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Ten questions concerning planning and design strategies for solar neighborhoods

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ABSTRACT

Planning of neighborhoods that efficiently implement active solar systems (e.g., solar thermal technologies, photovoltaics) and passive solar strategies (e.g., daylight control, sunlight access through optimized buildings' morphology, cool pavements, greeneries) is increasingly important to achieve positive energy and carbon neutrality targets, as well as to create livable urban spaces. In that regard, solar neighborhoods represent a virtuous series of solutions for communities that prioritize the exploitation of solar energy, with limited energy management systems. The ten questions answered in this article provide a critical overview of the technical, legislative, and environmental aspects to be considered in the planning and design of solar neighborhoods. The article moves from the categorization of "Solar Neighborhood" and the analysis of the state-of-the-art passive and active solar strategies to the identification of challenges and opportunities for solar solutions' deployment. Insights into legislative aspects and lessons learned from case studies are also provided. Ongoing trends in solar energy digitalization, competing use of urban surfaces, and multi-criteria design workflows for optimal use of solar energy are outlined, emphasizing how they generate new opportunities for urban planners, authorities, and citizens. A framework is introduced to guide the potential evolution of solar neighborhoods in the next decade and to support the design of urban areas and landscapes with architecturally integrated solar energy solutions.

1. Introduction

Climate and energy crises have accelerated the urgency to identify and implement tailored solutions to ensure energy security on a larger scale. Clean energy investments and energy efficiency are recommended in the guidelines included in the World Energy Outlook 2022 [1]. Nonetheless, existing buildings and neighborhoods have untapped potential for energy efficiency, while the availability of Renewable Energy Sources (RES) in the built environment, and among them the potential of solar energy, is far from being optimally exploited by both public and private investors. Globally, the Sustainable Development Goals (SDGs) [2] and various energy concepts (e.g., zero energy, positive energy) are set up to reduce the environmental impact of anthropogenic activities as well as to secure future energy supply from RES. Making buildings and neighborhoods more energy-efficient through refurbishment and/or new interventions by intensifying the use of RES is therefore fundamental to reduce greenhouse gas (GHG) emissions, towards positive energy districts (PED) and zero emission neighborhoods (ZEN). In that regard, an increased use of solar energy is one of the most effective strategies, as highlighted by the Sixth Intergovernmental Panel on Climate Change Assessment Report [3].

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List of abbreviations

AI	Artificial Intelligence
BIM	Building information modeling
BIPV	Building-integrated photovoltaic
BPV	Bifacial photovoltaic
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-aided design
EV	Electric vehicles
GHG	Greenhouse gases
GIS	Geographic information system
H	Building height
H/W	Height-to-width ratio
IEA	International Energy Agency
IoT	Internet of Things
KPI	Key performance indicators
LEED	Leadership in Energy and Environmental Design for Neighborhood Development
LiDAR	Light Detection and Ranging
LoD	Level of detail
NTNU	Norwegian University of Science and Technology
PED	Positive energy district
PET	Physiological Equivalent Temperature
PV	Photovoltaic
PVSD	Photovoltaic shading devices
PV/T	Hybrid photovoltaic/thermal
RES	Renewable energy sources
SDG	Sustainable Development Goal
SHC	Solar Heating and Cooling
SN	Solar Neighborhood
ST	Solar thermal
UBEM	Urban building energy modeling
UN	United Nations
UHI	Urban heat island
UTCI	Urban Thermal Climate Index
UWG	Urban Weather Generator
W	Street width
ZEB	Zero-emission building
ZEN	Zero-emission neighborhood

Interactive platforms (i.e., Mapdwell[1] and Google sunroof[2]) for rooftop solar yield estimation, which cover most of the national building stock, have been developed in the United States of America. Conversely, in Europe and China, similar tools are spotted or ad-hoc initiatives from virtuous municipalities and regions [4,5]. In some cases, these platforms (e.g., Helsinki[3] and the Swiss solar cadaster[4]) are capable of extending the mapping of the solar energy potential to the facades. This is especially important at high-latitude locations, where vertical surfaces can harvest high amounts of solar irradiation. Such instruments allow urban planners and architects to support the integration of active solar systems (e.g., photovoltaics, solar thermal) into the urban surfaces (e.g., ground, facades, roofs, street furniture, infrastructures), contributing to increasing the share of the energy production from RES [6–9]. In addition, these platforms can also provide useful information on the implementation of passive solar strategies [10–12] such as solar gains and daylight access to reduce the energy use in buildings, as well as to improve the inhabitants' indoor and outdoor thermal and visual comfort.

Although the optimal and extensive use of passive and active solar strategies can pave the way towards a more sustainable model of urban development [13], the rapid growth of cities and urban densification happening in many countries often lacks specific standards regulating the right-to-light (i.e., a legally enforceable right to a reasonable proportion of the natural unobstructed flow of direct solar radiation) at neighborhood level [14,15], resulting in reduced efficiency of solar strategies and solar energy potential. In fact, codes and standards that exist about right-to-light in numerous countries primarily regulate sunlight and the insolation of building interiors [16,17]. Similarly, the right-to-shade (i.e., a right to access shade in public spaces or to shield building portions from direct sunlight) is not legally recognized [18–20], and it is rarely mentioned in the literature despite its importance in hot climates and in connection to the raising frequency of extreme events such as heat waves [21].

Achieving a tradeoff between the right-to-light and right-to-shade for a specific combination of location and surface use is among the most complex tasks for urban planners and architects, especially since solar irradiation varies markedly during the day and the year. Such a task has impacts on solar accessibility of outdoor and indoor spaces as well as on performance levels of active and passive solar strategies. On the one hand, right-to-light is usually prioritized in temperate, continental, and polar climate zones, where the energy demand for heating is predominant. On the other hand, the right-to-shade is demonstrated to be more important in zones where the energy demand for cooling is dominant, such as the tropical and dry climate zones. Moreover, planning for shaded areas is fundamental to creating a more livable built environment and mitigating the urban heat island (UHI) effects (i.e., overheating of the urban surfaces). However, there are cases where both optimal exposure to sunlight (resulting from right-to-light) and low surface temperature (resulting from right-to-shade) are required, such as for building-integrated photovoltaic (BIPV) systems. BIPV systems need high solar accessibility to efficiently generate electricity, but the absence of shading in the surroundings contributes to increasing the air temperature, thus worsening performances. Therefore, it becomes more and more important to provide country-specific standards for the application of active and passive solar design strategies, as well as to find a balance of right-to-light and right-to-shade already in the early urban planning phases to avoid pitfalls and common mistakes (i.e., complex overshadowing effect in the built environment and uncontrolled mutual solar reflections among buildings and the ground) in the development of existing and/or new neighborhoods. Finally, long-term temporal fluctuations of solar energy due to climate changes are also to be considered. In fact, extreme weather events are expected to increase in both frequency and intensity, by impacting the identification of the tradeoff between the right-to-light and right-to-shade. For example, heat waves can result in higher solar irradiance due to the low presence of clouds, on the one hand; while increasing the air temperature and accelerating the aging rate of solar active systems [22], on the other hand.

In this framework, among the scientific studies on solar energy planning and design, the outcomes from the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 51 "Solar Energy in Urban Planning" (2013–2017)[5] and the ongoing SHC Task 63 "Solar Neighborhood Planning"[6] underline the need to investigate the neighborhood scale by looking at multiple solar-related aspects ranging from active and passive solar strategies, design concepts, and energy systems,

[1] mapdwell.com (accessed in 20.03.2023).
[2] sunroof.withgoogle.com (accessed in 20.03.2023).
[3] kartta.hel.fi (accessed in 20.03.2023).
[4] uvek-gis.admin.ch (accessed in 20.03.2023).
[5] task51.iea-shc.org (accessed in 20.03.2023).
[6] task63.iea-shc.org (accessed in 20.03.2023).

to economic aspects, societal and environmental impacts, stakeholder and researchers' engagement and citizens participation. The ambition is to support key actors (e.g., developers, property owners/associations, architects, urban planners, municipalities, institutions) towards the implementation of long-term planning and design solutions for neighborhoods that prioritize the exploitation of solar energy, with limited energy management systems.

The hereby ten questions article aims to identify the existing barriers and challenges in solar energy planning and to present the most common strategies, methods, and approaches for solar neighborhood planning and design through the insights from developers, architects, consultants, researchers, urban planners, municipalities, and other institutions. In addition, case studies and lessons learned are documented to show practices of successful implementations in solar neighborhoods. The research objectives of the study are: (i) to provide a clear definition of the solar neighborhood concept with respect to other existing neighborhood classifications (i.e., ZEN, PED), (ii) to outline recommendations and practices to design solar neighborhoods by identifying solar related variables, constrains and potential solutions, and (iii) to shape the future research trajectories and technical aspects to take into account for solar neighborhood planning and design, based on identified challenges and opportunities, with insights on the legislative agenda. The hereby presented study has a large impact on the SDGs from the United Nations (UN) [2] by contributing to the advancement of the ones listed in Table 1.

Table 1
List of the UN SDGs partially or fully addressed by the current study.

SDG1 - No Poverty	Active solar strategies for energy production that are proposed in this study for solar neighborhoods contribute to reducing fuel poverty, thus advancing SDG1.
SDG2 - Zero Hunger	Initiatives concerning urban farming and local food production within solar neighborhoods permit improving access to food resources for everyone, contributing to SDG2.
SDG3 - Good Health and Wellbeing	Achievements from this study allow for enhancing human indoor and outdoor comfort conditions within the solar neighborhood environment, improving human health and wellbeing.
SDG7 - Affordable and Clean Energy	Clean energy production and energy self-sufficiency are two important aspects in the design of solar neighborhoods, as well as to accomplish the SDG7.
SDG9 - Industry Innovation and Infrastructure	The present study can impact industry, innovation, and infrastructure, particularly with regard to active and passive solar solutions.
SDG10 - Reduced Inequalities	The study proposes a wide range of solutions that can be implemented in solar neighborhoods in relation to the climate context. Therefore, every country can apply solar neighborhood design principles to achieve carbon neutrality and energy self-sufficiency, regardless of the economic context, thus reducing inequalities.
SDG11 - Sustainable Cities and Communities	The multi-criteria analysis for solar neighborhood design, which is outlined in this study considers economy, environmental, energy, and social variables through specific performance indicators. This approach to neighborhood planning enables more sustainable cities and communities.
SDG13 - Climate Action	Design and technology solutions identified in this work can contribute to (i) mitigating urban overheating; (ii) decreasing the amount of carbon emissions in the atmosphere, and (iii) compensating the carbon footprint of the neighborhood by generating clean energy from RES.
SDG15 - Life on Land	The design principles characterizing the solar neighborhood positively impact biodiversity, reintroducing animal species in areas they used to inhabit before human-induced transformations.

The article is structured around ten questions concerning solar neighborhood planning and design (Fig. 1).

It moves from the definition of the solar neighborhood concept (section 2.1) to the identification of the aspects to consider in a multi-criteria analysis for neighborhood design (section 2.2). Then, the active and passive strategies used to exploit the solar energy potential are described (section 2.3) besides representative and successful solar neighborhood design experiences at various latitudes (section 2.4). A focus on challenges in deploying and implementing passive (section 2.5) and active (section 2.6) solar strategies follows. The digitalization of the built environment and its potential to support the planning of solar neighborhoods is discussed (section 2.7), while the impact of solar neighborhoods on the total environment, here defined as the built, natural, and social environments where a community grows, lives, works, and ages, is also assessed (section 2.8). The last two questions look into the future of solar neighborhoods by identifying the needs in the legislative agenda (section 2.9) and the main aspects (e.g., architectural integration of solar systems, energy flexibility, digitalization techniques) to be developed in the future (section 2.10).

2. Ten questions (and answers) concerning solar neighborhood planning

2.1. What is a solar neighborhood?

While the main neighborhoods' definitions currently in use are based on the achieved emission and energy targets (i.e., zero emission neighborhood, positive energy district), the categorization of neighborhoods proposed in this study is identified with respect to the exploited RES. Such a definition is determined by upscaling (i.e., from the building to the neighborhood scale) and adapting the classification proposed by Lund et al. [23] for zero-emission buildings (ZEBs), which distinguishes four types of ZEBs in reference to energy demand and installed RES typology (e.g., a Wind-ZEB is a ZEB with relatively low electricity demand and on-site active exploitation of wind). Following this, a solar neighborhood is primarily a neighborhood, hence an urbanized area either with a single function (e.g., residential neighborhood, commercial district) or with a mix of human activities and interactions (e.g., dwellings, workplaces, shops, civic buildings, parks), in which the full and optimal exploitation of the sun is prioritized. It can be part of a high-, medium-, or low-density urban area, a remote rural development, or it can represent an isolated community [24]. Further, solar neighborhoods exist as virtual entities in which datasets of monitored solar and energy variables (e.g., solar energy production, solar energy gains, solar energy potential, level of illuminance, and sunlight exposure) are stored [25,26] and processed with specific decision-making tools (e.g., energy district distribution, energy price) to predict short-, medium-, and long-term scenarios and to identify efficient management strategies for active and passive solar solutions [27,28].

Planning and design strategies for a solar neighborhood can be applied to both new and existing urban development areas and can contribute to achieving positive energy budgets and carbon neutrality in cities. In this regard, the interactions between solar neighborhoods (SN), zero-emission neighborhoods (ZEN), and positive energy districts (PED) are paramount (Fig. 2). This study exclusively focuses on the SN and its sub-domains, which are numbered from 1 to 4 in Fig. 2 while the other neighborhood types, such as ZEN and PED, are out of the scope of this work.

Therefore, the following categorization is proposed for the solar neighborhoods:

- **Pure (or target-free) solar neighborhoods** (i.e., category 1 in Fig. 2) are communities that prioritize the exploitation of solar energy, with limited energy management systems. Buildings'

Fig. 1. Visualization of the ten areas concerning solar neighborhood planning and design strategies treated in this article.

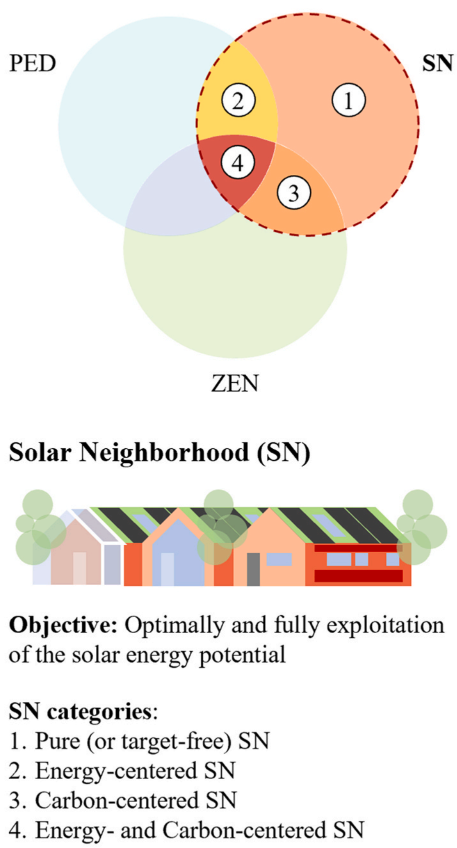


Fig. 2. Interaction between solar neighborhoods and other neighborhood concepts, such as zero-emission neighborhoods and positive energy districts, existing in the literature [23,29,30].

morphology and relations as well as building envelope and technological/material features are designed to maximize the efficiency of passive and active solar strategies. Furthermore, these solar neighborhoods are characterized by a microclimate that enables adequate thermal and visual comfort, and high life standards, both indoors and outdoors.

- **Energy-centered solar neighborhoods** (i.e., category 2 in Fig. 2) implement the use of active solar strategies through advanced energy storage and management systems to enhance energy flexibility, resilience to energy price fluctuations, and independence on energy imports. The low energy demand of these neighborhoods is entirely met by on-site renewable energy mix, in which solar energy plays a major role along with the other RES such as wind and geothermal.
- **Carbon-centered solar neighborhoods** (i.e., category 3 in Fig. 2) prioritize the application of passive solar strategies and the use of low-carbon technologies/materials to improve the energy efficiency of the building stock while reducing its carbon footprint. Additionally, active solar systems are implemented in these neighborhoods to minimize the reliance on fossil fuels and achieve carbon neutrality.
- **Energy- and Carbon-centered solar neighborhoods** (i.e., category 4 in Fig. 2), present characteristics proper of both energy- and carbon-centered solar neighborhoods achieving energy and carbon targets.

Measurable criteria or thresholds for solar neighborhoods are still to be defined and represent a knowledge gap. Nonetheless, several criteria are worth further investigation to differentiate between a solar neighborhood and other neighborhood typologies. For example, the share of energy generated from the solar source, the amount of self-consumed energy from photovoltaics (PVs), and the improvement in visual/thermal comfort achieved through passive solar strategies.

In solar neighborhoods, buildings' morphological forms and relations (i.e., building height - H, distance between buildings or width of the street - W) are firstly optimized by guaranteeing either access to or shading from sunlight, accordingly to the specific needs (e.g., direct access to sunlight is preferable for PV modules, not always for pedestrians [19,31]) and climate context (e.g., right-to-shade can be more relevant than right-to-light in extremely hot climate zones). Besides the neighborhood's layout, the application of passive solar design solutions and the optimal localization and installation of active solar systems integrated (e.g., BIPV) or added (i.e., building added photovoltaics) into urban surfaces (e.g., building envelope, shelters, ad-hoc structures, etc.) are prioritized aspects in solar neighborhood planning. Active and passive solar strategies and technology-oriented solutions implemented at multiple scales, ranging from building to neighborhood and urban development scale, are beneficial for outdoor and indoor thermal and visual comfort, air quality, energy demand, and reduction of GHG in the atmosphere. This approach guarantees future-proof cities, independent of energy imports and fossil fuels [32]. In addition, it pursues long-term solar accessibility for creating a more sustainable, livable, and healthy built environment. In solar neighborhoods, challenges arise around the competing uses of urban surfaces (see section 2.2) and around the implementation of solar strategies in high-density settlements.

Another key aspect in planning solar neighborhoods, particularly in mixed-use districts, is the identification of synergies among the human activities' schedule and the energy management strategies to minimize the energy consumption through 'peak shaving' (i.e., coupling residential and office buildings lead to more homogenous distribution of the energy consumption throughout the day) [33]. Besides this, energy storage technologies (e.g., phase change materials, electric batteries, seasonal thermal energy storage) [34–36], energy distribution (e.g., smart grid, flexibility grid) [37,38], and sector coupling concepts (e.g., power-to-heat, power-to-mobility, power-to-hydrogen) [39,40] represent important solutions to enhance the energy flexibility of solar neighborhoods towards a match between energy delivered and the energy load profiles in terms of place, time, and quantity. However, such energy management characteristics are more peculiar to both energy-centered solar neighborhoods and energy- and carbon-centered solar neighborhoods than pure solar neighborhoods and carbon-centered solar neighborhoods. The latter, on the contrary, are primarily characterized by limited energy management systems.

2.2. Which aspects should be considered in the planning and design process of a solar neighborhood?

Solar neighborhoods are complex built environments to plan and design. Numerous design variables (e.g., urban morphology, installation/integration of PVs, location of passive heating/cooling systems) involving different spatial domains (e.g., indoor, building envelope, and outdoor) require to be addressed simultaneously due to their impact on a wide range of aspects (e.g., energy, economy, environment, society, microclimate, user comfort) and related metrics [41]. The main metrics to consider in solar neighborhood planning and design are presented in Table 2 and grouped into four categories - geometrical, latitudinal, external climatic, and internal climatic - depending on the complexity of the input data, as in Ref. [42]. Table 2 highlights that the metrics are not limited to solar. In fact, several studies on multi-criteria approaches to solar planning [43–46] showed that focusing exclusively on solar-related metrics (e.g., solar potential, daylight accessibility, solar heat gains), often provides a partial view.

In this regard, the competing uses of an urban surface in a solar neighborhood are exemplary. The competing use of surfaces arises when defining the way to exploit the solar energy potential of the available urban surfaces [47]. Indeed, the same surface can have multiple potential usages (e.g., green surface, PV surface, highly reflective surface), and the same strategy can impact different metrics at different scales (e.g., indoor daylighting, solar heat gains, energy generation). For example, solutions to enhance access to daylight also increase solar thermal stress, worsening the users' thermal comfort on hot days if the solar radiation is uncontrolled through solar shading devices. Similarly, installing solar panels on roofs or facades to implement solar energy generation may cause unwilling solar reflections in the built environment and alter the radiative properties of urban surfaces, thus influencing both the visual comfort at the pedestrian level and the microclimate [48,49]. Furthermore, competing uses could arise between solar strategies and other interventions. In this regard, the key urban actors usually opt for solutions that enable the direct and immediate increase of the economic value of buildings and neighborhoods' properties (e.g., new additional volumes/stories, terraces, balconies). However, they neglect that such actions contribute to generating high-density settlements where a large portion of building façades, pedestrian paths, or public spaces may be partially or totally shaded from direct sunlight, compromising the performance of the urban surfaces, single or group of buildings, and the quality of private and public spaces. Therefore, when it comes to solar neighborhood planning and design, there is a need for a holistic approach [5,35,50–52] to address several aspects simultaneously by taking into account the following criteria:

- **Energy criteria**: e.g., energy production, energy demand for heating/cooling, energy demand for lighting, storage capacity, grid capacity;
- **Economy criteria**: e.g., capital expenditures, operating expenditures, payback period of the investments for the implemented solar strategies;

Table 2
Taxonomy of metrics in solar neighborhood planning divided into the four categories identified by Ref. [42].

	Geometrical	Latitudinal	External Climatic	Internal Climatic
Input data	- Urban layout - Site and buildings' orientations - Site layout and form - Urban density	- Urban layout - Site layout and form - Latitude location	- Urban layout - Site layout and form - Latitude location - Local weather	- Urban layout - Site layout and form - Latitude location - Local weather - Buildings' geometry - Materials' properties - Buildings' functions
Metrics	<u>Solar</u> - Sky view factor - Sky exposure factor - Vertical sky component <u>Morphology</u> - Floor-to-area ratio - Volume-to-area ratio - Surface-to-volume ratio - Height-to-width ratio - Window-to-wall ratio - Open space ratio - Floor space index <u>User comfort</u> - Biophilia factor <u>Society</u> - Visual impact	<u>Solar</u> - Area of permanent shadow - Two-hour area - Direct sunlight - Shading mask - Daylight factor <u>Energy</u> - Grid capacity	<u>Solar</u> - Annual sunlight hours - Solar potential <u>Energy</u> - Energy generation - Storage capacity <u>Environment</u> - Biodiversity <u>Climate</u> - Urban heat intensity - Microclimate variations	<u>Solar</u> - Daylight autonomy - Illuminance - Solar heat gains - Spatial distributing glare <u>Energy</u> - Energy use for heating and cooling - Energy use for lighting - Energy self-consumption - Energy coverage - Specific yield <u>Environment</u> - Carbon emissions - Emission balance <u>Economy</u> - Capital expenditures - Operating expenditures - Payback period - Profitability - Net present value <u>User comfort</u> - Thermal comfort - Visual comfort - Air quality <u>Society</u> - Fuel poverty

- **Environmental criteria**: e.g., carbon emissions, emissions balance (i.e., trade-off between compensated/offset emissions and emissions that are directly or indirectly caused by the neighborhood);
- **Social criteria**: e.g., visual impact, accessibility, stakeholder engagement, community participation, affordability, and equity;
- **User comfort criteria**: e.g., air quality, visual and thermal indoor and outdoor comfort.

This list of criteria is not exhaustive and depends on the constructive dialogue between stakeholders (e.g., public authorities, sociologists, social scientists, urban planners, architects, and engineers) and researchers; and how they are able, through a holistic approach, to converge their interests and objectives by prioritizing some aspects against others. For example, a private investor would mainly focus on economic indicators, whereas a municipality would rather find a balance between environmental, social, economic, and energy benefits.

It is crucial to determine the design objectives and to identify potential competing uses of urban surfaces from the early stage of the planning process [47,53]. As proposed by Formolli et al. [41], this leads to include multiple spatial domains (e.g., indoor, building envelope, and outdoor) as well as multiple scales (e.g., building, neighborhood, urban development) in the solar neighborhood design workflow. In fact, design solutions and technologies applied at different spatial domains and/or scales can influence each other, not necessarily in a negative way. For example, indoor daylight accessibility is influenced by the mutual inter-building solar reflections and/or shadowing effects from the surrounding built environment. Similarly, the energy production from a BIPV façade (building scale) is determined by its solar potential (neighborhood scale). Also, the coatings applied to the building envelope contribute to determining both the indoor and outdoor environment, with impacts, among others, on both the microclimate and the building energy demand [54–56]. In the planning and design process of a mixed-use solar neighborhood, activities taking place within the buildings are defined based on solar availability. In this regard, buildings with good exposure to direct sunlight during the morning hours are selected to be schools and offices, while buildings that are well-exposed to sunlight during the afternoon hours are suitable for housing. In that regard, Natanian [33] has developed a two-phase workflow that aims to optimize mixed-use district designs in hot climate zones to reach energy balance and environmental performance. Such workflow allows supporting diverse morphological configurations by optimizing solar accessibility towards zero energy and livable districts.

Therefore, implementing an inter-disciplinary, holistic, and multi-criteria approach, which addresses the different competing uses of urban surfaces and their impacts on the total environment (see section 2.8) by operating at multiple scales and spatial domains, represents the key-approach of the solar neighborhood planning and design. Furthermore, such an approach facilitates replicability and avoids common urban planning mistakes encountered by others in an urban densification process [57] while fostering interaction between researchers and city authorities [58,59] as well as citizens' engagement [60,61].

2.3. Which are the passive and active solar strategies in solar neighborhoods?

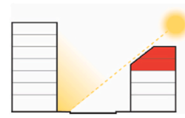
In solar neighborhoods, passive and active solar strategies are implemented at different scales to develop climate-responsive settlements able to face the current and future short-, mid- and long-term climate conditions. At the neighborhood scale, the passive solar strategies leverage the inherent properties of sunlight and the neighborhood's design to improve thermal and visual comfort, while reducing energy consumption for heating, cooling, and lighting [62].

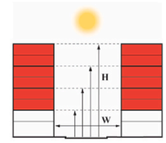
The **passive solar strategies** applied at the **neighborhood scale** contribute to shaping the district morphology and massing (PS1 in Table 3), determining, among the others, buildings height (H), inter-building distance (i.e., width of the street – W), aspects ratio H/W (PS2), and district orientation (PS6). These together with the layout and pattern (PS5) of a solar neighborhood are influenced by the latitude and local climate, and they determine the solar energy potential of the urban surfaces (Table 3).

At the **building scale**, several **passive solar strategies** can be applied (Table 4). Building form, morphological type (e.g., courtyard, high-rise), and thermal mass (PS7 in Table 4) alongside room depth and window-to-wall ratio (PS9) determine the penetration of natural light into the building's interiors. In those cases where the building morphology is particularly constrained (e.g., existing and historical neighborhoods) as well as in high-rise neighborhoods, which constitute the common tendency of the urban growth happening today in cities,

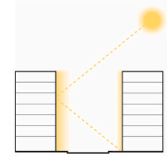
Table 3
Passive solar strategies applied to the planning and design at the neighborhood scale.

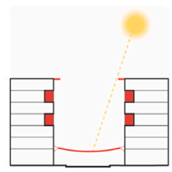
Passive Solar Strategies – Neighborhood scale

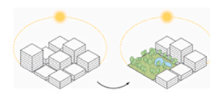

PS1 – Urban morphology and massing



PS2 – Aspect ratio H/W


PS3 – Urban surfaces' reflectivity


PS4 – Urban shading devices


PS5 – Urban layout, and patterns

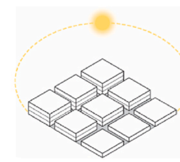
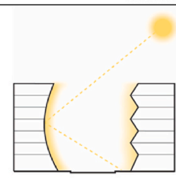
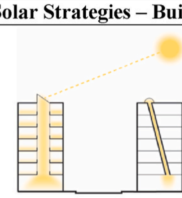
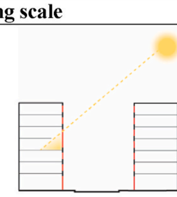

PS6 – Street and district orientation

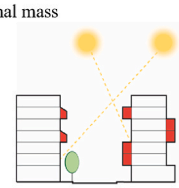
Table 4
Passive solar strategies applied to the planning and design at the building scale.

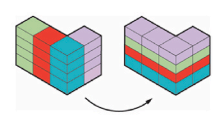
Passive Solar Strategies – Building scale


PS7 – Building form, morphological types, and thermal mass


PS8 – Glazed atriums and light-ducts


PS9 – Room depth and window-to-wall ratio


PS10 – Shading, overhangs, and sunspaces or solar greenhouses


PS11 – Distribution of functions and program

technological solutions such as light chimneys and tubular skylights (PS8) can be implemented for passive daylight control indoors [63].

Among the passive solar strategies applied at the building scale, there are the use of windows and glazed walls (PS9), massive walls (PS7) (e.g., Trombe walls) [64,65], and sunspaces or solar greenhouses (PS10). These can act as direct-gain passive systems while allowing – in the case of windows and glazed surfaces – appropriate levels of daylight to be achieved. Especially sunspaces and solar greenhouses represent valuable solutions in high-density settlements, by enabling the creation of additional covered spaces, although exposed to high levels of solar radiation and a wide temperature range [66].

All these strategies as well as the distribution of functions and program (PS11) require a proper design, that considers the local climate (e.g., air and surface temperature, humidity, air pressure), urban complex phenomena (e.g., inter-building reflections, overshadowing), and urban surfaces' thermal properties, to avoid indoor overheating and outdoor thermal stress [49,67,68]. In solar neighborhoods, municipalities should support the design process by providing house-owners with guidelines and recommendations about surface uses.

Shading systems (PS10) are often coupled to the glazed areas as heat avoidance systems, aiming at protecting from direct solar radiation and reducing cooling energy use and peak loads. These solutions permit enhancing the buildings' energy efficiency and indoor thermal comfort while lowering carbon emissions [69]. Shading devices can also be installed within neighborhoods (PS4 in Table 3) (e.g., projecting roofs, lodges, shade sails) to avoid the thermal stress of pedestrians. This is particularly important in climate change hotspots with an enhanced warming trend like the Mediterranean region [70].

The use of **other passive strategies** includes materials and solutions that interact with solar radiation to control surface temperature and the related impacts on the outdoor and indoor environment (Table 5). This is the case, for example, of conventional cool materials (light-colored and colored cool materials [71]), thermochromic pigments [72], retro-reflective materials [11,73–75], photocatalytic materials [76], phase change materials [77,78], photoluminescent paints [79,80], and supercool materials (i.e., engineered surfaces exploiting Passive Daytime Radiative Cooling [10,81]). These solutions can be used on pavements (PS12 N in Table 5) or building envelopes (PS12B) and are increasingly important in hot arid regions where urban greeneries might struggle. In solar neighborhoods, the most suitable surfaces are identified through simulations by considering complex phenomena that can either limit the materials' effectiveness or cause undesired drawbacks (e.g., glaring, excessive cooling in winter, etc.).

Another relevant element interacting with solar radiation within solar neighborhoods is urban greening. The vegetation can be located both on ground spaces (PS14 N) (e.g., private and public parks, tree-lined streets) and on the building envelope (PS14B) (e.g., green roofs, vertical greening systems, balcony gardens) [82]. Urban greening contributes as a passive technique for energy saving, through (i) evaporative cooling, (ii) thermal insulation, and (iii) shadow provided by the vegetation layer [65]. A green façade/roof can reduce the indoor temperature by absorbing solar radiation, leading to energy savings for cooling in summer conditions. However, these solutions should be designed in such a way that solar heat gains through the building envelope are not hindered in winter to avoid increasing the heating demand [83–85]. Urban greening can also aim at the provision of food within the neighborhood boundaries, as in the case of urban agriculture [86].

Finally, solar radiation influences the cooling capacity of water bodies (PS13), both natural and artificial, and evaporative techniques (e.g., mist spraying, water curtains, watering techniques) [87]. This also applies to evaporative pavements (e.g., permeable, porous, pervious, and water-retaining pavements), designed to be applied on ground surfaces to retain water for evaporative cooling purposes and prevent storm-water runoff [88].

Active solar strategies are implemented **at neighborhood** and **building scale** (Table 6) to exploit solar irradiation to generate either electricity or thermal energy through solar active systems (AS1B and AS1N in Table 6) such as PV, solar thermal (ST), and hybrid photovoltaic/thermal systems (PV/T). Heliostat and sun-tracking reflector systems (AS2) for active daylight control and for concentrating and directing sunlight onto surfaces that would otherwise be shaded are also labeled as active solar strategies, requiring electric power to function. These systems are particularly useful in highly dense built environments [89].

Inter-building areas, pavement and roads, barriers, and urban furniture represent suitable surfaces for solar energy generation at neighborhood scale (AS1N). PV modules can be added to pavements and roads, while asphalt solar collectors are being developed to employ the solar energy absorbed by the pavement for heating/cooling applications (e.g., melting snow on roads [90], building heating, pavement cooling [91,92]). In addition, PV road barriers, PV carports, PV-integrated urban furniture (e.g., street lighting, bus shelters, benches [93]), and solar-powered urban artworks are being tested to exploit the energy generation potential within the urban fabric [92].

Furthermore, active solar strategies include solutions for individual buildings. In fact, solar panels can be exploited in buildings (AS1B) as an additional external layer, or integrated into the envelope as specific architectural systems, like BIPV [94,95] and building-integrated solar thermal systems [96]. On façades, these might be added as a cladding element on opaque surfaces, integrated into curtain wall systems, or integrated into windows [97] and other transparent architectural elements [98,99]. On roofs, PV modules and ST collectors can be added to the outer surface [98] or substitute the entire technological system, while PV-enhanced roof tiles and shingles allow replacing the external layer. Semi-transparent solutions can also be used on roof covering [100]. Among the PV technologies, the deployment of bifacial PV (BPV) and PV-integrated shading devices (PVSD) [101,102] is gaining more and more attention. The former is applied in both built environments and landscapes, especially at high latitudes where the sun geometry represents an advantage for the optimal exploitation of vertical BPV. The latter has a twofold function, combining energy generation with the advantages of a shading device (e.g., protecting from natural light in summer, enabling solar heat gains in winter) [103].

PV/T systems[7] enable energy generation and active heat recovery with liquid (i.e., water-cooled PV/T) or forced air (i.e., air-cooled PV/T),

Table 5
Other passive solar strategies applied to the planning and design at the neighborhood and building scale.

Other Passive Solar Strategies – Neighborhood & Building scale

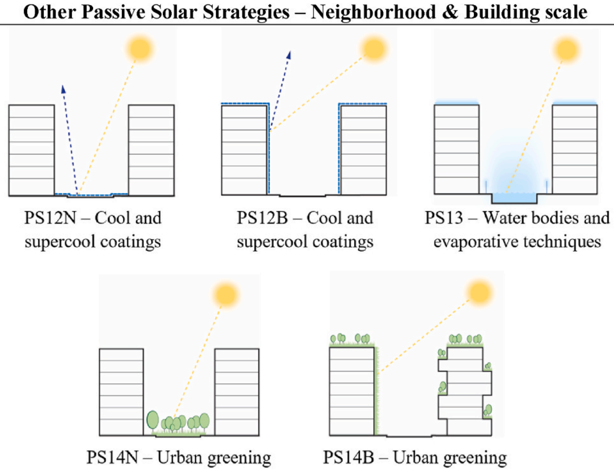
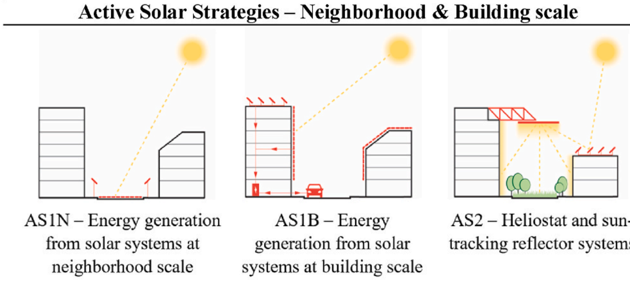


Table 6
Active solar strategies applied to the planning and design at the neighborhood and building scale.

Active Solar Strategies – Neighborhood & Building scale



[7] task60.iea-shc.org (accessed in 28.03.2023).

in either a closed or open loop respectively [104]. These systems are particularly suitable for applications with limited roof space (i.e., high-rise buildings), as their energy production per unit surface area is higher than that of side-by-side PV and ST, and the manufacturing and installation costs are lower [105]. In solar neighborhoods, the share of PV, ST, and PV/T is determined at the neighborhood level depending on grid capacity and the exploited heating fuel, among the others.

When it comes to densified urban areas, solutions that **integrate active and passive solar strategies** on the same surface should be prioritized. In this regard, solar panels and greening - often in

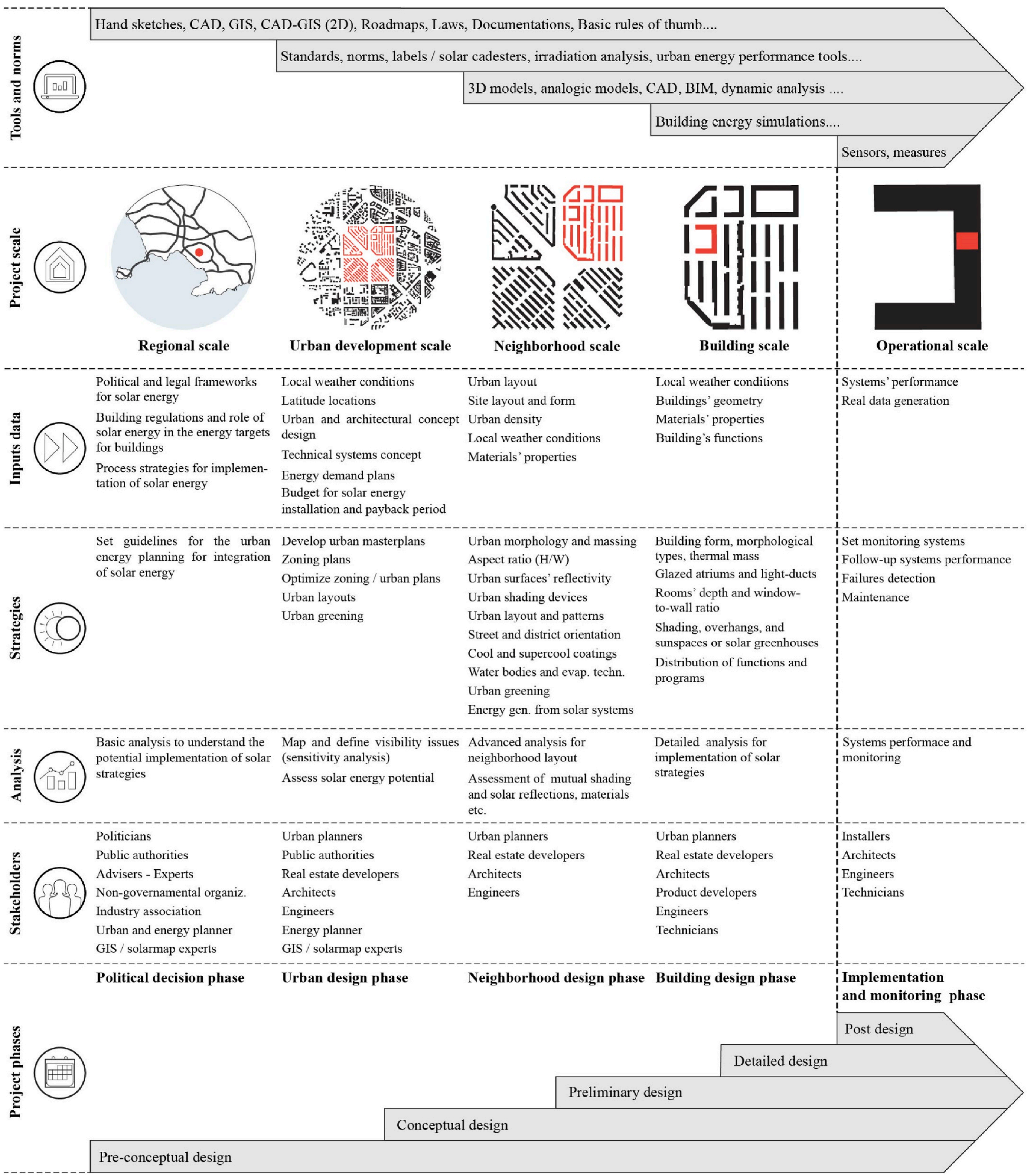


Fig. 3. Project scales and phases of the planning and design process for solar neighborhoods. Solar planning and design strategies applied at different spatial scales. Description of the tools and norms used in the different project stages. Modified from Refs. [115,116].

competition - can work in synergy, as in the case of bio-solar or multi-functional solar-green roofs [106,107] and façade [108]. These solutions can, on one side, provide potential habitats for certain plant and insect species and increase plant diversity, and, on the other side, increase the efficiency and useful lifetime of solar panels thanks to the localized reduction of air temperature caused by vegetation [109,110]. Several other solutions are also being developed: vertically mounted BPV can be combined either with green roofs [111] or highly reflective materials [112], while solar panels are being coupled to vertical farming through the novel concept of productive façades [113].

2.4. How are the passive and active solar strategies applied in solar neighborhoods?

The optimal implementation of passive and active solar strategies is fundamental in solar neighborhoods. This process requires considering all spatial scales, ranging from urban regional and urban development scale, down to neighborhood and building scale, and their interdependency (Fig. 3). For example, the optimized solar accessibility of buildings' facades and the indoor daylighting distribution (i.e., building scale) can be achieved only if the site plan allows natural light penetration into the urban canyon (i.e., neighborhood scale). The implementation of solar strategies determines, among others, (i) the urban layout and morphology at the urban development scale, (ii) the buildings' block configuration, orientation, volume, and form at the neighborhood scale, (iii) the facade exposure, the room depth, and the window-to-wall ratio at the building scale. Consequently, there is a wide range of factors to be considered during the planning process (see section 2.2). This sets solar energy planning apart from conventional urban planning, which typically begins with assessing the spatial characteristics of an area and later addresses energy-related issues. Given the complexity of this process, it necessitates the integration of various technical and non-technical perspectives, particularly considering the lengthy timeline associated with the planning process [58,114].

Five case studies, virtuous applications of planning and design strategies for solar neighborhoods in different climates and locations, are briefly presented and described (Table 7).

One Central Park, in Sydney, Australia (Lat. 33.9° S), is a dual high-rise mixed-use development (5.6 ha). In 2006, the New South Wales Planning Minister called the site under state control with a revised masterplan approved in 2007. The precinct aimed to provide appropriate street and block connectivity whilst achieving good solar access in a highly densified urban landscape (PS6) that also promotes sustainable living and public community spaces. It is an exemplary case study of daylight enhancement at a large scale using an active solar strategy. 40 dual-axis tracking heliostats (each 6.5 m^2) mounted on the East Tower redirect the light (AS2) to the underside of a cantilevered reflector frame composed of 320 fixed mirrors (each 1.25 m^2) mounted on the West Tower. Approximately 800 W/m^2 are delivered under clear sky conditions to the underling atrium commercial space, lap pool, and park (PS5, PS14 N), which would otherwise be in the shade. Over 30,000 m^2 of the site has green plantings (PS14B), with also a large vertical living façade. This encompasses 5 km of linear planter boxes accommodating over 85,000 plants with over 250 different species. The façade itself reduces the heat load of the buildings by 15–20%. The urban renew project objective was to deliver approximately 2200 apartments and 925 student dwellings, accommodating around 5300 residents. Additionally, some 25,000 m^2 of premium commercial office space and 20,000 m^2 of retail space caters for 1750 people to also work within the Central Park precinct.

West5 is a mixed-use community in London, Canada (Lat. 43.0° N). At the beginning of the project, the province of Ontario had in place the 'Green Energy Act' (repealed in 2019) that regulated building energy efficiency and RES generation. The local government supported the realization of the project through incentives related to energy efficiency, green buildings, electric vehicles (EV), on-site renewables, and cool roofs (PS12B). Also, at the federal level, energy-efficient building and community incentives were applied to the development of this net-zero energy mixed-use high-rise settlement. Initially, a feasibility study was carried out to demonstrate the impact of various solar technologies and energy efficiency measures in a new urban development area (PS5). This feasibility study and the related measures were adopted later in the actual project. Besides building envelopes (AS1B), PV systems are integrated into several urban elements such as parking lots and shelters (AS1N). The size of the PV plant in West5 is 1.7 MW_p, with an annual yield of 900 kWh/kW_p (in 2021). Even without considering the carbon offset from rooftop PV, the project compensates approximately 200 $tCO_{2\text{-eq}}$ per year. Passive heating is guaranteed through optimal orientation of the whole neighborhood (PS6) and buildings (PS7), position of windows (PS9), and thermal massing (PS7). Buildings within this solar neighborhood are characterized by energy use intensity ranging from 91 kWh/m^2 for residential buildings to 92 kWh/m^2 for health and institutional buildings, and 124 kWh/m^2 for office buildings.

Norwegian University of Science and Technology (NTNU) Gløshaugen is a university campus in Trondheim, Norway (Lat. 63.4° N). In 2015, the Norwegian Government initiated a large redevelopment process for the site with the vision of establishing a ZEN through the refurbishment of the existing building stocks, the realization of new up-to-standard and plus energy buildings, and the extensive implementation of passive and active strategies in the whole precinct. The recently constructed and under-development buildings posed attention to the surrounding urban layout and patterns (PS5), and their shapes and volume distribution (PS7) are modified throughout the design process to preserve existing recreational and historical heritage areas. Glass-covered connections between buildings create luminous informal meeting spaces and enhance visual comfort, while the use of glazed atriums acts as light wells for offices and classrooms overlooking them (PS8). About the active solar strategies, the largest installation is found in the ZEB Laboratory: a total of 963 m^2 BIPV (184 kW_p) are installed on the tilted roof, facades, and solar pergola (AS1B). Other active solar installations include (i) a system of 62 PV panels (20 kW_p) with 11 different angles and azimuth orientations installed on a rooftop, (ii) a 12.5 kW_p system integrated into the ZEB Living Laboratory, (iii) and PV, ST, and PV/T panels added on the roof of the ZEB Test Cell. The PV power and energy production of the campus is 4956 kW_p and 3477 MWh/yr, respectively.

Violino district is a residential social-housing neighborhood in Brescia, Italy (Lat. 45.5° N), designed according to bioclimatic principles. The municipality was heavily involved in the planning process by purchasing the land and setting energy and sustainability targets in the call for tenders. Architects, installers, and consultants collaborated in the urban and neighborhood design phases, providing solutions to meet the targets. The terraced house typology, the main building typology in the neighborhood (112 units), was adapted to the street layout by a partial rotation of the buildings' masses (PS1) to ensure solar accessibility. Two five-story multi-family houses are positioned on the north side of the settlement to avoid overshadowing (PS5). The distribution of volumes and functions at the building level (PS7, PS11) was also designed considering right-to-light principles, with the most used spaces (i.e., living room, kitchen, and bedrooms) placed on the south and west sides of the habitation units. Moreover, most of the terraced houses feature south-facing solar greenhouses (PS10), internally painted in dark-hues to maximize solar heat gains. Regarding active solar strategies, each terraced house is equipped with a 1.3 kW_p PV system, while the two multi-family houses have 5 to 20 kW_p PV systems (AS1B). PV modules' orientation is either horizontal or tilted 30° southwest. The project was also subjected to two monitoring campaigns in its post-design phase to (i) evaluate the performance of the PV systems and (ii) test smart energy management systems to minimize electricity costs.

The **Science and Technology Park Adlershof**, is a mixed-use development area located in Berlin, Germany (Lat. 52.4° N), encompassing offices, a university campus, research institutes, industries,

Table 7
Summary of the case studies with the main active and passive solar strategies applied.

Case study		Which?	How?	Who?	When?
One Central Park		Passive strategies PS5; PS6; PS14 N; PS14B. Active strategies AS2 Type of SN Pure SN (new)	The light from tracking heliostats and fixed mirrors is redirected into indoor and outdoor space. Application of solar design, the use of irrigated green façades, and Low-E glazing to limit energy demand and promote indoor climatic.	Urban planners Real estate developers Architects Engineers	Urban design phase Neighborhood design phase
West5		Passive strategies PS1; PS5; PS6; PS7; PS9, PS12B Active strategies AS1N; AS1B Type of SN Energy- and Carbon-centered SN (new)	Use of extensive green areas, solar passive heating through optimally oriented windows and thermal massing. Solar streetlights, solar parkades, and PV panels on different surfaces are monitored to evaluate the buildings' operation. Daylighting control systems to reduce the need for artificial lighting and overheating.	Land owner Urban planners Architects Researchers Installers Product producers	Urban design phase Neighborhood design phase Implementation-Monitoring phase
NTNU Gløshaugen		Passive strategies PS5; PS7; PS8 Active strategies AS1B Type of SN Carbon-centered SN (existing)	Glass-covered connections and large glazed courtyards to bring natural daylight to offices and classrooms. PV and BIPV of roofs and facades of several buildings.	Government Contractors User groups Academic cluster user groups	Political decision phase Neighborhood design phase
Violino district		Passive strategies PS1; PS5; PS7; PS10; PS11 Active strategies AS1B Type of SN Pure SN (new)	Competition initiated by the Municipality for realizing a social housing project through a holistic sustainable approach. Request for quantifiable requirements to assess the project's quality and sustainability.	Municipality Urban and energy planners Architects Engineers	Political decision phase Neighborhood design phase Implementation-Monitoring phase
Park Adlershof		Passive strategies PS7; P10; PS14B Active strategies AS1B Type of SN Pure SN (existing)	Defined as an urban development area since 1994. The master plan is adapted to the functional diverse needs and mixed functions.	Municipalities Urban decision-makers Architects Operators of Technology Parks	Political decision phase Neighborhood design phase Implementation-Monitoring phase

residential and commercial buildings, and green areas. The City of Berlin has the goal to be climate neutral by 2050. In this framework, the Park Adlershof was subjected to a 35-year planning process aiming to reduce energy demand to 30% by 2020. The first PV system in Adlershof was a façade integrated semi-transparent system, installed in 1998. Nowadays, many examples of active solar systems are present in the area. Among them, a research center characterized by a slight curve façade (PS7) entirely covered by PV panels (AS1B), and the headquarter of a PV manufacturer, whose façade is equipped with a demonstrative 210 kW_p system of PVSD (PS10). In Park Adlershof, green roofs are obligatory to retain storm water and to minimize the UHI effect (PS14B). Nonetheless, PV systems are accepted as an alternative measure, resulting in an installed PV power of more than 2 MW_p. Finally, energy flexibility was another focus of the project. Buildings are connected to the district heating network and the local grid is planned to support additional ST energy production in the future.

The case studies presented above illustrate the possibilities offered by solar neighborhood planning and design strategies that bring together daylight provision and on-site energy generation. The implementation of passive and active solar solutions in these case studies highlights the importance of performing ad-hoc analyses (e.g., solar potential, daylighting, energy) that consider different scales and their inter-dependency, throughout the urban planning process. Also, routines built into the planning process are demonstrated to determine the successful development of solar strategies. However, due to the involvement of many different stakeholders with different competences, priorities and interests, the overall duration and targets of the planning process may vary considerably. It is therefore important to involve all the relevant urban actors from the early stages of the design process to embed innovative concepts and technologies from research into real applications.

2.5. What are the challenges of implementing passive solar strategies into solar neighborhoods?

Integrating passive solar strategies into solar neighborhoods presents various challenges at both building and neighborhood scales, concerning the design aspects and regulatory compliance requirements. These challenges range from the building components and materials to the building typologies, and from neighborhood layout to urban development planning (Table 8).

Table 8
Summary of the challenges to adopt passive solar strategies in solar neighborhoods.

Critical aspects	Challenges
Social	• Balancing building uses with passive strategies that are optimal for those uses, evaluate the tradeoffs between conflicting uses of solar gain and between scales. • Increase user acceptance and impact of passive solar strategies in highly sensitive/constrained urban areas.
Layout	• Guarantee daylight and visual comfort in narrow street canyons and dense areas. • Mitigate UHI effects and inter-building reflections. • Design effective technological solutions in relation to building shape, orientation, and interior layout. • Apply building form and massing which guarantee right-to-light or right-to-shade according to the building uses.
Material	• Improve indoor/outdoor thermal comfort. • Adoption of new materials to improve daylight and visual comfort.
Modeling	• Develop form-finding optimization workflows for solar neighborhoods. • Reduce computational time for solar energy-related simulations. • Include the model of natural elements (e.g., trees, vegetation). • Develop digital clones of non-conventional materials and technologies.

Social. Human activity and user interaction within the neighborhood determine the potential for the implementation of passive solar strategies. The main challenge consists of balancing building uses with passive strategies that are optimal for those uses, evaluating the tradeoffs between conflicting uses of solar gain (e.g., self-shading to avoid glare phenomena vs. solar exposure to avoid poor visibility and visual discomfort) and between scales (solar passive strategies vary depending on the scale, encompassing buildings, neighborhoods, and urban developments), considering a possible presence of active systems (e.g., large windows might be easily preferred to passively cooling surfaces treated with highly reflective materials, if an efficient district cooling system is present). Additional challenges concern increasing user acceptance of passive strategies to enhance visual (e.g., photoluminescent treatments, light chimneys) and thermal comfort (e.g., greeneries, supercool materials, greenhouses) in neighborhoods with high constrains (e.g., geometric, climatic, legal, economic, historical) that prohibit, or significantly limit, interventions in size, location, and design [117–119].

Layout. At the neighborhood level, narrow streets and high-density development can generate unsought inter-building effects (e.g., mutual and complex shading, multiple solar inter-building reflections) with an impact on solar accessibility within the neighborhood environment [120]. The main challenges associated with the neighborhood configuration concern (i) the optimal exploitation of solar accessibility to enhance visual comfort in narrow urban canyons and in densely built areas, and (ii) the mitigation of UHI effects and solar inter-building reflections to guarantee adequate indoor and outdoor thermal comfort. At the building level, shape, orientation, and interior layout influence the implementation of passive solar technologies. In that regard, the main challenge is the optimal design of building form and massing which guarantee right-to-light or right-to-shade according to the building uses, enabling to regulate the penetration of natural light through light shelves and shading systems, as well as controlling the indoor environment through solar chimneys and double-skin façades [121,122].

Materials. Retro-reflective, supercool, and photoluminescent materials are proposed in solar neighborhoods to address these main challenges: (i) decreasing the temperature of the urban surfaces (i.e., reducing UHI effects); (ii) improving users' outdoor thermal comfort in summer; (iii) increasing the impact on passive heating in winter and cooling in summer; and (iv) guaranteeing visual comfort and energy saving for artificial lighting. However, these materials present some drawbacks such as glare to neighboring buildings, reduced solar gains in winter, and aging issues [123–125]. Although building finishes and claddings are usually covered at the building level, the multi-scale approach applied to the design of solar neighborhoods aims at defining materials applied to urban surfaces, avoiding the drawbacks mentioned above as well as the occurrence of shading phenomena that can reduce their efficiency.

Modeling. Estimating the impact of passive solar strategies is fundamental for decision-making within the solar neighborhood planning process. The main challenge regards the implementation of a form-finding optimization workflow for solar neighborhoods capable of (i) modeling natural elements (e.g., trees and vegetation) (ii) integrating multiple spatial scales (i.e., component, building, neighborhood, and city), and urban domains (i.e., outdoor, envelope, indoor) with (iii) low computational time. Alongside this, there is a need to (iv) develop digital clones of materials and technologies such as coatings with angular-dependent properties, radiative coolers, electro-chromic windows, and photoluminescent pigments, which behave and perform differently from conventional materials.

2.6. What are the challenges of implementing active solar strategies into solar neighborhoods?

The challenges of increasing solar energy production in the solar

Table 9
Summary of the challenges to adopt active solar strategies in solar neighborhoods.

Critical aspects	Challenges
Location	• Balance the competing uses of surfaces by implementing multi-functional solutions.
Urban planning	• Couple solar access and urban planning with respect to the type of interventions. • Electrification of heating and cooling systems, often linked to solar energy generation, but particularly constrained in high-density neighborhoods.
Modeling	• Develop simple approaches to process inter-building reflections. • Make data available from the early-design stages of the project. • Develop key performance indicators (KPIs) to effectively visualize and communicate results. • Develop urban canopy models to assess the impact of BIPV on the urban microclimate.
Architectural integration	• Achieve high quality of integration through colored panels, layout, and sustainable materials. • Adapting urban regulations for heritage protected areas.
Energy management	• Implement peak shaving strategies (e.g., batteries, smart devices). • Increase self-consumption of energy produced on-site.
Social acceptance	• Increase end-user acceptance of active solar strategies through a structured legislative agenda.
Economy	• Reduce the cost of investment for certain complex solar installations.

neighborhoods can be grouped around the following seven aspects (Table 9).

Location. In buildings, active solar systems are usually preferred to opaque parts of the roofs and façades, particularly when these show a high solar energy potential. However, such surfaces are often also suitable for the implementation of passive solar strategies (e.g., green surfaces, windows, etc.). Similarly, in outdoor areas, the competing uses of the inter-building surfaces result in the exploitation of available parts of the areas for other purposes than solar energy production (e.g., mobility and transportation, pedestrian paths, parks, and squares). The major challenge related to the location of active solar systems concerns the development of multi-functional solutions, combining the capability to produce energy with other purposes, which permits to extend the applicability of such systems to other infrastructures (e.g., solar anti-noise barriers) or uses (e.g., hybrid solar green roofs, active solar windows, etc.).

Urban planning. On-site renewable energy production is becoming more frequently addressed in legal frameworks and building codes, and installing PV can be considered a standard practice. Nonetheless, developers are still reluctant to integrate PV into building envelopes due to the higher costs compared to traditional claddings as well as the challenges concerning architectural integration and fire safety. BIPV on the roof and façade present constraints like the conditions of the elements and their ability to support the weight of solar panels, the clutter of the roof, and the economic profitability [5]. Integration of PV into urban surfaces requires coupling the solar access analysis to urban planning, differentiating between new developments and retrofitting interventions. Challenges arise about self-shading within the district, as well as the absence of solar potential data to detect suitable areas for solar panels. In this regard, multi-layer cadasters (combining information layers about solar potential, shadow casting, heritage, open spaces to be covered, etc.) can play a key role in a holistic approach to designing solar neighborhoods and support the decision process to prioritize investments. Another challenge is the electrification of heating and cooling systems, often linked to solar energy generation, but particularly constrained in high-density neighborhoods. Indeed, such urban environments provide limited ground space for geothermal heat pumps or roof space on high buildings for air-source heat pumps, which compete with the surface areas required for solar panels. This necessitates planning global energy supply strategies that centralize energy production at the neighborhood scale, such as district thermal networks based on centralized geothermal heat pumps and solar energy [126].

Modeling. Several municipalities and public authorities have supported the development of solar cadasters of buildings' roofs as support instruments to inform owners of areas with solar potential, through various key performance indicators that allow to identify urban areas suitable for installing solar systems early in the planning process. Processing shadow casting and solar potential at the neighborhood scale based on Light Detection and Ranging (LiDAR) data is rather straightforward [127,128], but estimating the building's potential for solar energy production is much more complex, particularly when considering vertical façades and inter-building reflections [129]. The main challenges related to solar energy production concern (i) the development of simplified and reliable modeling approaches to process solar inter-building reflections at neighborhood scale, (ii) data availability for decision-making generally limited in the beginning of the urban planning process, (iii) key performance indicators (KPIs) to visualize and communicate results in more user-friendly ways, and (iv) the development of an urban canopy model to assess the impact of BIPV on both the local climate and microclimate [130].

Architectural integration. Increasing the solar energy production and the density of active solar systems while maintaining the visual aesthetics of the neighborhood is challenging and requires a particular effort on architectural integration. The next generation of active solar systems is expected to overcome this issue by (i) developing solar panel solutions that are more visually integrated (e.g., colored panels, solar tiles) [131,132], while (ii) selecting sustainable materials to reduce their carbon footprint [133] and (iii) defining guidelines concerning the layout of solar modules when integrated on roofs and façades (e.g., multiple and isolated solar patches, unique and continuous area with solar panels). Furthermore, achieving the architectural integration of PV or ST systems and their visual harmonization with the urban surface poses a further challenge regarding (iv) urban regulations, particularly in historical zones where the use of active solar systems is often forbidden or subject to very strict regulations.

Energy management. There is a general agreement among national and local governments to boost solar energy production through distributed solar energy systems in urban areas. However, the peak demand on the grid is rarely solved by solar energy, and a massive infusion of energy into the grid without a significant demand for it may result in local low-voltage grid collapse. The main challenge related to energy management concerns the implementation of peak-shaving measures such as energy storage systems and sector coupling concepts (e.g., power-to-X concepts) [134], smart devices that work when the sun is shining, and the promotion of self-consumption strategies towards a better autonomy from the grid [135,136].

Social acceptance. The aspects presented above raised the issues of managing many conflicts of interest of the competing uses of urban surfaces, dealing with the complexity of initiating solar design projects, and achieving autonomy from the grid. Therefore, social acceptance of solar projects by end-users is the major issue to trigger solar projects. Simplification of legal frameworks and authorization procedures for installation, information, and communication are important drivers to boost the solar market in this regard.

Economic issues. Active solar installations can often be expensive, which may discourage property owners from investing in them, and make the cost of renting or selling buildings prohibitive. However, solar installations are typically subsidized by national or local governments (see section 2.9). For example, in Switzerland, the Federal Government provides non-recurrent remuneration that covers up to 30% of the investment costs for reference systems. This remuneration is higher for integrated solar systems, as well as for vertical installations on facades. Furthermore, given the context of rising electricity prices in Europe, the self-consumption of solar energy helps to reduce electricity bills and expedite the return on investment.

2.7. How can the digitalization of the built environment support the planning of solar neighborhoods?

The effective design of solar neighborhoods within the heterogeneous and complex dynamics of the urban system poses several challenges related to the physical characterization of the urban environment. This involves various complex phenomena (e.g., dynamic overshadowing, inter-building reflections, alteration of microclimate conditions), as well as technical aspects primarily associated with the complexity of numerical simulation models, which may require significant computational time depending on the scale and the desired level of detail [137].

In this regard, the process of digitalizing the built environment is imperative and it involves a series of actions aimed at acquiring, modeling, simulating, monitoring, and analyzing urban data through digital tools [138]. This data encompasses, among others, information about geometry, technical features of urban surfaces, construction standards, microclimate, energy grid, usage schedules, electricity infrastructure, or socio-economic aspects. Utilizing digital workflows is crucial to facilitate decision-making across the production of various KPIs (see section 2.2). Such KPIs extend beyond building energy efficiency and solar power generation potential, encompassing aspects like daylight access, biophilia and biodiversity, visual impact, outdoor thermal comfort, and social and economic factors [46]. Moreover, given the urge to implement solar energy strategies, digital built environments are necessary to test, deploy, and implement solutions at a wide scale. An overview of existing workflows and tools for solar neighborhood planning, as well as the KPIs commonly used by researchers, urban planners, and stakeholders to communicate the technical outcomes and data in a user-friendly way to both public authorities and citizens is presented in Ref. [30].

An illustration of a digital workflow for the estimation of the rooftop solar irradiance of the Greater Geneva region is depicted in Fig. 4. The solar cadaster is made accessible through two channels: (i) a comprehensive database containing detailed information on roofs and buildings, available for download from the geoportal of the State of Geneva, and (ii) a web application that presents essential indicators to the public (see Social impacts in section 2.8). The current version of the solar cadaster exclusively offers data on solar potential for roofs and other surfaces like existing or potential carports. Consequently, it primarily focuses on facilitating active solar energy strategies by identifying the best-irradiated surfaces for solar panel installations (see challenges identified in section 2.6). Besides that, it encompasses irradiation and shading raster maps for the entire regional territory, available at various time scales (e.g., hourly, daily, monthly, yearly), which can support passive solar strategies (see challenges identified in section 2.5). The simulation engine has been designed to also analyze solar radiation on facades, with a specific emphasis on solar reflection in urban canyons at a large scale, as initially introduced in Ref. [129]. Consequently, the solar cadaster is slated for a forthcoming update that will include the facade component, providing a more comprehensive analysis of solar potential in the region.

A digital built environment aims to provide a holistic environment. Nevertheless, there are different levels of complexity and accuracy. These levels of detail are similar to the classification of the KPIs described in section 2.2 and, as they increased in complexity, they allow the computation of more and more complex and/or diverse indicators.

Handling and modeling geometry. One fundamental application of digital technologies in solar neighborhood design involves creating a digital geometrical representation of the built environment. This can be achieved using established approaches such as computer-aided design (CAD), Building Information Modeling (BIM), and Geographic Information System (GIS). The difference between these approaches lies in the scale and level of detail (LoD) required, which significantly impacts the quality of simulation outputs [139]. CAD is commonly used for detailed modeling of individual buildings or small groups with a high

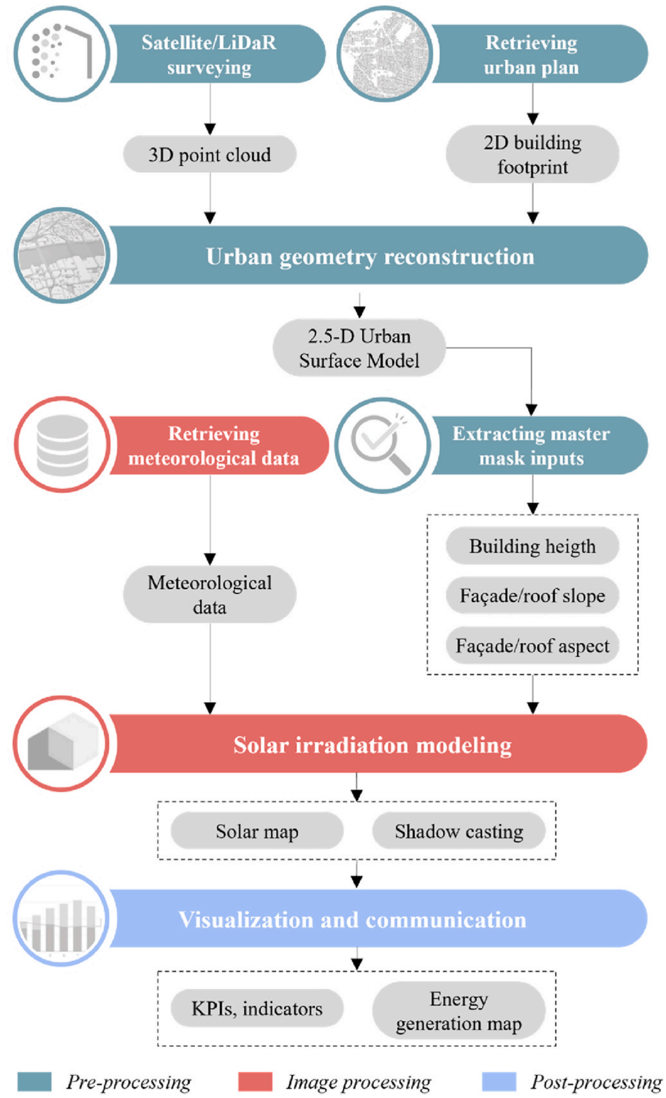


Fig. 4. Example of the digital environment of the whole process of solar modeling on roofs and facades for the solar cadaster on the scale of Greater Geneva (about 2000 km^2). Modified from Ref. [127].

level of detail (LoD 3), including features like window placements and façade details. BIM encompasses and extends CAD capabilities by managing digital representations of physical and functional characteristics, fostering collaboration and interoperability among stakeholders [140,141]. For city-level representations, GIS-based tools are utilized but may necessitate lower detail due to computational constraints [142]. As the extent of the model increases, a decrease in detail is necessary. Nevertheless, more and more detailed models are handled through GIS tools, thanks to improvements in data handling as well as the increasing quality of available data (e.g., detailed LiDAR or photogrammetry data). Many cities already have such LoD models available for existing buildings, but the level of detail can vary significantly from simple 2D footprints to high-fidelity and textured three-dimensional models [143]. Hybrid models combining GIS/LiDAR with CAD allow comprehensive urban environment representation. This first step allows for the calculation of the morphological indicators as presented in section 2.2.

Weather conditions and Solar Radiation. Another key element when dealing with the modeling of the physics of solar neighborhoods is the weather data, allowing the simulation of specific meteorological conditions. A weather data file is a dataset linked to a spatial localization, that provides climatic data with a specific time step (from minutes to hours), usually for a whole year. These data could either correspond to past recordings or to 'Typical Meteorological Years' (i.e., a 'statistical' year that is representative of the weather observed in the previous decade or more). Such data can be obtained through weather agencies or databases such as the EpwMap from the Ladybug Tools,[8] the National Solar Radiation Database from the National Renewable Energy Laboratory,[9] and the Meteonorm[10] software. Recently, a certain number of future climate models have also been developed to modify weather datasets to account for climate changes [144,145]. This weather data and the geometry are necessary to calculate solar radiation received on roofs and façades as well as all sorts of solar metrics (see section 2.2). One of the main challenges remains here the modeling of the façades and the related solar radiation exchanges. Indeed, unlike roofs, existing façades are more difficult to cartography from aerial imagery and more complex in terms of texture (e.g., presence of windows, balconies, superstructure elements, etc.) and physics (inter-reflections with surrounding buildings, specular reflections from the windows).

Energy usage modeling. While there are differences in models and approaches for simulating solar radiation, current tools handle these calculations well, when the geometry is sufficiently detailed and reasonable in size. On the contrary, modeling the usage of solar energy (both active and passive) in solar neighborhoods is more complex. A similar holistic digital workflow should account for both energy consumption and usage of each building while assessing the energy self-consumption potential [146]. This requires detailed knowledge of the thermal properties of building components and involves the use of Urban Building Energy Modeling (UBEM), a physics-based approach that enables simulating thermal performances, space conditioning loads, and energy usage of multiple buildings at the urban scale [147]. Non-geometric building properties such as construction characteristics, age, and heating, ventilation, and air conditioning systems are essential inputs for UBEM. The choice of UBEM type depends on the level of detail and scale, with some using physics-based simulation engines and others relying on reduced-order models. Most UBEM tools integrate GIS-based datasets or use CityGML-based virtual city models [148].

Urban Microclimate. In urban areas, the microclimate strongly influences building energy use [149,150] and solar systems' performances [151,152]. A solar neighborhood is rarely an isolated entity, and it should account for the energy exchanges with the surrounding areas and the energy infrastructures already in place (e.g., district heating plant, energy storage systems) which may drastically redefine the design and planning strategies to be implemented. When considering relatively small and/or new neighborhoods, electric and thermal needs, as well as outdoor and indoor thermal conditions can be easily modeled since the building geometry and thermal properties of each component are known. For example, microclimate conditions and users' thermal comfort can be evaluated through computational fluid dynamics models that are able to assess the impact of wind and thermal stratification (e.g., ENVI–met, Solene-Microclimat). However, when considering large and/or existing urban areas, it is more difficult to reliably represent the neighborhood microclimate due to the scarcity of information about the thermal properties of the buildings' components and the need to apply some simplification to reduce the computational time. To that aim, parametric microclimate models are preferred, such as the Urban Weather Generator (UWG) [149,153,154], which modifies rural weather station temperature data based on the geometrical and thermal characteristics of the neighborhood.

In conclusion, the digitalization of the built environment is a complex operation that allows many actors to acquire useful data, carry out performance predictions with various time horizons, analyze and compare different strategies and solutions in the early urban design phase, and assess the impact of other factors such as climate change on the urban environment. The choice of digital tools and workflows is highly dependent on the required level of detail and scale. Digitalization is also key for the visualization of relevant solar data which, together with understandable KPIs and a user-friendly interface, can facilitate the stakeholders' involvement in the design process, promote the social acceptability of solar applications, and support municipalities in the development of roadmaps for solar energy implementation (see section 2.8). However, despite the numerous tools available nowadays, many of them still fall short of interoperability. Solar design workflows mostly consist of a model chain (i.e., a chain of tools) and only a few of them provide the sufficient level of integration that is sought by building and urban design practitioners. The availability of data is another common barrier in the digitalization of the built environment. In fact, municipalities rarely have the time and infrastructure resources (e.g., sensors, data acquisition systems) needed for data acquisition and digitalization activities. Therefore, private parties usually perform such tasks providing limited access to the data.

2.8. *How can the planning strategies and design solutions for solar neighborhoods impact on the 'total environment'?*

The 'total environment' benefits from the creation of solar neighborhoods through a global enhancement of the life quality of its inhabitants, thus boosting the social acceptability of solar energy. As discussed in section 2.2, the active and passive solar strategies affect metrics concerning various disciplines besides solar, such as local climate and microclimate, users' comfort, energy, and carbon emissions. In this answer, the multiple impacts of solar neighborhoods are quantified and presented in three main groups: (i) environmental, (ii) economy and energy, and (iii) social impacts (Fig. 5).

Environmental impact. When it comes to the impacts of solar neighborhoods on microclimate and emissions released in the atmosphere, low-carbon materials (e.g., local timber constructive elements, recycled materials) and solutions that reduce the exploitation of fossil fuel (e.g., transportation of raw materials through EV) can be applied to directly decrease the GHG emissions. One example is the ZEB Laboratory in the NTNU Gløshaugen campus case study (see section 2.4), where bio-diesel trucks were specifically selected to transport the timber structure elements. Besides these solutions, the envelope of the ZEB Laboratory is covered by around 960 m^2 of BIPVs (184 kW_p) to achieve the zero-emission target. The whole BIPV system has compensated for more than 38,000 $kgCO_{2\text{-eq}}$ since it was opened in 2020, and around 15,000 $kgCO_{2\text{-eq}}$ throughout 2022. Indeed, counterbalancing GHG emissions by implementing active solar systems (e.g., photovoltaic panels, solar thermal panels, hybrid panels a common practice [155,156], although the compensation potential varies in space and time depending on the composition of the national electricity mix [157]. Moreover, urban greeneries (e.g., green roofs and façades, parks, streets trees) can be exploited to sequester carbon dioxide such as in the One Central Park case study in Sydney, Australia (see section 2.4). A square meter of green roof or façade can absorb from 0.143 to 2.070 $kgCO_{2\text{-eq}}$ per year through its bioactivity [158], while an adult plant can absorb between 10 $kgCO_{2\text{-eq}}$ per year and 50 $kgCO_{2\text{-eq}}$ per year [159].

Treating urban surfaces with cool (e.g., retro-reflective materials, highly reflective materials) and supercool materials (e.g., radiative cool materials) creates a favorable microclimate in the built environment that reduces both the concentration of pollutants and the urban overheating [160]. In this regard, the replacement of conventional pavements with reflective and evaporative surfaces in Ref. [161] resulted in a reduction of the ground surface temperatures up to 14.0 °C and a consequent decrease of the air temperature at pedestrian level between 0.6 and 1.2 °C, during summer.

Permeable surfaces, water bodies, and vegetation can similarly contribute to mitigating UHI effects, with a positive impact on biodiversity. In the West5 case study from Canada (see section 2.4), the

[8] ladybug.tools/epwmap (accessed in 20.03.2023).
[9] nsrdb.nrel.gov/data-viewer (accessed in 20.03.2023).
[10] meteonorm.com (accessed in 20.03.2023).

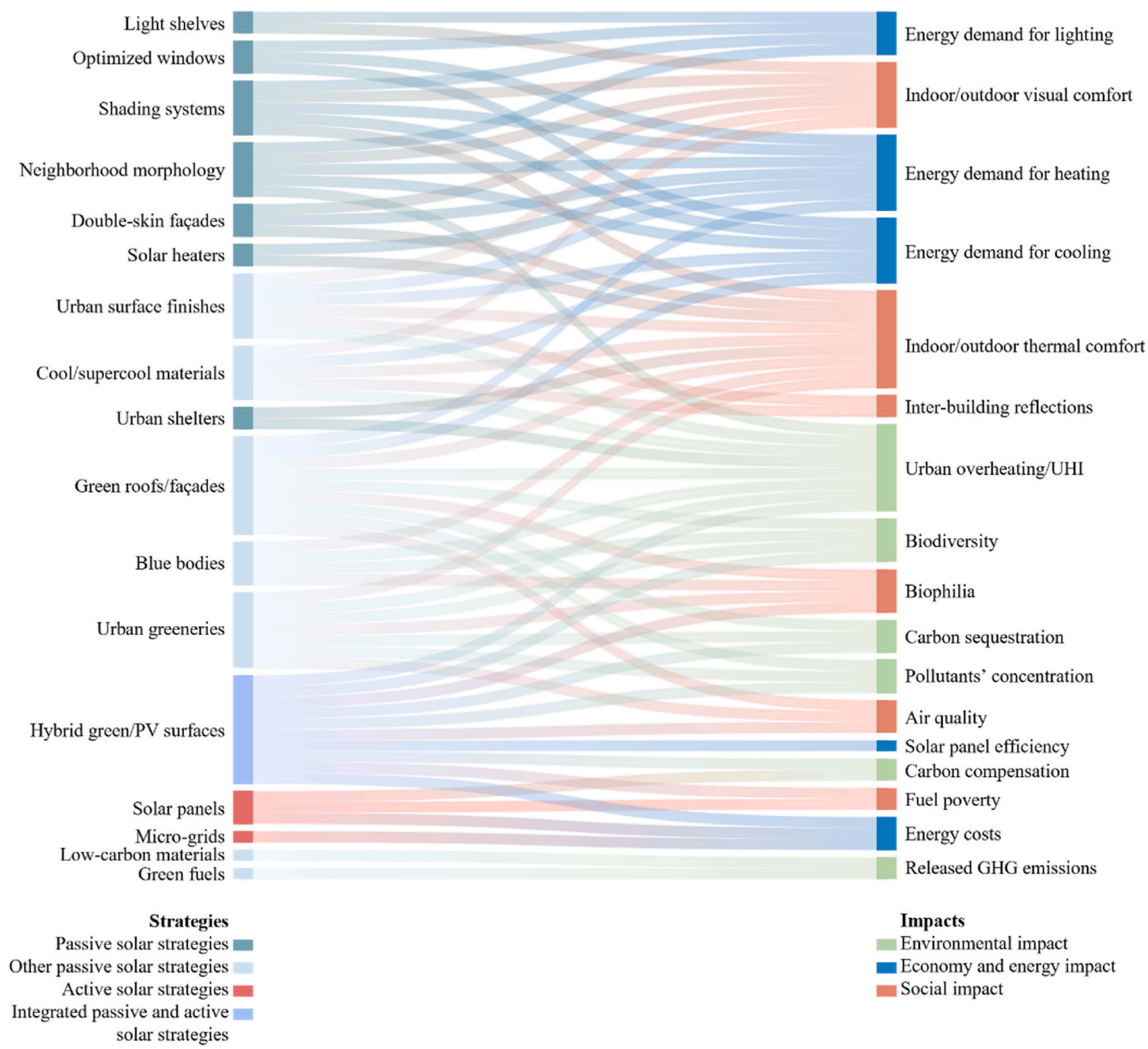


Fig. 5. Solar strategies implemented in solar neighborhoods and their impacts on the 'total environment' (i.e., environmental impact, economy and energy impact, social impact).

natural surfaces designed within the solar neighborhood have permitted the reintroduction of animal species such as bees in areas they used to inhabit before human-induced transformations. Similarly, the green roof studied in Refs. [162,163] could support four times the avian, and nine times the insect diversity when compared to a conventional roof.

Economy and energy impact. Solar neighborhoods impact the economy and energy sectors. In general, the economic impact of the integration of solar strategies in a neighborhood lays in the revitalization of the areas, with new housing and economic activities, and in strengthening business opportunities with new employment alternatives. This is best exemplified by the case studies of Science and Technology Park Adlershof (Germany) and West5 (Canada) where today a mix of new companies, scientific organizations, and single-family houses are located.

On the other hand, the energy impact is demonstrated through the active solar systems integrated within the urban fabric of the Violino district (Italy) and NTNU Gløshaugen (Norway) case studies (see section 2.4). The latitude and orientation (i.e., azimuthal and zenithal angle), and also the efficiency of the PV module determine the energy output. For example, the PV installation in the Violino district demonstrates a comparable annual energy output to that in the ZEB Living Laboratory at NTNU Gløshaugen (130 kWh/m^2 per year). This discrepancy is attributable, in part, to the different efficiency values of the PV cells, as well as the orientation of the panels in the Violino district, which is not optimized for the specific latitude (see section 2.4).

Furthermore, synergies between active solar strategies and passive cooling create better conditions for energy production by stabilizing temperatures on hot days and increasing the efficiency of PV systems by up to 5–10% in summer [107,164]. In fact, when temperatures rise above 25 °C, the efficiency of PV panels decreases [165,166]. In that sense, it is valuable to highlight the work performed within the IEA SHC Task 63 on the use of surfaces [53] and the contribution of other researchers worldwide such as the technological solutions combining PV shading devices and green surfaces developed by Tablada et al. [113].

At the grid level, on-site energy generation and self-consumption lead to the decentralization of the energy grid by reducing transmission and distribution losses, and the need for expensive transmission and distribution infrastructure. The implementation of micro-grids, peer-to-peer energy trading, and sector coupling concepts have the potential to reduce energy costs for consumers. In the study by Long et al. [167], this reduction for a residential community was quantified at 30% compared to a conventional peer-to-grid energy trading scheme.

Finally, passive solar design solutions such as solar air heaters and double-skin façades permit to reduce the energy demand for heating and cooling in the range of 30–50%, depending on the building's design and microclimate [168,169]. Moreover, the optimal design of openings to exploit natural light coupled with energy-efficient lighting technologies permits to decrease the energy consumption for lighting by around 30%, even though it is strictly correlated to location, orientation, and design, as well as to lighting fixtures and controls strategies used [170].

Social impact. Impacts on society and quality of life are achieved in solar neighborhoods by reducing fuel poverty through active solar systems [171], as well as by empowering citizens with direct control over energy production, supply, and solar accessibility [172]. The digitalization of the built environment is a crucial aspect in that sense, enabling extensive monitoring activities and direct access to data, as well as the social acceptability of solar strategies and gamification strategies to enhance citizens' involvement. In that regard, the solar cadaster of Geneve, Switzerland, as well as the Solar City program in Halifax,[11] Canada, offer a collaborative platform and innovative solar energy options for homeowners to boost economic activities around the solar sector and engage citizens through community planning and information sessions.

The creation of solar neighborhoods might also potentially result in socio and spatial injustices within urban areas and become a vehicle for gentrification. Indeed, a growing body of literature is analyzing the contribution of new green infrastructure to gentrification [173], and the concept is recently being connected and expanded to other urban interventions, such as the energy rehabilitation of neighborhoods [174], the implementation of climate resilience and sustainability policies [175,176], and the transition to the use of RES [177]. In this framework, it is important to design and implement solar neighborhoods thoroughly considering, besides technical and aesthetical criteria, environmental and climate justice principles, avoiding any social inequality in the access to all the benefits produced by such neighborhoods.

Indoor and outdoor visual and thermal comfort of users within solar neighborhoods is determined by buildings' geometry, urban furniture, and technological/material features. Building shape and orientation as well as the design of windows and shading devices can enhance daylighting exploitation by ranges of 30–100%, depending on the location and the baseline scenario [178,179]. Urban shading structures move the perceived temperature level of a person to a less strong thermal stress, reducing the mean radiant temperature, Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI) up to 24.8 °C, 12.0 °C, and 5.9 °C, respectively [180].

On the contrary, cool pavements can slightly worsen the level of thermal stress during the central hours of the day, due to the increased pedestrian exposure to shortwave radiation reflected from pavements and walls [181], as observed for cool pavements in Padua, Italy, through simulations (i.e., UTCI increases up to 0.6 °C in areas directly exposed to sunlight) [161]. Nonetheless, their capability to enhance indoor thermal comfort is universally recognized [71]. Compared to a conventional envelope, light-colored paint materials reduce discomfort hours by around 75%, in a hot-dry climate [182], while a Trombe wall enhanced with phase-change materials achieves a 7% reduction in a hot summer and cold winter region [183]. It is worth mentioning that some cool materials (e.g., high- and retro-reflective materials) tend to reduce the passive heat gains throughout the year by negatively impacting indoor thermal comfort during winter. The unplanned use of highly reflective materials within solar neighborhoods may potentially cause uncontrolled concentration of solar irradiance at the pedestrian level. Diffusely reflective façades increase the solar irradiance at the pedestrian level by approximately 30%, while specular reflective façades can triple that amount [184]. Conversely, retro-reflective coatings can reduce the daily glare probability by around 5% compared to highly reflective coatings [185].

The presence of trees and vegetation elements is fundamental to improving the quality of life and thermal comfort of persons by lowering urban surface temperatures, reducing micro-pollutant concentration, and making nature more accessible to people, enhancing their biophilia. In the One Central Park case study, over 30,000 m^2 of the site has been green planted, with a large vertical living façade that grows and changes color with the seasons. The façade itself reduces the heat load of the building by 15–20%, with a positive contribution to reducing undesirable UHI effects.

2.9. *What legislative agenda is needed to support solar neighborhoods?*

The legislative agenda together with policymakers' initiatives plays a key role in the adoption of solar neighborhoods. Their influence extends across multiple dimensions (e.g., regulatory frameworks, incentives, guidelines), emphasizing their importance in shaping sustainable urban development. By offering financial support and overseeing collaborations among the different stakeholders, policymakers can contribute to reducing barriers to entry and driving market transformation, accelerating the development and uptake of solar neighborhood solutions. This question focuses on the essential attributes of the legislative agenda to support solar neighborhoods, moving from the assessment of existing building regulations concerning solar energy to standards and certifications about broader themes such as energy efficiency and environmental sustainability, at building and neighborhood levels. Through this analysis, the key components required to create an effective and comprehensive legislative framework to promote the advancement of solar neighborhoods are identified.

In a global context, most countries have established standards to ensure access to sunlight at the individual building level. However, a gap persists in terms of codes and guidelines for regulating sunlight access and the application of active and passive solar strategies at the neighborhood scale. In the Canadian context, each province and sometimes cities have different approaches to solar access. The City of Toronto Official Plan[12] states that new developments in existing neighborhoods must allow for the provision of sunlight and views of the sky for the residents of new and existing buildings. In Europe, various regulations directly or indirectly related to solar access can be distinguished. For instance, in Italy, the Integrated National Energy and Climate Plan sets some growth targets for power and thermal energy from renewable sources at the national level, including solar energy [186]. Regarding passive solar, some Italian regional laws require ensuring an appropriate level of visual comfort through daylighting and its integration with artificial lighting sources [187]. In Norway, the national regulation TEK 17 [188] used to specified requirements to enhance direct solar access, including a minimum threshold to guarantee a satisfactory level of sun exposure for housing units and communal outdoor areas (e.g., at least 5 h in spring and autumn equinoxes). However, this guidance was repealed from TEK17 in 2021, allowing local municipalities to set specific requirements based on local conditions, while some guidelines have been provided by the Norwegian Association of Consulting Engineers.[13] In Sweden, detailed development plans are required to include description of the geometry of buildings such as building height, ridge height, total building height and roof inclination. The described geometry could have a direct effect on the performance of future solar energy systems installed in the area, as well as passive strategies implemented in the neighborhood. Legal judgments on solar access in Australia have also highlighted inconsistent interpretations of 'nuisance' in common law [189]. Similarly, solar access protection through easements or covenants can be overruled through jurisdictional state law [190]. This reinforces the importance of overarching legislative reform that promotes and protects solar neighborhood planning now and into the future.

Regarding solar technology implementation in the built

[11] halifax.ca (accessed in 28.03.2023).

[12] toronto.ca/city-government/planning-development/official-plan-guidelines/official-plan (accessed in 20.03.2023).

[13] rif.no/wp-content (accessed in 20.03.2023).

environment, many countries have established building codes and permitting requirements that are mostly related to installation, safety, and structural considerations of active solar technologies, related to different types of buildings [191]. For example, the integration of PV modules into building envelopes or other surfaces within urban environments often encounters restrictions linked to considerations of visual aesthetics and structural and fire safety. Besides this, various policy mechanisms for solar modules have been adopted, which include feed-in tariffs, net metering, portfolio standards, project and tendering applications, tax exemptions, and research and development incentives. In particular, Germany, France, and Canada employ financial support measures like subsidies, feed-in tariffs, premium feed-in tariffs, and loans [192]. Similarly, China offers subsidies for small-scale projects, significantly reducing the total investment costs. In India, income tax reduction, accelerated depreciation, customs tax exemptions, production-based incentives, and obligation to purchase renewable energy have been established [192]. The USA primarily implements tax exemptions to incentivize private investments in a liberal market. In this regard, the effectiveness of incentives that directly lower consumer prices without imposing administrative burdens should be highlighted [193]. On the contrary, incentives that are extended over prolonged periods, demand administrative participation, or necessitate tax payment prior to collection are not advisable.

Furthermore, numerous voluntary standards and certificates address aspects beyond solar accessibility yet remaining pertinent within solar neighborhood planning. These include energy efficiency, sustainability within the built environment, and renewable energy production. Standards such as the ASHRAE/ICC/USGBC/IES Standard 189.1–2017[14] provide guidelines regarding sustainability, energy efficiency, indoor environmental quality, material and resources, and construction and plans for operation, by also setting minimum requirements for on-site renewable energy production. Besides this, the Green Globes Assessment Protocol for Commercial Buildings,[15] the Passive House Institute US [194], the Building Research Establishment Environmental Assessment Method (BREEAM) [195], and the Green Globes Certification [196] provide different methods for evaluating various aspects (e.g., energy, indoor environment, site, water, resources, emissions, project and environmental management) of both residential and commercial buildings. At the neighborhood level, the Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND) [197], the SITES from the Green Business Certification Inc. [198], the Living Building Challenge [199], and the Net ZEB Certification from the International Living Future Institute [200] constitute third party verified rating system covering a range of sustainability issues, including, among the others, healthy environment, pollution and risks, energy efficiency, ecology, sustainable sites, management and quality of service, economic aspects, and community.

As the initiatives to achieve positive energy and carbon neutrality targets increase, the integration of high-energy performance criteria and the deployment of solar energy is becoming an integral part of the planning and design process [201]. To support that, legislation on solar measures must be considered at early stages. Greater coherence between planning instruments and energy-related measures is also necessary to better calibrate energy demand and supply. This involves recognizing that passive and active solar solutions require different approaches depending on geo-locational and energy usage characteristics. Therefore, developing national codes that regulate long-term solar access at the neighborhood scale, particularly in high-density contexts, is needed to significantly improve the energy performance and sustainability of cities and communities. Finally, it is worth highlighting the importance of a legislative response to innovative approaches such as the one applied in the One Central Park case study, where light is redirected through heliostats and mirrors to brighten spaces that would otherwise be in full shade.

In conclusion, to establish a robust framework for supporting solar neighborhoods, a comprehensive legislative agenda should be developed based on the following points:

- **Incentives and subsidies** to promote the economic viability and adoption of solar technologies, particularly the passive ones, in communities aiming at significantly reducing energy consumption, and potentially achieving net zero energy status;
- **Regulations** to streamline the process of obtaining permits for the installation of active and passive solar solutions in residential and commercial areas, as well as in public and private spaces;
- **Guidelines** for architectural design that balance aesthetics with solar technology deployment;
- **Collaboration** between local governments, businesses, and communities to collectively drive solar neighborhood initiatives;
- **Standards for measuring and certifying** the performance levels achieved within solar neighborhoods based on a group of KPIs which are not limited to solar (see section 2.2).

2.10. What is next in planning and design strategies for solar neighborhoods?

Future trends in the research and implementation of solar neighborhoods can be identified. To begin with, two fundamental aspects of energy-centered solar neighborhood planning would be: (i) substantial breakthroughs in electricity storage capabilities and development of more efficient and economically affordable systems and (ii) development of smart grids allowing a seamless share of onsite electricity production within the neighborhood's boundaries. Legislative barriers currently in place worldwide will need to be overcome in that sense, while vehicle-to-grid technologies, implying a bidirectional flow of electricity between EV and the grid, are one promising solution to modulate energy demand and supply in those markets with a large share of EV [202]. Solar neighborhoods are expected to accelerate the penetration of distributed solar systems in the built environment, making these technologies more visible, affordable, and acceptable to citizens. However, despite the increased visibility of solar technologies proven to be an effective solution to foster social acceptability and adoption [203, 204], it often clashes with the need to limit visual exposure in sensitive urban areas [205,206]. The challenge to combine these two diverging aspects will have to be addressed through a higher quality of architectural integration of solar systems and a wider availability of products (i.e., different colors, hues, sizes, and patterns) in the market to enable greater flexibility in the design.

As in the energy sector, self-sufficiency in terms of food supply is another important aspect in the planning of solar neighborhoods, particularly when it comes to carbon-centered solar neighborhoods. The increment of permeable surfaces can boost the implementation of urban farming techniques. Parasitic architectural elements in the form of greenhouses and cultivated surfaces coupled with PV systems should be integrated into the buildings' envelope, guaranteeing direct access to local food sources. In the planning and design of solar neighborhoods, more attention should be placed on the "total environment", through the development of a framework to evaluate conflicts and synergies of different surface uses. This will require the integration of vegetation models in the workflows [207] and high LoD three-dimensional models to perform the planning and the design of solar neighborhoods. In fact, the presence of vegetation elements is often neglected due to the inherent complexity of modeling them. The development of novel methodologies for high LoD three-dimensional models should consider both the modeling of trees and urban furniture, building envelopes and architectural elements (e.g., balconies, louvers, overhang parts), and the detection of surface materials and their optical properties, without overly affecting the computational time. This has a pivotal role in

[14] ashrae.org (accessed in 20.03.2023).
[15] thegbi.org (accessed in 20.03.2023).

improving the accuracy of the analysis and the reliability of the results. In addition, developing workflows to simulate the emerging surface treatments and coatings (e.g., icephobic layers, retro-reflective coatings, radiative coolers, electrochromic windows, etc.) with optical and thermal properties determined by parameters different than of traditional materials (e.g., reflectivity, absorption, transparency, specularity, roughness) will be important to be considered in the future urban planning process of solar neighborhoods. Moreover, the inclusion of dynamic behaviors of the urban environment (e.g., seasonal variability of deciduous trees, variable reflectance of the terrain due to the presence of snow) should become standard practice when performing simulations spanning different seasons under current and future climate scenarios.

Solar assessments and optimizations combining different spatial domains of the urban environment (i.e., outdoor, building envelopes, indoor) as well as different uses of buildings are rare [41]. The development of multi-domain approaches able to weigh various solar KPIs within the same workflow can be seen as an objective to better discretize the complexity of the built environment in the future. To achieve the "total environment", greater emphasis should be placed on environmental quality factors (e.g., comfort, daylight, air quality) during the selection of the KPIs to trade-off. Nowadays, the predominant holistic methodologies prioritize the optimization of energy and economic KPIs, relegating the evaluation of environmental impact and quality factors to a secondary position.

All these aspects are expected to be facilitated in the years to come by a broader digitalization of the building environment, supported by an extensive application of the Internet of Things (IoT), co-simulation approaches, advanced computer techniques (e.g., machine/deep learning, Artificial Intelligence - AI), and orchestration of real monitored data to realize more reliable and detailed digital twin of the built environment. In that regard, the combination of high LoD models of urban surfaces and high-resolution data can pave the way for digital twin platforms to conduct real-time solar analysis (i.e., solar maps) with multiple goals (e.g., optimal localization/integration of solar systems, optimize energy management strategies, detection of failures) and monitoring data that can provide valuable insights into the performance and optimization of solar energy systems. Moreover, advanced visualization techniques and indicators will make solar neighborhood planning instruments more accessible to the generic public. Finally, while the full potential of digital twin platforms is far from being fully exploited, the integration of deep learning techniques into holistic workflows [208] is fundamentally reshaping the simulation, analysis, and optimization of complex systems. This approach not only unlocks unparalleled levels of accuracy, efficiency, and adaptability, but also adeptly manages disconnected spatial scales (e.g., component, building, neighborhood, city) and diverse temporal domains, spanning short-, mid-, and long-term horizons.

3. Conclusions and further developments

Ten questions concerning planning and design strategies for solar neighborhoods have been addressed in this paper by discussing a wide range of aspects and related topics. For the first time, a classification is proposed for solar neighborhoods, which consist of neighborhoods primarily utilizing solar energy as RES. Four types of solar neighborhoods have been identified in section 2.1: the pure (or target-free) solar neighborhoods, the energy-centered solar neighborhoods, the carbon-centered solar neighborhoods, and the energy- and carbon-centered solar neighborhoods.

The workflow for planning solar neighborhoods is outlined after a comprehensive description of the design variables. In this regard, an overview of the passive and active solar strategies was provided together with examples of successful applications under different climatic conditions and urban contexts. The present study highlights the need for an inter-disciplinary and multi-criteria approach that can operate at multiple scales, ranging from building to neighborhood and city, and spatial domains (i.e., outdoor, building envelopes, and indoor), addressing the different competing uses of urban surfaces, along with their impacts on the total environment. Moreover, challenges, barriers, and drivers of solar neighborhoods are addressed. Driving forces that encourage the implementation of active and passive solar strategies in existing and new neighborhoods concern financial, environmental, and health incentives. Increasing energy efficiency, reducing energy consumption, reinstating a natural landscape to mitigate the effects of climate change-induced hazards, tackling UHI phenomena, enhancing air quality and comfort conditions within the cities, and assuring the right to light/shade and access to urban natural areas are some of the drivers identified in the ten answers. Nonetheless, significant challenges and barriers still exist. These are related to the social acceptability of solar strategies, the competing uses of urban surfaces, the drawbacks of some technologies (e.g., the impact of cool materials on energy demand for heating, solar energy production not correlated to energy demand), the lack of regulations about the exploitation of sunlight and access to shade, and the low profitability of most of the passive solar interventions.

Finally, the ten questions answered allowed to identify the knowledge gaps about solar neighborhood design and determine future research trends in this field. Future developments in solar neighborhood design concern:

- Identifying enhanced solutions for architectural integration of solar systems (i.e., different colors, hues, sizes, and patterns) to enable greater flexibility in the design.
- Integrating permeable surfaces in the built environment (i) to increase resilience to climate change effects and extreme weather events, and (ii) to enable direct food supply and urban farming.
- Implementing high LoD models for vegetation elements, urban furniture, and architectural features of buildings and neighborhoods without overly affecting the computational time of the analyses.
- Making a common practice to include the dynamic behaviors of the urban environment (e.g., the variation in transparency of deciduous trees, and the variable reflectance levels for the terrain due to the presence of snow) into the simulation process.
- Simulating the behavior of emerging surface treatments and technologies, such as icephobic layers, retroreflective coatings, thermochromic substrate, photoluminescent pigments, radiative coolers, electrochromic windows and their implications within the complex urban phenomena such as overshadowing effects and solar interbuilding reflections.
- Boosting the digitalization of the built environment, supported by an extensive application of the IoT, co-simulation approach and advanced computer techniques (e.g., machine/deep learning, AI), and orchestration of data to realize more reliable and detailed digital twins of buildings and cities.
- Promoting legal reforms to solar access protection and improved planning approval processes where informed decisions can be made.
- Defining business models for solar neighborhoods to ensure the long-term viability, scalability, and financial sustainability of solar initiatives, facilitating their widespread adoption and maximizing their impact on energy transition and environmental goals.

CRediT authorship contribution statement

Mattia Manni: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Matteo Formolli:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Alessia Boccalatte:** Writing – original draft, Investigation. **Silvia Croce:** Writing – original draft, Investigation. **Gilles Desthieux:** Writing – original draft, Investigation. **Caroline Hachem-Vermette:** Writing – original draft, Investigation. **Jouri Kanters:** Writing – original draft, Investigation. **Christophe Ménézo:** Writing – original draft, Investigation. **Mark Snow:** Writing – original draft, Investigation. **Martin Thebault:** Writing – original draft, Investigation. **Maria Wall:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Gabriele Lobaccaro:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, 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

No data was used for the research described in the article.

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