Fig. 1. The chosen area for investigation is the intersection of five streets. The East-West axis is represented by "Michael Georgalla Str." and is marked in yellow colour. On the North-South axis, there are four streets marked in green colour: "Charalambou Mouskou Str." (top-left), "Dim. Pouliou Str." (top-right), "9 Iouliou Str." (bottom-left), and "Oktovriou Str." (bottom-right) (accessed online 06/2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

rehabilitation that would in turn lead to energy consumption and production improvements.

3.1.2. Luleå, Sweden

Luleå, Sweden is a city located on the coast of northern Sweden and serves as the capital of Norrbotten County, the northernmost county in Sweden. The city has a sparse urban fabric with a relatively young building stock, which is a combination of the "pavilion" and the "patio" type of urban development [97]. The research investigation focuses on an urban sector at the intersection of "Storgatan Str." (East-West axis, marked with yellow colour in Fig. 2), "Smedjegatan Str." (North-South axis, marked with green colour on the left side of Fig. 2), and "Kungsgatan Str." (North-South axis, marked with green colour on the right side of Fig. 2). The street canyons in this area are 20 m wide and fronted mostly by 3-story buildings. The chosen area allows for the installation of building-integrated active solar systems, while the surrounding buildings are representative of the majority of Luleå's existing medium-sized buildings that require restoration in terms of energy consumption and production. Moreover, these streets are frequently used for public flea markets, and they are used by many pedestrians. The integration of active solar energy systems on neighbouring building facades could potentially impact thermal comfort urban dwellers at street level.

3.2. Climate analysis

The climate and energy characteristics of European countries vary across the North-South spectrum.

While Cyprus and other countries in the Mediterranean have a relatively stable daylight contribution across seasons (Fig. 3), and they tend to suffer from hot summer conditions (Fig. 4), northern countries, such as Sweden, are characterised by dark (Fig. 3), cold winters (Fig. 4) and extremely long days in the summer [98–100].

This facilitates a comparative study, between the European North and South, examining Building Integrated Photovoltaics (BIPVs) installation in urban areas and their effect on the microclimate of adjacent open spaces.

3.3. Simulations

ENVI-Met is used for simulating environmental conditions in urban settings and assessing the effects of atmosphere, vegetation, architecture, and materials [102]. ENVI-Met simulations performed using equations described in Bruse and Fleer [103] have been previously validated and constitute a well-proven tool for urban planners and architects, by utilizing observed data of various environmental parameters [77,104–111].

3.3.1. Existing situation

The simulations were performed for the summer solstice. The reason that the summer solstice was chosen, was because it is the most stressful period for building operations in terms of insolation, for both locations. For Limassol, the combination of high incident radiation values and high temperatures has a direct impact on the buildings, as well as on the thermal comfort of the users in public spaces. The users of public spaces in Luleå are directly affected by a combination of high incident radiation values and a nearly horizontal angle of natural lighting, both of which have an impact on dweller thermal comfort. The objective of the

Fig. 2. The selected area of investigation in Luleå, Sweden is situated at the intersection of "Storgatan Str." on the East-West axis, and "Smedjegatan Str." and "Kungsgatan Str." on the North-South axis. The streets are marked with green colour on the left and right sides of Fig. 2, while "Storgatan Str." is marked with yellow colour (accessed online 06/2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

simulations conducted, was to document the thermal conditions present in the public spaces associated with the urban sectors examined.

3.3.2. *Proposed situation*

Following simulations of the current state of the urban areas under investigation, a scenario was created where photovoltaics were integrated into the facades of buildings in both cities. To determine the most suitable locations for the integration of photovoltaics, the methodology of Vassiliades et al. [111] was employed. Specifically, PVSites [112] was used to analyse the incident radiation on the buildings, and to determine which surfaces received the highest amount of solar energy. An example of the results is shown in Fig. 5.

Although this serves as an initial indication of the geometries that are suitable for integrating active solar systems on building facades, it is not conclusive in determining the feasibility of building integration. A building may have a high average incident radiation value, but some of its individual facades may have lower values, making active solar system integration unfeasible [113]. Therefore, to determine the minimum required incident radiation for viable building integration, equation (1) was utilized:

$$ISR\left(\frac{kWh}{m^2 \cdot yr}\right) = \frac{IC\left(\frac{€}{m^2}\right)}{\eta \times Ce\left(\frac{€}{kWh}\right) \times YR} \quad (1)$$

where the annual incident solar radiation for the site is denoted as ISR ($kWh/m^2/yr$). The variables IC, η, Ce, and YR represent system installation cost ($€/m^2$), system performance (–), energy cost (€/kWh), and number of years for repayment (yr), respectively. Current technological data was considered, with photovoltaic performance estimated at approximately 19% and investment depreciation estimated at 9 years. The analysis found that for a façade to be a viable location for photovoltaic integration, it should receive at least 650 $kWh/m^2/yr$ of incident solar radiation for both cities.

The integration of photovoltaics on the southern facades for both cities was found feasible as expected, while for Limassol, partial integration was also modelled for west-and-east-facing facades.

It should be noted here that vertical PV installations have been tested in a number of urban configurations in Luleå. Luleå Energi, the local energy provider, has installed a number of them in their headquarters complex (Fig. 6). Also, as the result of the research project EnergiFORM [114,115], the experimental solar park Solvåg was built in Piteå (Fig. 7) where design principles and user centred insights were used in the

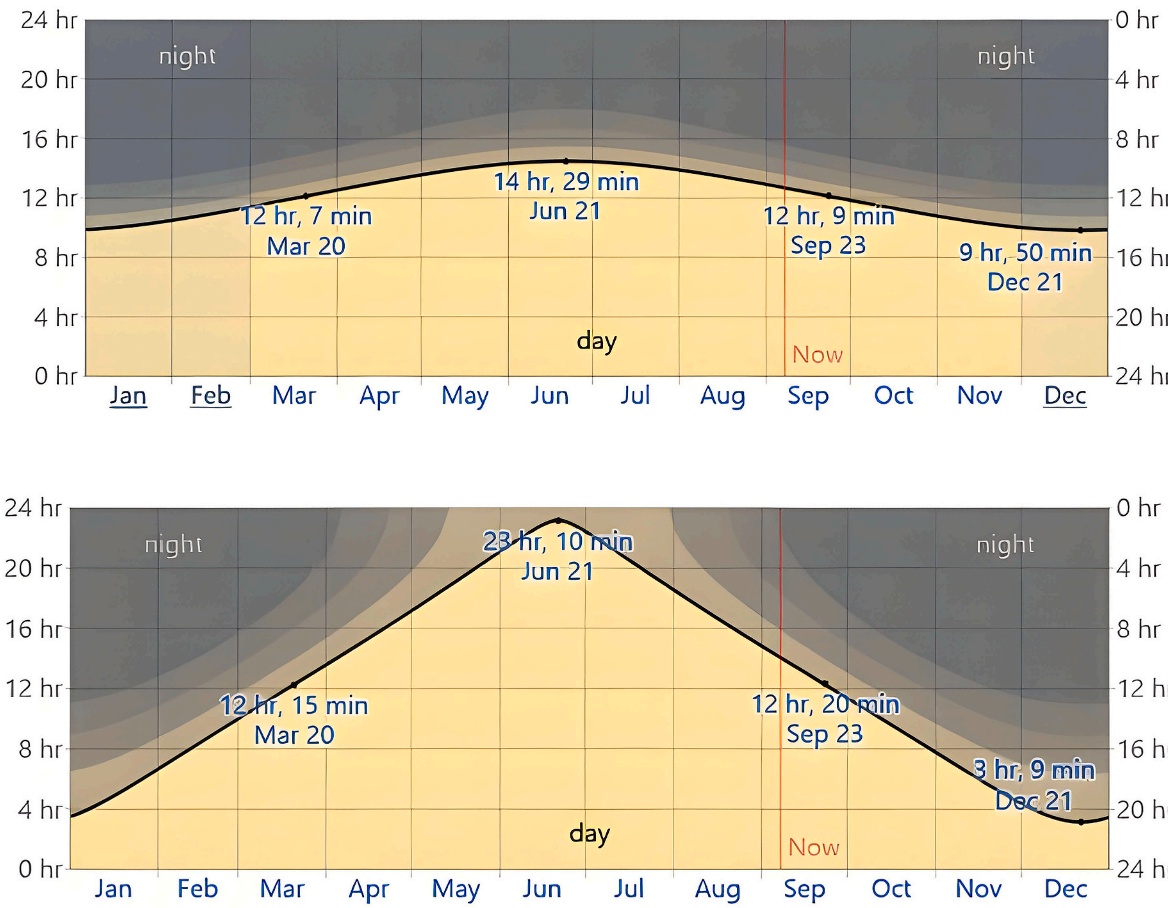

Fig. 3. Hours of Daylight and Twilight in Limassol (top) and Luleå (bottom). The number of hours during which the Sun is visible (black line). From bottom (most yellow) to top (most gray), the colour bands indicate: full daylight, twilight (civil, nautical and astronomical) and full night [101]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

design and placement of a PV ribbon installation at multiple orientations and solar angles.

Following the successful integration of PVs on the buildings, the thermal conditions in the adjacent public spaces were re-evaluated for the summer solstice, replicating the existing scenario. The simulations were conducted with the objective of documenting the changes in the thermal conditions.

3.3.3. *Proposed situation (with low emissivity PV panels)*

Having in mind the current trend to improve the efficiency of solar panels with the use of low emissivity coatings, this method was applied to the proposed situation, aiming to assess the influence it will have on the thermal comfort of the users in adjacent public spaces. Specifically, based on the findings of Barone et al. [88], an emissivity of 0.24 was selected, and applied on the PVs. Following the modification of the emissivity, additional simulations were conducted for both the existing and proposed scenarios during the summer solstice.

3.4. *Materials*

3.4.1. *Limassol, Cyprus*

The buildings in the area in question are mostly constructed with reinforced concrete and non-bearing masonry brick walls, with a thickness of about 20–30 cm and a finishing layer of cement mortar (3–4 cm). The floors are also made of reinforced concrete with a layer of concrete and mortar (25–30 cm) on top. Table 2 presents the materials used for Limassol, including the optical and thermophysical properties of the PV layer, which are based on typical monocrystalline silicon solar panels [77]. It should be noted here that the emissivity is changed for the PV panel to 0.24 for the simulations described in the subchapter “3.3.3. Proposed situation (with low emissivity PV panels)”.

3.4.2. *Luleå, Sweden*

Based on onsite observation and the preceding literature review, it was found that the majority of buildings in the study area were constructed with reinforced concrete columns, beams and floor plates, as well as non-bearing walls with a stratification of drywall-timber frame and insulation, and metal cladding, with a thickness of approximately 30 cm. The floors were also made of reinforced concrete, covered with a layer of concrete and mortar (25–30 cm). Therefore, Table 3 presents the materials used for Luleå, along with the optical and thermophysical properties of the PV layer. The PV properties were selected based on typical monocrystalline silicon solar panels [77]. Once again, it should be noted that the emissivity is changed for the PV panel to 0.24 for the simulations described in subchapter “3.3.3. Proposed situation (with low emissivity PV panels)”.

3.5. *Limitations and assumptions*

The ENVI-met software used to assess outdoor thermal comfort can only model PV panels as cladding material, which means that the photovoltaic and photothermal conversions cannot be accurately estimated, and the effective PV temperature cannot be calculated. This results in a slight overestimation of the temperature of PV panels, which affects outdoor comfort assessment. The PV panels modelled as cladding materials in ENVI-met entail all their optical and thermophysical

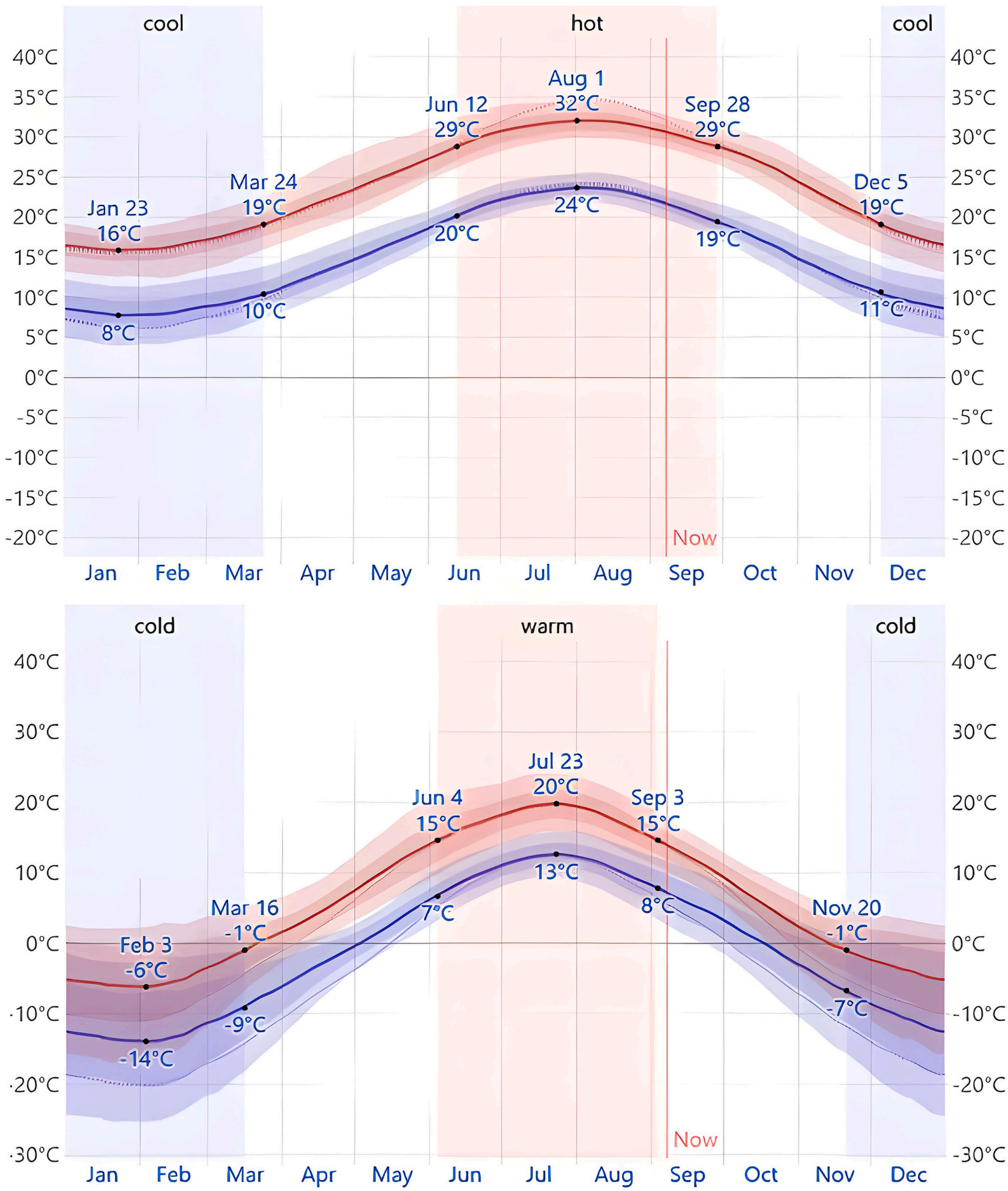

Fig. 4. Average High and Low Temperature in Limassol (top) and Luleå (bottom). The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures [101]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

properties based on typical PV panels, as listed in Tables 1 and 2

Consequently, the methodological approach of this study aims to provide design guidelines of a more abstract, yet comprehensive manner, as a result of the limitations of the study in conducting thorough experimental tests on the findings.

4. Results

In this section, the outcomes and their corresponding discourse are presented and they are organized according to each sub-topic of the study's research objectives.

4.1. Limassol, Cyprus

The research here has been centred on the East-West axis, specifically "Michael Georgalla Str.", and the North-South axis: "Charalambou Mouskou Str.", "Dim. Pouliou Str.", "9 Iouliou Str." and "Oktovriou Str.", as previously stated. Nevertheless, a broader zone was simulated in order to generate more accurate outcomes. The outcomes of the simulations performed for the summer solstice are shown for the existing, proposed, and proposed with low emissivity PV panels, as shown in Fig. 9.

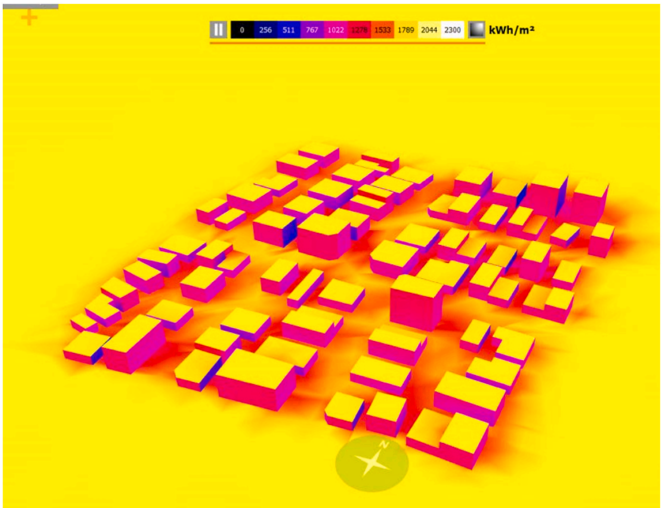

Fig. 5. The amount of solar energy on the buildings under study in Limassol, Cyprus, as it was calculated by PVSites.

4.1.1. PET

Results showed that the PET values fluctuate within a similar range (for example: 32.7–52.2 °C, PV: 33.3–55.1 °C; PVLE: 32.7–51.4 °C). The presence of PV panels causes a slight increase in PET due to the reflective nature of the materials. Higher PET values are mainly observed in the NS-orientated streets, where extensive reflection of solar radiation is expected. Due to the presence of lower buildings in the northern part of the study area, the PET values observed there are approximately 5 °C higher than in the southern part. This pattern holds for the PV scenario with higher magnitude, as well. One important point to note is the high maximum PET values observed in the PV scenario. This may result in "hotspots" in the neighbourhood environment, which may require further mitigation measures.

The comparison between the existing and the proposed situation (Fig. 10) showed that the PET values had marginally risen and fluctuated between 0.5 °C and 2.0 °C in their vast majority. The biggest difference was observed in the East-West axis, "Michael Georgalla Str.", where the PV building integration led to a rise of between 1.0 °C and 2.0 °C, wherein the North-South axes, "Charalambou Mouskou Str.", "Dim. Pouliou Str.", "9 Iouliou Str." and "Oktovriou Str.", the rise was even more marginal, between 0.5 °C and 1.0 °C. It should be noted here, that the changes noted in the PET values, do not have a major effect on the thermal conditions of the area, since the vast majority of the area under study remains within the "Hot" Thermal Grade classification of physiological perception, even after the building integration of the systems. There are slight differences between the two proposed scenarios where PV with Low Emissivity gives slightly lower PET values in general (in the range 0.5–1.0 °C).

Fig. 6. Luleå Energi Headquarter, Luleå (photo: Agatino Rizzo, 2022).

Fig. 7. The experimental solar park Solvåg, built in Piteå, Photo: Björn Ekelund.

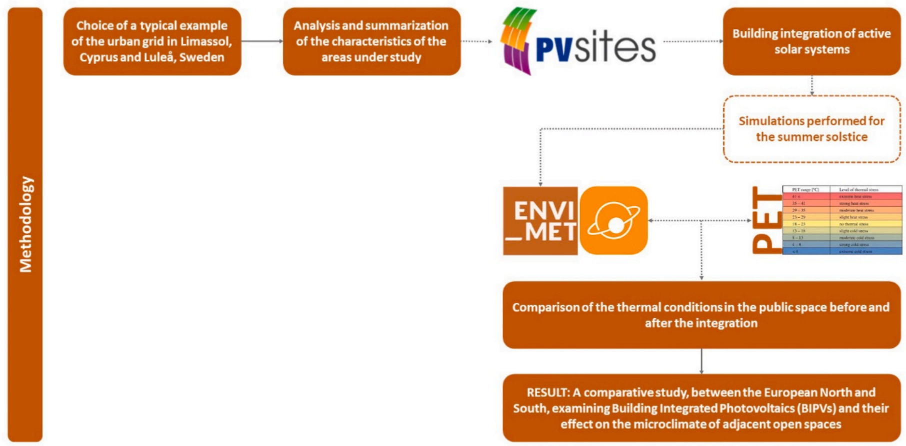

Fig. 8. An illustration of the methodological steps followed for the current research.

Table 2
Material characteristics for the simulations for Limassol.

Name	Absorption	Transmission	Reflection	Emissivity	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Density (kg/m^3)
Cement plaster	0.50	0.00	0.50	0.90	1000.00	1.00	1800.00
Brick Masonry	0.60	0.00	0.40	0.90	1000.00	0.40	1000.00
Glass	0.05	0.90	0.05	0.90	750.00	1.05	2500.00
PV Panel	1.00	0.00	0.00	0.84	700.00	0.15	3000.00

Table 3
Material characteristics for the simulations for Luleå.

Name	Absorption	Transmission	Reflection	Emissivity	Specific Heat [J/(kg·K)]	Thermal Conductivity [W/(m·K)]	Density (kg/m^3)
Cement plaster	0.50	0.00	0.50	0.90	1000.00	1.00	1800.00
Metal cladding	0.10	0.00	0.90	0.18	880.00	203.00	2700.00
Dry wall	0.29	0.00	0.50	0.85	1000.00	0.25	900.00
Glass	0.05	0.90	0.05	0.90	750.00	1.05	2500.00
PV Panel	1.00	0.00	0.00	0.84	700.00	0.15	3000.00

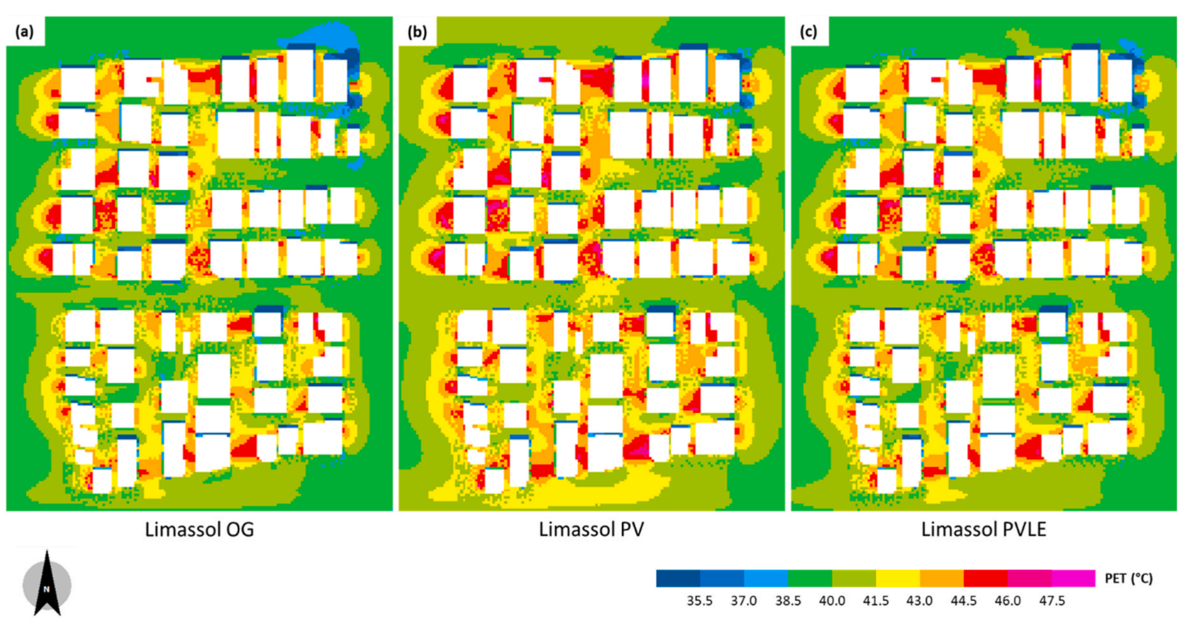

Fig. 9. PET values for the (a) existing, (b) proposed, and (c) proposed scenario with low emissivity PV panels for the summer solstice at 12:00 in Limassol, Cyprus.

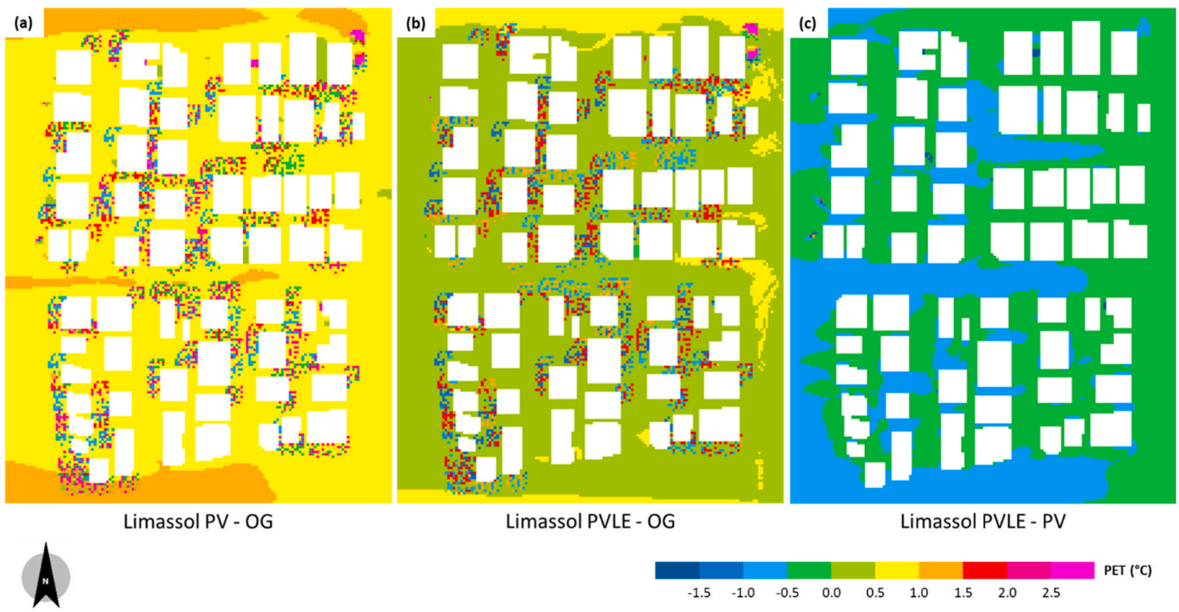

Fig. 10. The comparative analysis of (a) the existing and the proposed situations, (b) the existing and the proposed with low-emissivity PV panels, (c) the two proposed situations in Limassol, Cyprus on where the absolute difference in PET is presented.

4.1.2. Climatic analysis of Limassol results

Due to the higher solar angle in Limassol, higher direct shortwave solar radiation is received in street canyons, leading to higher PET values at pedestrian level. Extensive reflection of shortwave radiation in the narrow N–S street canyons leads to a nearly doubling the amount of reflected shortwave solar radiation compared to E-W streets. This also applies to the longwave radiation released from surrounding buildings and ground surfaces. E-W streets generally exhibit lower PET values due to the shading provided by surrounding buildings, suggesting that building height provides certain mitigation effects to the thermal discomfort felt at pedestrian levels while also having an effect on the solar energy potential of south-facing façades along E-W streets. Surprisingly, the higher reflected shortwave radiation is not observed in the proposed situation with low emissivity PV panels, which may be due to the higher incident angle of solar radiation, leading to less reflected radiation from the building surfaces (i.e. PV panels). This suggests that the presence of PV panels does not significantly cause thermal discomfort in summer months.

4.2. Luleå, Sweden

The study primarily focuses on "Storgatan" for the East-West axis and "Smedjegatan" and "Kungsgatan" for the North-South axes, as mentioned in the previous section. However, to achieve more accurate results, a broader area was simulated. The simulations conducted for the summer solstice are presented in Fig. 11 for the existing, proposed, and proposed with low emissivity PV panels.

4.2.1. PET

Results have shown that the PET values fluctuate within a similar range, although cases incorporating PV panels exhibited higher PET values (EX: 23.6–44.3 °C, PV: 28.3–53.9 °C; PVLE: 28.7–54.2 °C). Generally speaking, the E-W street (Storgatan) shows lower PET values (up to 15 °C difference) than the N–S street canyons (Smedjegatan and Kungsgatan), as a result of a lower solar angle and the presence of buildings on both sides. The pattern is similar across all three scenarios, but it is worth noting the presence of a more exposed public square between the two N–S streets investigated in this study. Similar to

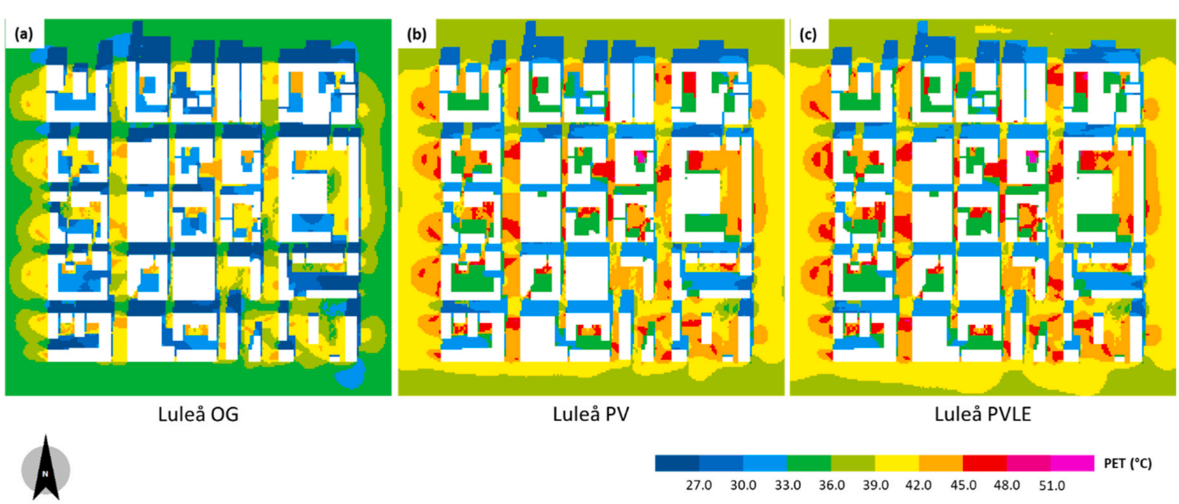

Fig. 11. PET values for the (a) existing, (b) proposed, and (c) proposed scenario with low emissivity PV panels for the summer solstice at 12:00 in Luleå, Sweden.

Limassol, the reflective nature of the PV panels results in higher PET values (around 3 °C in general). Nevertheless, several hotspots may require mitigation measures, especially in public spaces used and frequented by pedestrians.

The comparison between the existing and the proposed scenarios (Fig. 12) has shown a rise in the PET values fluctuating between 3.0 °C and 4.5 °C. The biggest difference was observed in the East-West axis, "Storgatan", where the building integration of PVs led to a rise between 4.5 °C and 6.0 °C, whereas in the North-South axes, of "Smedjegatan" and "Kungsgatan", the rise was smaller, and it fluctuated between 3.0 °C and 4.5 °C. It should be noted here that the changes in the PET values, affect the thermal conditions of the area. Specifically, in the East-West axes, the area under study changes from the "Comfortable" classification, to the "Slightly Warm"-one, whereas in the North-South axes, the area under study changes from "Warm" and "Hot" to "Hot" and "Very Hot" classifications of the Thermal Grade of physiological perception. These results show that PV building integration may have an impact in cities at higher latitudes, where there is comparatively increased solar radiation during the summer. However, there are no significant differences in PET values observed in the two proposed scenarios, suggesting that the use of materials of PV panels has a very limited impact on the thermal comfort at pedestrian level.

4.2.2. *Climatic analysis of results in Limassol*

In contrast to Limassol, where the solar angle reaches 78° in summer, the lower solar angle in Luleå leads to significant differences in thermal comfort conditions between street orientations, due to the presence of surrounding buildings. The considerably higher PET values are the result of high exposure to incident shortwave radiation in N–S streets in the middle of the day. On the other hand, E-W streets are heavily shadowed by the tall buildings to the south of the street. The regular street layout also demonstrates the distribution of thermal comfort conditions in outdoor environments. Higher PET values are observed close to street intersections due to their more exposed situation. The presence of solar panels leads to a slight increase in longwave radiation in enclosed areas, such as courtyards, which exhibit 10% increase in longwave radiation from surrounding surfaces, due to a higher proportion of sunlit surfaces in such locations. Furthermore, there may be a need for mitigation measures due to high PET values observed, which also has to take into account the acclimatization of inhabitants and the need for solar energy in dense urban cores.

5. Discussion and conclusion

The starting question of this study was How does building integration of active solar systems affect the thermal comfort in the publicly used spaces between buildings? To answer it Envi-MET has been used to simulate the thermal conditions at street level for a representative sample of the urban fabric in the selected cities, both before and after the integration of solar systems.

The results of the simulations point to a relatively controversial situation, with the initial hypothesis in which the building integration of PVs without low emissivity coatings can have an impact in the urban fabric in the summer, negligible in the southern latitudes, but more significant in the northern ones. Specifically, the results of the simulations in Limassol gave an initial indication that the building integration of PVs can be viable in the hot summers of the Mediterranean south, in terms of their effect on the thermal comfort in publicly used spaces between buildings. Their application, in parallel with other measures, which aim to improve the microclimate in the urban fabric, can balance the negative effects that have been noted, an aspect which may be further investigated. On the other hand, the results of the simulations in Luleå have shown more significant deviations in the thermal conditions before and after systems integration, proving that the increased time spans of solar radiation and the differentiation in the solar angles that are encountered in areas of higher latitudes during the summer, has an effect on the viability of such enterprises. This also indicates the need to explore integrated solutions and sustainable urban planning strategies that will allow the viable exploitation of solar energy in the Arctic North as well.

With regards to the building integration of PVs with low emissivity coatings, the differentiation in the readings in Limassol fluctuates by about 0,5 a degree Celsius rise from the simple PV integration, whereupon in Luleå the rise fluctuates by about 2° Celsius. This is a first indication that PV coatings have a negligible negative impact in hotter Mediterranean climates, like the one of Limassol, contrary to a bigger impact in northern artic climates, such as in Luleå. This is a first step in showing that even though the use of low emissivity coatings can have a positive impact on the performance of PVs, it can have a negative impact on the thermal comfort in public spaces, in cases like the ones presented herein. Of course, these results are based on a simulated environment and further investigation, such as field measurements and the use of various physical integration configurations, are needed.

In summing up the key findings may be enumerated as follows:

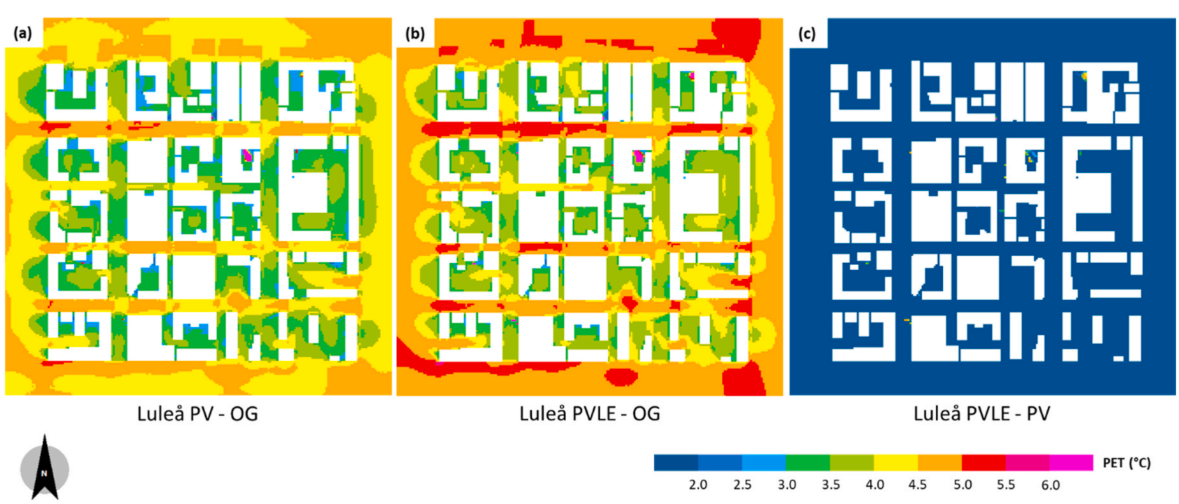

Fig. 12. The comparative analysis of (a) the existing and the proposed situations, (b) the existing and the proposed with low-emissivity PV panels, (c) the two proposed situations in Luleå, Sweden on where the absolute difference in PET is presented.

- PET values fluctuate within a similar range (Limassol: EX: 32.7–52.2 °C, PV: 33.3–55.1 °C; PVLE: 32.7–51.4 °C and Luleå: EX: 23.6–44.3 °C, PV: 28.3–53.9 °C; PVLE: 28.7–54.2 °C).
- In Limassol the presence of PV panels causes a slight increase in PET due to the reflective nature of the materials.
- Higher PET in NS-oriented streets, due to solar reflection in Limassol, while Luleå's E-W street has lower PET (up to 15 °C difference) than N–S streets due to lower solar angle and building presence on both sides.Limassol shows high max PET in PV scenario, creating "hot-spots," while Luleå's "hotspots" are scattered.
- In Limassol, PET values slightly increased by 0.5 °C–2.0 °C, while in Luleå, they rose by 3.0 °C–4.5 °C.
- In Limassol, PET changes have minor effects on thermal conditions, while in Luleå, they have a more significant impact.
- In Limassol, PV with Low Emissivity shows slightly lower PET values (0.5–1.0 °C), while in Luleå, no significant PET differences were observed in the two scenarios.
- Higher solar angle in Limassol results in elevated PET values due to increased direct shortwave solar radiation, while lower angles in Luleå cause notable thermal comfort variations among street orientations.
- Intense shortwave reflection in Limassol's N–S canyons nearly doubles both shortwave and longwave radiation, while Luleå's elevated PET values stem from significant exposure to incident shortwave radiation in midday N–S streets.
- In Limassol, E-W streets have lower PET values due to surrounding building shading, mitigating thermal discomfort at pedestrian levels and impacting south-facing façade solar energy potential. In Luleå, E-W streets are heavily shadowed by tall buildings to the south.
- In Limassol, low emissivity PV panels reduce reflected shortwave radiation due to higher incident angles, causing minimal additional thermal discomfort. In Luleå, solar panels slightly increase longwave radiation in enclosed areas, requiring mitigation measures for high PET values, considering inhabitants' acclimatization and solar energy needs.

In addition to the direct findings above, aspects of the work carried out confirm the work of Jannat et al. [20], Larsen [21], Sahnoune [22] and Mohajerani [23] et al., who argued that the materiality of building components and their thermal properties can affect user thermal comfort in urban areas. Additionally, this research adds to the findings of the studies by Wonorahardjo et al. [67,68], who investigated how the type and the materiality of the structures of the facades of the neighbouring buildings can affect the thermal conditions of public spaces. The research also enriches the work of Wen et al. [72] and Guo et al. [73], who dealt with the aspect of the reflectivity of the facades and its effect on the interstitial open and oftentimes public areas.

Building integration of active solar energy systems is becoming more and more widespread, transforming the built environment's materiality, since it starts to become an essential element in the energy refurbishment of existing structures. Therefore, it is essential to be able to understand these systems' indirect operation, beyond the limits of a building, and especially in totally different climatic conditions. The research results set a steppingstone towards the understanding of some of the indirect effects of solar systems building integration: how it affects the microclimate of the public space in extreme climatic conditions. The initial findings show that there are negative effects on the urban microclimate, but it is also encouraging that these effects may be mitigated thru appropriate urban design strategies.

5.1. Further research

In future research, additional urban conditions in Limassol and Luleå will be examined, including the consideration of different seasons, vegetation, and materiality. This will involve a parametric investigation and comparison of thermal conditions in public spaces before and after the integration of active solar systems, evaluated through various applications of solar urban planning strategies and existing urban morphologies. The ultimate goal is to propose a comprehensive methodology for analysing and arriving at the most appropriate combination of circumstances related to urban planning and solar system integration strategies for energy production, applicable across a wide range of climates from the Mediterranean south to the Arctic north.

CRediT authorship contribution statement

C. Vassiliades: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **K. Lau:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **R. Moiseos:** Software, Investigation, Data curation. **A. Buonomano:** Writing – review & editing, Supervision, Methodology, Conceptualization. **A. Savvides:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **A. Rizzo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We would like to express our sincere gratitude to "SUN – Natural resources for sustainability transitions" for their support in conducting this research.

Nomenclature

PET	Physiological Equivalent Temperature
GHI	Global Horizontal Irradiance
UHI	Urban Heat Island
MEMI	Munich Energy Balance Model for Individuals
UTCI	Universal Thermal Climate Index
BIPV	Building Integrated Photovoltaics
PV	Photovoltaics

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