Solar access indicators for urban planning

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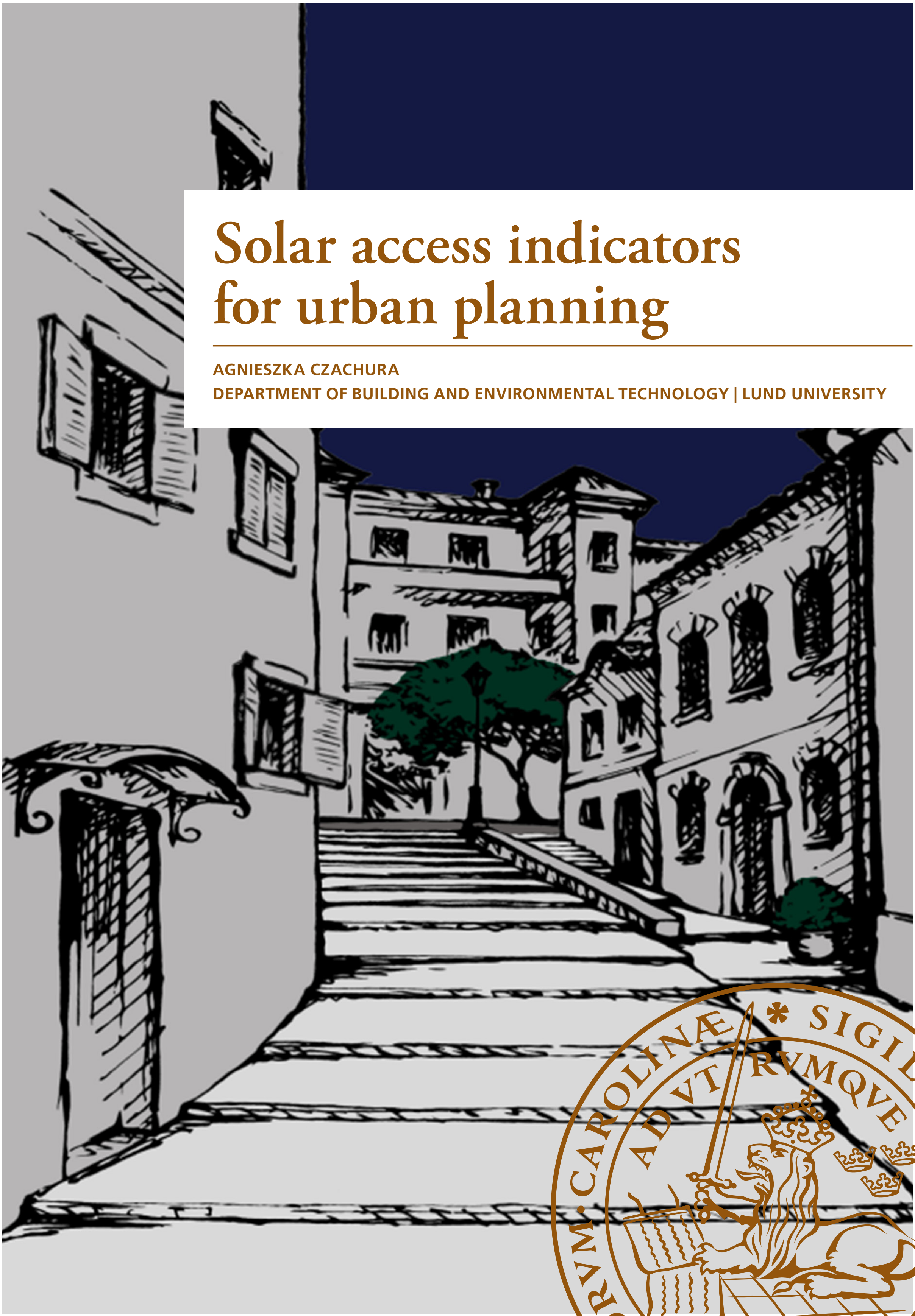

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Abstract

Solar access describes the amount and distribution of sunlight in living environments. Access to sunlight is crucial for the health and sustainability of cities. It is vital for people and vegetation, and for energy production and conservation. The amount of sunlight entering the city space is restricted by the urban layout, as buildings obstruct solar access by shading each other and the surroundings. Scarcity of land and growing urbanisation drive the densification of cities. As cities are built taller and tighter, less sunlight can reach the urban fabric. This problem becomes especially critical for higher latitudes.

Urban planners receive development directives that often stipulate higher densification of new and existing areas. Presently, some solar access aspects (daylighting and sunlighting) are legislated and evaluated at the late stages of building design, when it is often too late to change basic urban layout features to increase solar access. Thus, the urban planning level appears to be the appropriate design stage for solar access interventions. Having so many urban design objectives to deal with at this planning level, urban planners need simple methods to effectively introduce discussion of solar access into the design process. This thesis aims to contribute to this goal by investigating relevant metrics to identify suitable performance indicators for the purposes of solar access evaluation.

In the first phase, a literature review was conducted to identify existing solar access metrics. The metrics were analysed and arranged into a metric taxonomy. The ways in which assessment metrics are typically formulated were also investigated, which led to structuring of the metric formulation principles. These guidelines may help analysts to select or formulate suitable metrics for specific design evaluations.

In the next phase, the metrics that were identified from the literature review were further examined through correlation studies and statistical methods, including regression models. The study was conducted on neighbourhood models, typical for the Swedish context, including both generic design iterations and case studies. The relationships between metrics and urban density were investigated. The analysis identified four potential metrics (1. VSC, 2. SVF, 3. ASH_F, 4. RD_G) which can help assess solar access at the urban planning phase. They adhere to four design objectives for solar access, recognised as: 1) daylighting indoors, 2) daylighting outdoors, 3) sunlighting indoors, and 4) sunlighting outdoors. These metrics are well-correlated with urban density and with other metrics, yet remain relatively simple.

Finally, two assessment methods that use and apply the identified performance indicators were suggested. Both models require the analyst to input the urban density and choose a target metric. Then, using the metric datasets created in this thesis, the assessment models return either 1) urban design proposals for a given development plot or 2) expected value ranges for a given metric to position the proposed design in reference to the previously simulated cases. The first method leaves less creative space for the planners, while the second method gives only reference values for estimation of the potential to improve a design.

Future work should aim to focus on establishing metric thresholds, i.e., performance benchmarks, as this would further develop workflows for solar access evaluations. Evidence-based research is required to establish recommended solar access levels for the complex network of wellbeing and energy objectives.

Key words: solar access, urban planning, performance indicator, daylighting, sunlighting, neighbourhood, metric taxonomy, urban density

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Acknowledgements

This thesis came to life with support from the Swedish Energy Agency, whom I want to thank for entrusting us with this research. I hope that the results will contribute to the practice of developing sustainable and healthy neighbourhoods.

I would like to express my gratitude to my supervisors Maria Wall, Jouri Kanters, and Niko Gentile for guiding me on this academic journey. I am looking forward to continuing this path with you. I am fortunate to have your support and mentorship. Thank you for all the knowledge you passed on to me.

Big thanks to the research community involved in IEA SHC Task 63 for inspiring discussions and many valuable insights. I hope we will continue to share our experiences.

To my family and friends, I am eternally grateful for your infinite supply of uplifting thoughts and encouraging words. Especially big loving thanks to my partner, whose kindness, support, and companionship mean everything to me.

List of publications

Appended publications

The publications of this licentiate thesis are listed below. All papers were peer-reviewed and published with open access.

Paper I:	Czachura, A.; Kanters, J.; Gentile, N.; Wall, M. Solar Performance Metrics in Urban Planning: A Review and Taxonomy. Buildings 2022, 12, doi:10.3390/buildings12040393.
Paper II:	Czachura, A.; Gentile, N.; Kanters, J.; Wall, M. Selection of Weather Files and Their Importance for Building Performance Simulations in the Light of Climate Change and Urban Heat Islands. In Proceedings of the ISES Solar World Congress 2021, pp. 1218-1227, 2022, doi:10.18086/swc.2021.46.02
Paper III:	Czachura, A.; Gentile, N.; Kanters, J.; Wall, M. Identifying Potential Indicators of Neighbourhood Solar Access in Urban Planning. Buildings. 2022, 12, doi:10.3390/buildings12101575.

The author’s contribution to the appended publications

Paper I:	The author conducted the review, analysed the data, and wrote the paper.
Paper II:	The author designed the study, carried out the analysis, and wrote the paper.
Paper III:	The author designed the study, carried out simulations, analysed the data, and wrote the paper.

Other publications by the author in the field

Czachura, A.; Davidsson, H. Integrated Daylight and Energy Evaluation of Passive Solar Shadings in a Nordic Climate. In Proceedings of the ISES EuroSun 2020 Conference; July 19 2021; pp. 32–40.

Baker, N.; Belmonte Monteiro, R.; Boccalatte, A.; Bouty, K.; Brozovsky, J.; Caliot, C.; Campamà Pizarro, R.; Compagnon, R.; Czachura, A.; Desthieux, G.; et al. Identification of Existing Tools and Workflows for Solar Neighborhood Planning. IEA SHC Task 63 - Solar Neighbourhood Planning 2022.

Data availability

The data produced in this licentiate thesis as part of Paper III was published with open access in the Swedish National Data Service with the reference number SND-ID: 2022-137.

Terminology

This section explains some of the key terms used throughout this thesis. Figures 1 and 2 visualise some of these concepts.

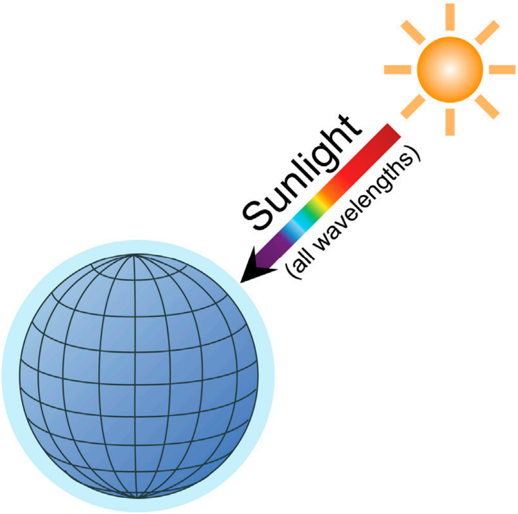


Figure 1
Sunlight is a generic term describing radiation in all spectra that comes from the sun.

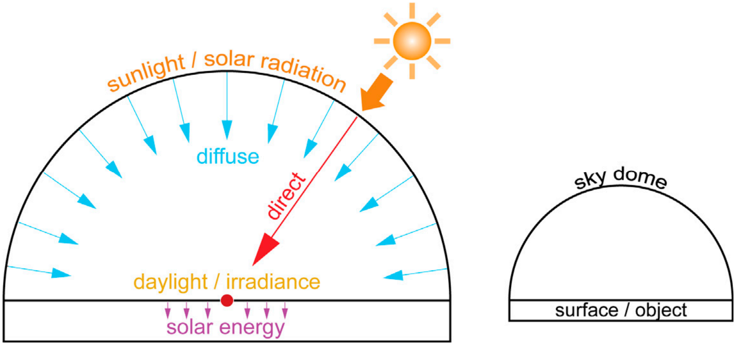


Figure 2
Diagram visualising some of the applied solar concepts and terms.

Sunlight – radiation that comes from the sun, along the entire solar electromagnetic wavelength spectrum (Figure 1).

Sunlighting – design-driven provision of solar access by direct sunlight. The term refers to the connectedness of direct solar rays with the target surfaces of the environment and is typically computed via geometrical analysis using solar vectors (directions of direct solar rays). Sunlighting is thus often expressed by duration of sunlight on a surface, rather than its intensity. No distinction is made between different light spectra. The term "sunlighting” is used in daylighting research to distinguish the provision of the direct sunlight component from the total measured daylight (P. Littlefair, 2001). “Sunlighting” has also been referred to as direct solar access (de Luca & Dogan, 2019). Building Research Establishment (BRE) guide “Site layout and planning for daylight and sunlight” uses “sunlighting” to indicate indoor and outdoor direct solar access (P. J. Littlefair et al., 2022). In the European Standard (EN 17037), the sunlighting objective is defined as “exposure to sunlight” (SSI & CEN, 2021). Some regulations for sunlighting of indoor spaces exist and vary locally (de Luca & Dogan, 2019).

Solar radiation – electromagnetic wavelengths from the sun, with the emphasis on the radiant flux (power). This is a technical term used to refer to the power of radiation coming from the sun. After solar radiation reaches the atmosphere, it splits into a diffuse and a direct component of solar radiation (Figure 2). When solar radiation hits a surface or an object, the value that expresses solar power per area is solar irradiance.

Daylight – a photometric term for the visible portion of radiation from sunlight, i.e., eye sensitivity-weighted radiation in the interval 380-740 nm.

Daylighting – a strategy to use daylight for illuminating e.g. an indoor space. For example, a window is a daylighting component. There are two methods for predicting the level of daylighting in a space: 1) static daylight modelling and 2) dynamic daylight modelling (also known as climate-based daylight modelling). The former uses a diffuse cloudy sky model (without direct sun), while the latter is typically computed with an annual simulation using hourly-based sky models connected to local weather data. Current Swedish and European daylighting regulations require compliance with a static daylight metric (Daylight Factor) (Boverket, 2011; SSI & CEN, 2021). Therefore, in this thesis, daylighting is mainly understood as provision of daylight from a diffuse cloudy sky, irrespective of the sun’s position in the sky.

Solar access – a general concept that describes the amount and distribution of sunlight in living environments. This is a general term that defines the connectedness of sun and sky to the environment and its target surfaces.

Solar energy – energy from the sun received by objects on Earth (Figure 2). Depending on how this energy is used, there are passive and active solar energy strategies. Passive techniques usually imply a simple utilisation of solar energy without mechanical systems, whereas active techniques involve the use of mechanised systems (e.g., photovoltaics).

Neighbourhood – in this thesis, defined as a small residential urban area that is not intersected by large high-speed roads, hosting a cluster of buildings.

1. Introduction

1.1. Background

The European building sector is responsible for 40 % of Europe's energy use and 38 % of greenhouse gas emissions (European Commission Department of Energy, 2020). Energy efficiency, healthy environments, and renewable energy sources represent future targets of European development that are highly relevant for the urban planning and building industries (European Commission, 2019). With 75 % of Europe's population living in urban areas (World Bank, 2022), cities will play a major role in accomplishing sustainability goals.

Solar radiation is a valuable energy source that has the potential to decarbonise future cities (Victoria et al., 2021). Solar energy can be harvested directly in cities through the application of active solar energy systems. These may consist of solar thermal collectors to provide hot water or photovoltaic systems to supply electricity directly to buildings and to the power grid. Solar energy is Europe's fastest-growing renewable energy source (Eurostat, 2022). Yet with an average of 37 % of electricity coming from renewables and solar making up only 14 % of renewable sources (Eurostat, 2022), there is a need to implement more solar energy systems and integrate them into urban spaces.

Sunlight contributes to the sustainability of the built environment even through its passive use. First, direct sunlight on buildings and their openings provides internal heat gains and therefore has a significant influence on the building's operational energy use and thermal balance. In heating-dominated climates, direct sunlight through the windows has a positive effect on the building's energy use in winter as it can provide valuable and free energy as passive solar heating. However, in the summer, even in colder climates, sunlight might become a liability, as it adds unwanted heat into buildings and causes overheating (Czachura & Davidsson, 2021), which in turn creates a need for mechanical cooling systems. Second, energy use for electrical lighting in buildings may be reduced by ensuring ample daylight indoors.

Alongside the energy implications of sunlight in cities, there are also important wellbeing-related aspects that should not be neglected. Solar energy affects thermal comfort, both indoors and outdoors. The right amount of daylight improves productivity, but too much light can cause glare issues and visual discomfort. There are also important health advantages to direct contact with sunlight such as improved mood (Rosenthal et al., 1984), better immune response (Holick, 2004), and reduced exposure to microbes (Fahimipour et al., 2018).

Purposely planned solar access to urban areas ensures good solar radiation levels for people, vegetation, building interiors, and strategic surfaces (Figure 3). However, too much sunlight in cities can sometimes lead to accumulation of heat and, if there is insufficient heat dissipation and an abundance of heat-absorbing materials, the urban heat island effect may be activated. Heatwaves are linked with increased mortality (D'Ippoliti et al., 2010), and thus resilience in cities includes preparedness and mitigation regarding extreme temperature events at the level of city planning.

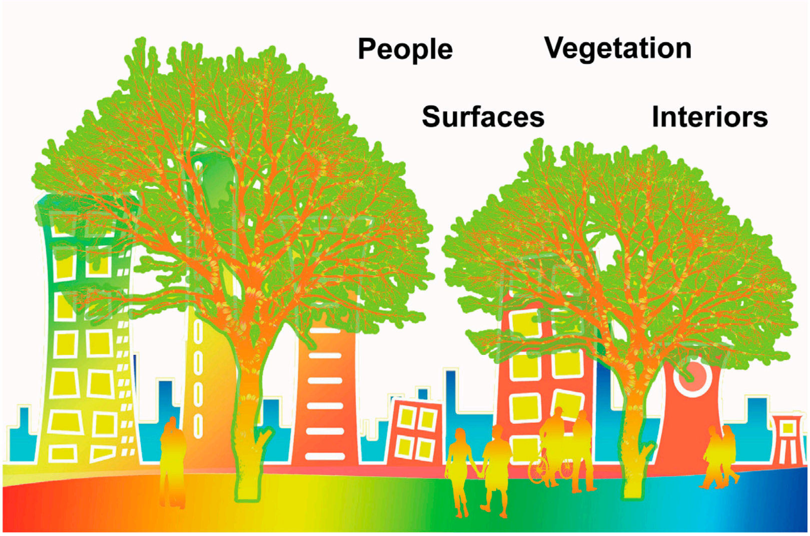


Figure 3
Solar access in cities should ensure sustainable sunlight distribution for people, vegetation, indoor environments, and outdoor surface applications, e.g., PV.

Sunlight boosts another aspect of resilient and climate-neutral cities: vegetation, including local food production. Cities have great potential to produce food at the source (Ljubojević, 2021). An added benefit of increased greenery coverage in cities is reduction of heat island effects (Dimoudi & Nikolopoulou, 2003). Plants have specific light requirements, and thus strategies aimed at effective use of urban surfaces for vegetation growth require prior sunlight assessments at the planning level.

Solar access to urban areas is affected by both natural and man-made obstructions. Landscape features, greenery, and built structures shape the distribution of sunlight into the city fabric. In areas of higher urban density, self-shading and mutual shading of buildings occurs. The amount of solar access allowed into outdoor areas and onto building façade (and further into the interiors) is largely defined at the urban planning level, as building masses are drafted at this stage. For future sustainable cities, it is critical to plan neighbourhoods and relative building masses in neighbourhoods in such a way that appropriate solar access can be guaranteed in the final built environment.

1.2. Theoretical framework

Solar access is considered a broad and general term covering various aspects of sunlight penetration and solar distribution in the urban fabric. It may quantify, using relevant indicators, the level of sky or solar path connectedness to specific target areas of the environment. It may also represent specific levels of solar irradiance on the target surfaces, where certain performance design objectives are applied. Solar access can be expressed in various ways, for instance using measures of daylight, direct sunlight, or by total amounts of solar radiation.

In this thesis, energy and wellbeing are considered the principal objectives of the provision of solar access. Figure 4 presents a map of solar access objectives along with specific performance goals connected to these objectives.

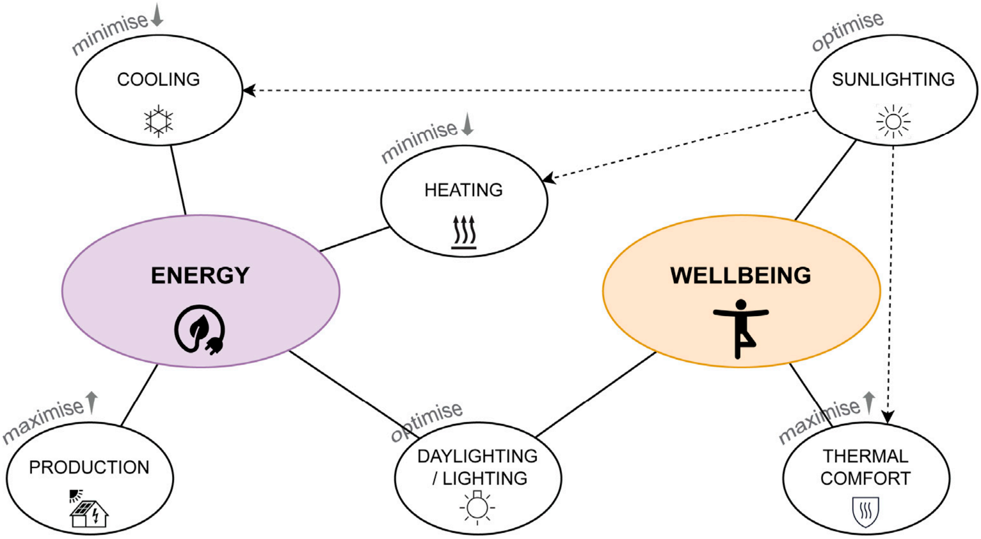


Figure 4
Two main objectives for provision of solar access in urban areas: energy and wellbeing. The items around the main objectives constitute design goals for ensuring good building performance.

In terms of current European legislation, sunlighting is a design goal associated mainly with objectives related to wellbeing (SSI & CEN, 2021). Yet naturally, direct sunlight will impact the thermal balance in the sunlit environment, as indicated in Figure 4. Some local regulations for sunlighting of indoor spaces exist, presenting different evaluation models and performance targets (de Luca & Dogan, 2019). In the European Standard (EN 17037), the recommended sunlighting levels are specified for a point located on the window surface, pertaining to sunlighting of the indoor space (SSI & CEN, 2021).

Solar access needs to be optimised because it brings both positive and negative effects on the quality and performance of urban spaces and buildings. Sunlighting and daylighting are clear examples of design goals that require optimisation (Figure 4), since too much sunlight and/or daylight can have a negative impact on performance. For example, winter solar gains reduce heating demands, but summer solar gains increase cooling demands. Visual and thermal comfort are also compromised by excessive sunlighting and daylighting.

1.3. Problem statement

Cities are growing, and as urbanisation intensifies (World Bank, 2022), densification of existing neighbourhoods and expansion to non-urban land is observed (Angel et al., 2021). City planning must accommodate for a large influx of people in the coming decades (Angel et al., 2021; Mattson et al., 2015). It is projected that by 2050, urban inhabitants will amount to two thirds of the global population (United Nations, 2019). One of the political intentions behind the densification of cities and taller developments instead of expanding the city borders is to protect agricultural land (Seto et al., 2011). Yet, the densification trend has a negative impact on solar access in cities (Bournas & Dubois, 2019), reducing the amount of sunlight and daylight in living environments.

Solar access is an important aspect of urban design. However, from the urban planning perspective, it is one of many complex design issues involving, e.g., wind, transportation, safety, noise, and pollution (Grandjean & Gilgen, 1976). Thus, planning for solar access requires simple methods that are matched to the primitive stage of building design. The urban planning phase begins the building design process by introducing rough building masses at a low level of detail (LoD). Yet, design decisions made at this stage have important implications for solar access. The geometrical constraints of an urban plan determine how much sunlight will be allowed into cities (both indoor and outdoor spaces) and how it will be distributed. The amount of solar access defined by man-made obstructions is virtually unalterable until the end of the service life of buildings and/or neighbourhoods.

Presently, there is no legislative framework for measuring and reporting the solar access quality of urban plans. However, there are legal requirements for the amount of daylight in buildings, which are implemented at the later stages of building design when façade details and internal layouts are established. Europe's example of this legislation is EN 17037 (SSI & CEN, 2021), which regulates daylighting provision using either the Daylight Factor (DF) metric or a more advanced climate-based approach. For sunlighting of building interiors, there is no hard legislation in Europe, and different approaches to measuring sunlighting levels are applied in different countries (de Luca & Dogan, 2019). Europe's EN 17037 sunlighting recommendation suggests a minimum level (duration) of direct sunlight access (cloudless conditions) reaching a window surface, calculated on a reference date (SSI & CEN, 2021).

The requirements for indoor daylight and sunlight levels may be hard to meet at the later stages of building design because of insufficient provision of solar access (Šprah & Košir, 2020). Urban planners may neglect to include solar access in design considerations due to lack of time or competence, or inability to alter planning decisions (e.g., urban density) made at the governance level (Kanters & Wall, 2018; Mattson et al., 2015). Simple evaluation procedures are needed to optimise solar access in densified cities, yet suitable methods are lacking (Nault et al., 2015). Consequently, highly obstructed solar access must be compensated for in the later stage of building planning by large window sizes (Chokhachian et al., 2020), which may lead to glare and overheating issues (Czachura & Davidsson, 2021) as well as higher heating demands in wintertime. In order to meet the daylighting standard required in the late design stages, Swedish urban planners who took part in a workshop expressed the need to prioritise provision of solar access for daylighting in their plans (Kanters et al., 2021).

Metrics that are prescribed in legislation and used to assess the performance of advanced building designs are often ill-suited for early design evaluations at the urban planning level because of their high complexity. These metrics require sophisticated inputs that are unknown in the early design stages. Details such as window arrangement and properties, façade elements (e.g., balconies), roof shapes, and internal layouts are necessary for calculating certain typical performance metrics, for instance pertaining to daylighting or energy use, but in the urban planning phase, many of the inputs have not yet been determined. This design stage requires simple metrics that can be obtained quickly and easily, as urban planning practices are multidisciplinary and cover a wide range of issues. There has been no consensus yet on the recommended metrics for solar evaluation of urban plans, and the metrics that are currently used for solar access assessments have not been supported by enough evidence to sustain their application as performance indicators.

1.4. Aims and purpose

The general purpose of the research carried out in this thesis is to develop early design assessment methods and planning routines for improved solar access in neighbourhoods. The research seeks to identify suitable metrics that can be used in prediction and assessment models. The goal is to establish performance indicators that can facilitate planning for good solar access (Figure 5).

The context for the presented research is the Northern European and in particular the Swedish built environment and urban planning practice. However, the implications of this research could be relevant for other locations with similar solar access conditions.

The specific goals of the thesis are to:

- Systematise existing knowledge about the function, purpose, and formulation of metrics;
- Create a systematic taxonomy of solar performance metrics used for urban and building design assessments;
- Demonstrate metric correlations for increased understanding of their mutual relationships;
- Expand the metric base by adding new metrics as potential candidates for performance indicators;
- Create a database of simulated solar metric values;
- Find simple metrics with high suitability for accurately assessing solar access in urban planning;
- Suggest preliminary methods of applying metric datasets in planning for solar access; and,
- Check the viability of weather data for calculating metrics, particularly solar weather parameters.

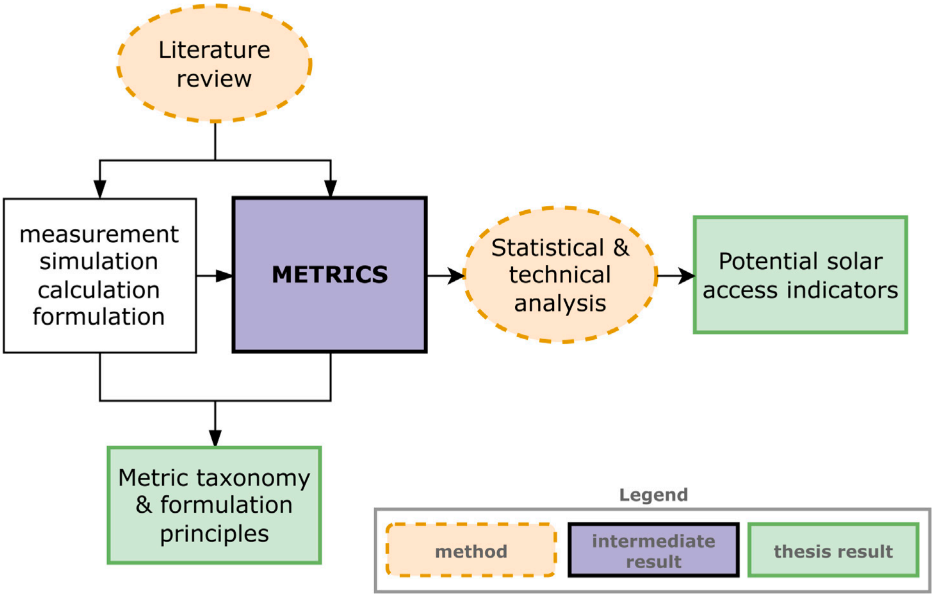


Figure 5
Simplified workflow of methods and findings of the thesis.

1.5. Limitations

This thesis focussed on identifying solar access metrics specifically targeted for the urban planning stage. Therefore, complex late-stage metrics were not considered.

Furthermore, the selection of neighbourhood was limited to homogenous and evenly spaced layouts with continuous building heights. The uniform heights of the buildings in this thesis ensure that the roofs are not obstructed by other buildings. Thus, solar access was measured only on vertical façade surfaces and horizontal ground surfaces, disregarding the solar access on the roofs.

The aspects of solar access in focus in this thesis were limited to wellbeing- and energy-related objectives; other aspects such as effects on microclimate and vegetation growth were not considered.

1.6. Research questions

This thesis aims to answer the following main research question (RQ):

RQ: Which metrics are suitable as performance indicators of solar access in the assessment of urban plans?

There are several other relevant questions that are associated with the main RQ and which this thesis seeks to answer; these are listed below.

Q1: How are metrics developed depending on the purpose of assessment?

Q2: How can metrics related to solar access research be classified based on the complexity of data inputs?

Q3: Are the legislated solar access metrics well-correlated?

Q4: Can simpler metrics substitute more complex ones in measuring solar access?

Q5: How can solar access metrics be applied in solar neighbourhood assessments at the urban planning level?

2. Methods

An overview of the methods applied in this thesis is presented in Figure 6. Methods are grouped by the scope of the three different papers, which are appended to this thesis. The flow of the applied methods leads to study outcomes that aim to answer the main and subsidiary research questions, as marked with circles in Figure 6.

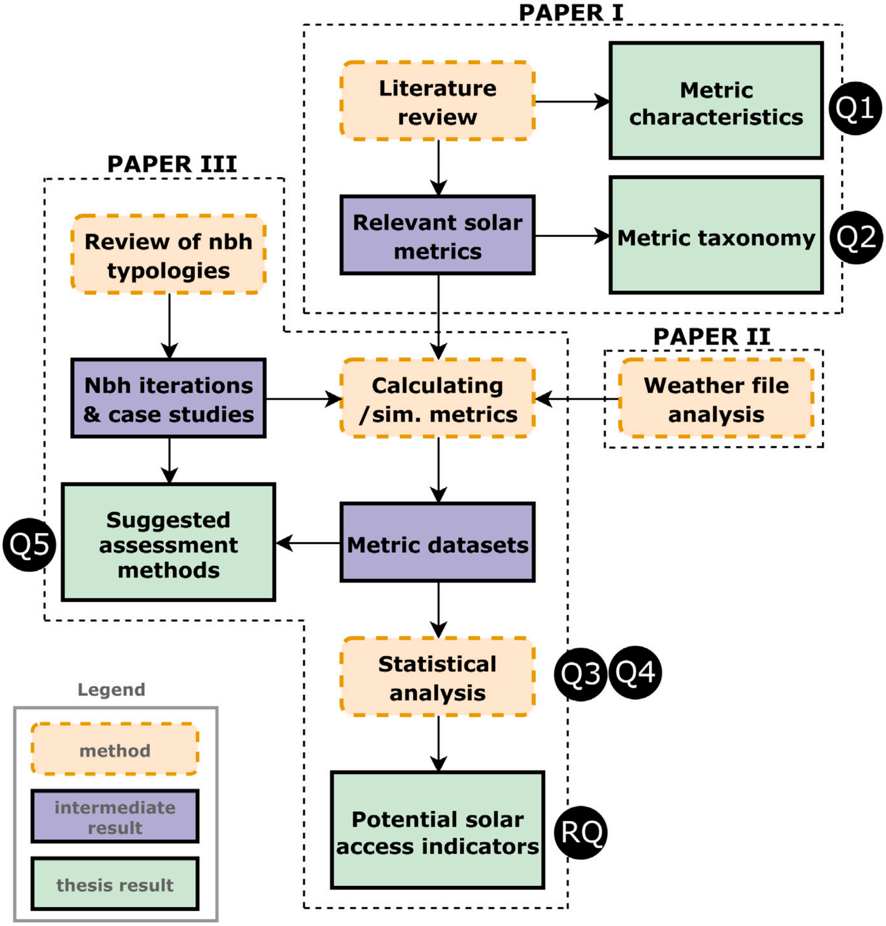


Figure 6
Flowchart of the methods and results of the thesis, including links to the research questions (black circles). ‘Neighbourhood’ is abbreviated as ‘Nbh’.

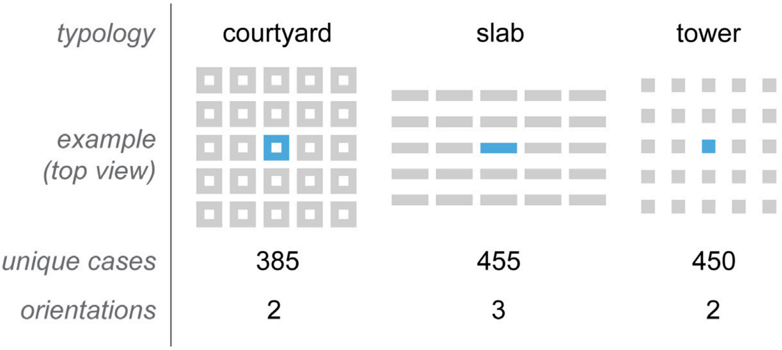
The initial phase consisted of a literature review (Paper I), which provided the relevant solar metrics for subsequent steps. In Paper II, an analysis of simulation weather data and climate parameters was conducted to validate weather file selection for solar assessments. This was a pre-study to determine the sensitivity of solar weather parameters and to inform the choice of appropriate weather data source for the next study. Paper III examined the relevant solar metrics that were obtained by simulating neighbourhood models. To prepare the models for the metric analysis, a review of neighbourhood typologies in the Swedish context was conducted. Consequently, the neighbourhood models, the relevant metrics, and the suitable weather file were used to calculate metric datasets using validated building simulation software. The generated metric datasets were further analysed using statistical methods to identify potential solar access indicators.

The approach used for the review in Paper I was integrative (Snyder, 2019). The search for relevant scientific papers was carried out in the Scopus scientific database (Elsevier, 2020) using three main concept keywords (with synonyms): solar access, metric, and neighbourhood.

Metrics found in the literature were analysed focussing on the following aspects: a) general descriptions and uses of metrics, b) methods of metric formulation, c) methods of metric communication, and d) functions of metrics.

Some metrics that were identified from the literature review as potential performance indicator candidates were applied further in the technical analysis of metrics. Other metrics were developed and formulated specifically for this analysis to broaden the base of metrics in the study.

Two types of neighbourhood models were used for the analysis of metrics included in Paper III: iteration-based designs and case studies. The case study set of neighbourhood models was used to validate the findings from the iteration datasets. Three typologies were selected for the neighbourhood models: courtyard, slab, and tower (Figure 7). These were identified as the most common neighbourhood types in the Swedish context. With varying heights, side dimensions, and building offsets, the dataset of iteration designs consisted of 1,290 unique design cases. Including the different rotation (orientation) angles applied to the geometries, the modelling set consisted of 3,035 cases. The neighbourhood designs were homogeneous, which means that each was generated using a uniform building type of equal size and shape, which was then replicated into a 5 x 5 neighbourhood grid. The modelling level of detail (LoD) was kept at LoD1, which means that the roofs were modelled flat, and there were no façade details assigned.



typology	courtyard	slab	tower
example (top view)			
unique cases	385	455	450
orientations	2	3	2

Figure 7
The studied neighbourhood iteration cases.

The neighbourhood case studies were selected from Malmö city districts. They were nearly homogeneous and of one of the same three types as the iteration-based neighbourhoods (Figure 8). Modelling resolution was also kept at LoD1. The neighbourhood models did not include any urban landscape elements other than the buildings. Selection criteria for identifying relevant neighbourhood case studies were established. These criteria also helped define the boundaries of any given neighbourhood.

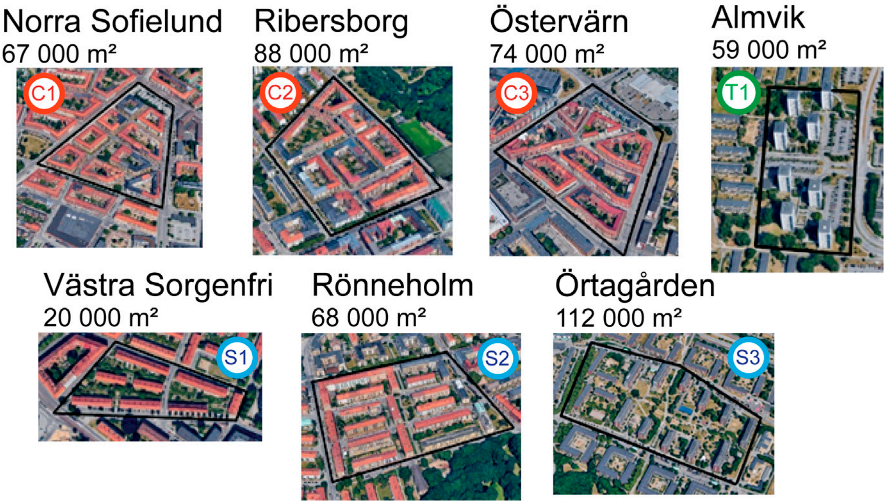


Figure 8
Malmö neighbourhood case studies used in the metric analysis. C – courtyard, S – slab, T – tower.

Some notable metrics that were analysed in this thesis are listed and described in Table 1. The metrics were in part obtained from the literature, while some were generated for the purpose of this study to fill evident gaps between the available metric types. Metrics were calculated for the whole neighbourhood or for a subject area. Metrics referring to the outdoor solar access were calculated for the ground surface, while those reflecting the solar access indoors through apertures were calculated for the façades, as shown in Figure 9. Furthermore, metrics that were calculated for the façades considered either the whole façade as a grid or just a string of points at the approximate level of ground-floor windows (Figure 10).

Table 1
Examples of metrics selected for analysis.

Acronym	Name	Subject	Calculation or simulation method [unit]
FAR	Floor Area Ratio	whole	Ratio of gross floor area to plot area [m²/m²; used as unitless]
VAR	Volume Area Ratio	whole	Ratio of gross building volume to plot area [m³/m²; used as unitless]
SVF	Sky View Factor	ground	Grid-based (1 m), 145 sky patches, cosine-weighted sky dome [%]
VSC	Vertical Sky Component	façade (string)	At 1.4 m height, 1,024 sky patches, CIE overcast sky [%]
RD_G	Reference Day (Sunlight Hours)	ground	Grid-based (1 m), ray intersection, average hours of direct sunshine on 21 March [h]
RD_F	Reference Day (Sunlight Hours)	façade (string)	Grid-based (1 m), ray intersection, average hours of direct sunshine on 21 March [h]
ASH_G	Annual Sunlight Hours	ground	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors [-]
ASH_F	Annual Sunlight Hours	façade (string)	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors [-]
RAD_F	Solar radiation (mean)	façade	Grid-based (1 m), annual solar radiation mean per façade area [kWh/m²]

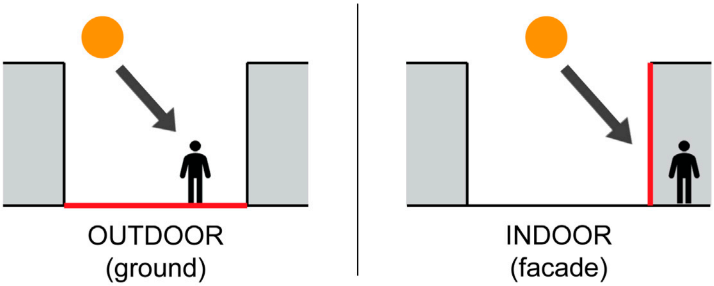


Figure 9
Two types of analysis surfaces (ground—left, façade—right) used to assess the outdoor and indoor environment.

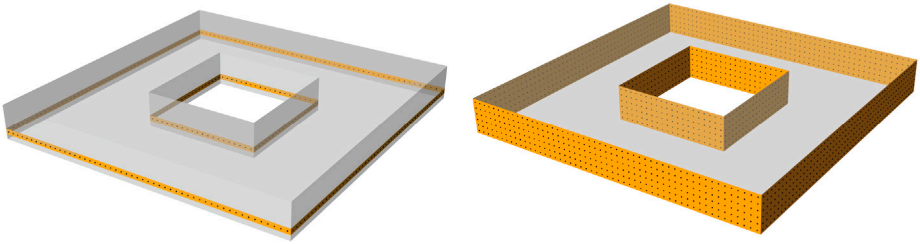


Figure 10
Two types of point grids used in simulation for façade-based metrics. Left: single string of points at 1.4 m height. Right: the whole façade made into a grid of points.

The neighbourhood models were modelled in Rhinoceros 7 (McNeel & Associates, 2021) and Grasshopper (McNeel & Associates, 2022). The metrics were calculated for two locations: Frankfurt and Stockholm, using EnergyPlus weather files (EnergyPlus, 2021), where applicable. Climate and location-based simulations were conducted in Grasshopper using Ladybug tools (Ladybug Tools, 2021). Metric datasets were then analysed using statistical methods, such as regression analysis, data distribution analysis, and correlation analysis. Statistical analyses were conducted in RStudio (RStudio Team, 2021).

3. Results

This section presents the main findings of the thesis, which were also depicted in Figure 6. Sections 3.1 (Metric characteristics) and 3.2 (Metric taxonomy) recap the findings of Paper I. Section 3.3 (Weather file analysis) summarises the results of Paper II. Lastly, sections 3.4 (Potential solar access indicators) and 3.5 (Suggested assessment methods) present the main results of Paper III.

3.1. Metric characteristics

A metric is defined as "a system for measuring something" (Cambridge University Press, 2022). There is a variety of metrics used in solar access studies. The results of the literature review on solar performance metrics specify three key characteristics of metrics, which play an important role in formulating meaningful metrics for performance assessments. These characteristics are metric functions (Figure 11), methods of metric formulation (Figure 12), and methods of metric communication (Figure 13). These characteristics may be used as formulation principles when creating a metric intended for design assessments and performance predictions. Metrics that are formulated in a more systematic way may help practitioners and researchers to achieve better clarity of assessment methods, increased understanding of results, and higher precision of design evaluations. While the focus of the analysis was on solar performance metrics, the metric characteristics (formulation principles) are more general and could also be applied to other engineering fields.

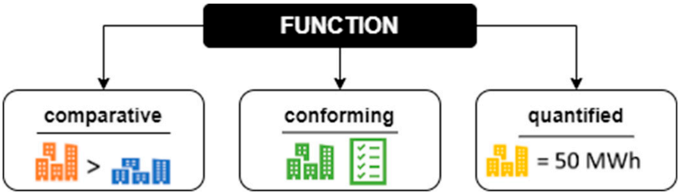


Figure 11
Metric functions were identified as comparative, conforming, or quantified.

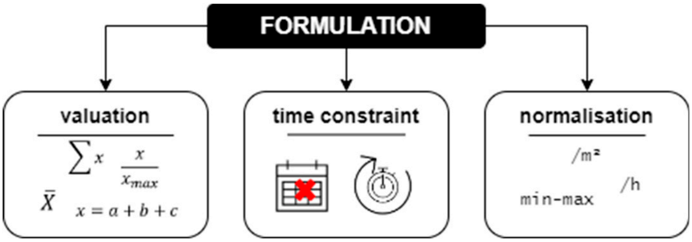


Figure 12
Metric formulation techniques may involve valuation methods, time constraints, and normalisation methods.

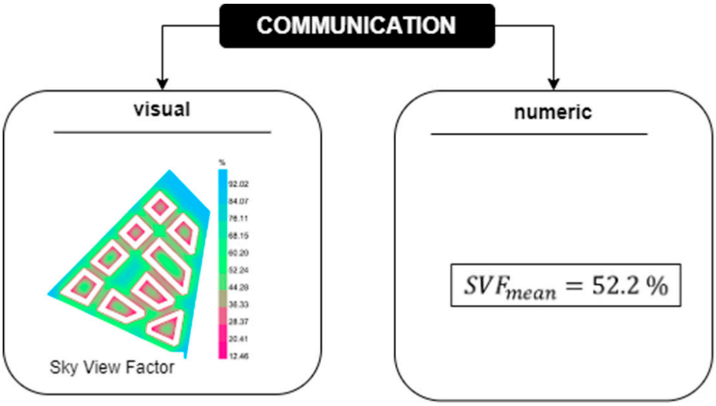
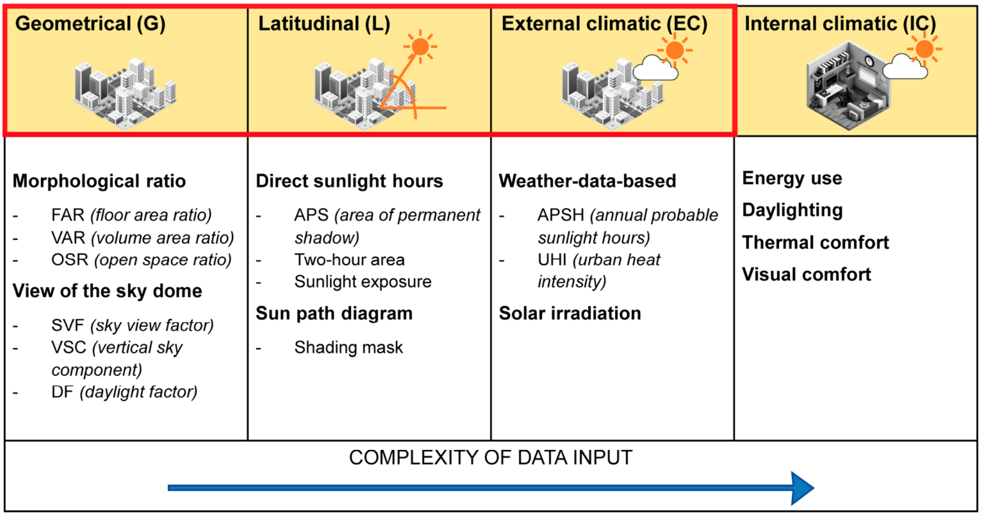


Figure 13
Two main methods of communicating metrics are visual (via graphical displays) and numeric (via numbers). This example shows the Sky View Factor metric calculated and presented graphically: a visual metric (left), and as an average value: a numeric metric (right).

3.2. Metric taxonomy

The metrics identified through the literature review were grouped into metric groups and classes and were placed in a taxonomy of solar building performance metrics (Figure 14). The taxonomy was developed based on the type and complexity of data input needed to obtain a metric. Four metric classes were identified: geometrical (G), latitudinal (L), external climatic (EC), and internal climatic (IC). The classes evolve from the lowest complexity of data input (G-metrics) to the highest complexity input (IC-metrics). Within these classes, there are groups of metrics that further distinguish between different types of metrics based on their features and calculation methods.



Geometrical (G)	Latitudinal (L)	External climatic (EC)	Internal climatic (IC)
Morphological ratio - FAR *(floor area ratio)* - VAR *(volume area ratio)* - OSR *(open space ratio)* **View of the sky dome** - SVF *(sky view factor)* - VSC *(vertical sky component)* - DF *(daylight factor)*	**Direct sunlight hours** - APS *(area of permanent shadow)* - Two-hour area - Sunlight exposure **Sun path diagram** - Shading mask	**Weather-data-based** - APSH *(annual probable sunlight hours)* - UHI *(urban heat intensity)* **Solar irradiation**	**Energy use** **Daylighting** **Thermal comfort** **Visual comfort**

Figure 14
Metric taxonomy presenting metric classes in the top row and metric groups in the middle row, including some examples of metrics (bulleted). The metric classes that were found suitable for early design assessments are highlighted in red.

The types of data input required to calculate a solar performance metric of any given class are presented in Table 2. At the urban planning stage, information about façade and internal design details is not available; therefore, only G-, L-, and EC-metrics appear suitable for solar assessments at the urban planning level.

Table 2
Types of data input required to obtain metrics belonging to the four classes.

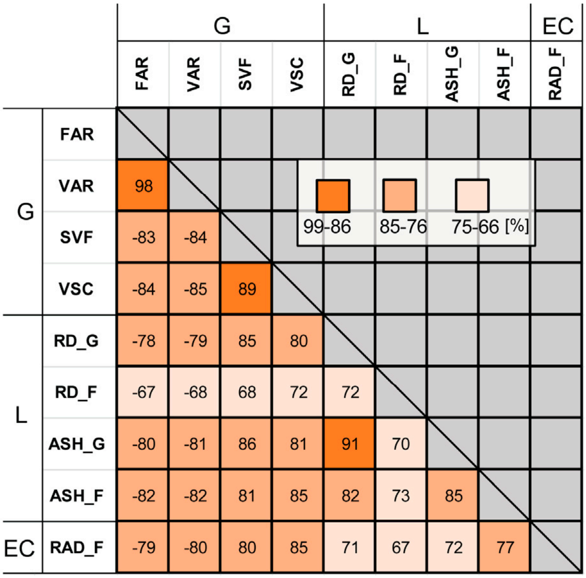
Data input	**Metric classes**			
	G	**L**	**EC**	**IC**
geometrical dimensions	✓	✓	✓	✓
latitude		✓	✓	✓
orientation		✓	✓	✓
insolation (climate)			✓	✓
façade details (incl. window placements)			(✓)	✓
internal layouts and schedules				✓

3.3. Weather file analysis

The analysis indicated that careful selection of weather files for simulations is crucial for hygrothermal parameters but has little impact on solar parameters of the climate. Hygrothermal parameters are influenced by climate change factors and the impact of proximity to urban centres (urban heat island effect). In both scenarios, the study showed that temperatures increase on average. However, with regard to solar parameters, there was no significant statistical difference observed between different weather files. This suggests that there seems not to be a need for special care when selecting weather files for solar access studies. More care should be applied to the selection of weather files for building performance assessments involving hygrothermal aspects.

3.4. Potential solar access indicators

The analysis carried out in Paper III revealed that solar metrics of varying complexity have a high level of correlation to one another, which is demonstrated in Figure 15. It is important to note that simpler metrics (of lower complexity) correlate well with higher complexity metrics. Furthermore, the analysis showed good correlation scores between urban density metrics (FAR, VAR) and other solar access metrics.



		G				L				EC
		FAR	VAR	SVF	VSC	RD_G	RD_F	ASH_G	ASH_F	RAD_F
G	FAR									
	VAR	98								
	SVF	-83	-84							
	VSC	-84	-85	89						
L	RD_G	-78	-79	85	80					
	RD_F	-67	-68	68	72	72				
	ASH_G	-80	-81	86	81	91	70			
	ASH_F	-82	-82	81	85	82	73	85		
EC	RAD_F	-79	-80	80	85	71	67	72	77	

Figure 15
Correlation scores of selected metric pairs.

Floor Area Ratio (FAR) and Volume Area Ratio (VAR) are two very similar indicators that express urban density. This study found VAR to be a more adequate measure of density for solar performance applications, as it is irrespective of floor height, making it easier to compare studies of different built forms.

Radiation metric (RAD_F) showed high sensitivity to deviations from homogeneity in urban design. Façade shapes, non-right corner angles, and irregular layouts may significantly affect the estimated radiation value. This was demonstrated by a difference between the homogeneous iterated design cases and the case studies, despite having the same LoD. Effectively, the regression lines for case studies did not match the regression lines of the iteration-based design cases for RAD_F. This observation suggests that quantitative assessments of solar radiation in the massing stages are futile. Precise energy potential estimation at this design stage is unachievable because radiation-based metrics are sensitive to late design details and will further become reduced as urban masses shape into more sophisticated forms.

It can be argued that simple metrics are sufficient early indicators of solar radiation potential at the urban scale. High correlation scores were observed between these metrics (Figure 15). Previous studies have demonstrated the potential of SVF as a solar radiation predictor (Chatzipoulka et al., 2018; Chatzipoulka & Nikolopoulou, 2018). Since high estimation precision cannot be achieved and radiation analyses are more complex and time-consuming, simple metrics appear as suitable candidates for early comparative indications of solar radiation potential.

The analysis of metrics led to the identification of four distinct objectives for solar access in urban settings. The objectives are a combination of target environment (indoor or outdoor) and target solar access aspect (daylighting or sunlighting). Generally, at the urban planning level, indoor solar access is assessed at the façade level, while outdoor solar access can be measured at both ground and façade level in case of special solar façade applications. In this thesis, however, the recommendation is that general outdoor solar access for good living environments is assessed on the ground surface.

Based on the analysis of metrics, four suitable early assessment metrics were suggested for each of the solar access objectives (Table 3). These metrics showed good correlation scores and were validated by case studies that closely match the relationship curves of all design cases (Figure 16).

Table 3
Four metrics identified as potential performance indicators of solar access at the urban planning level. Each metric serves a different assessment objective.

	Indoors	**Outdoors**
Daylighting	VSC	SVF
Sunlighting	ASH_F	RD_G

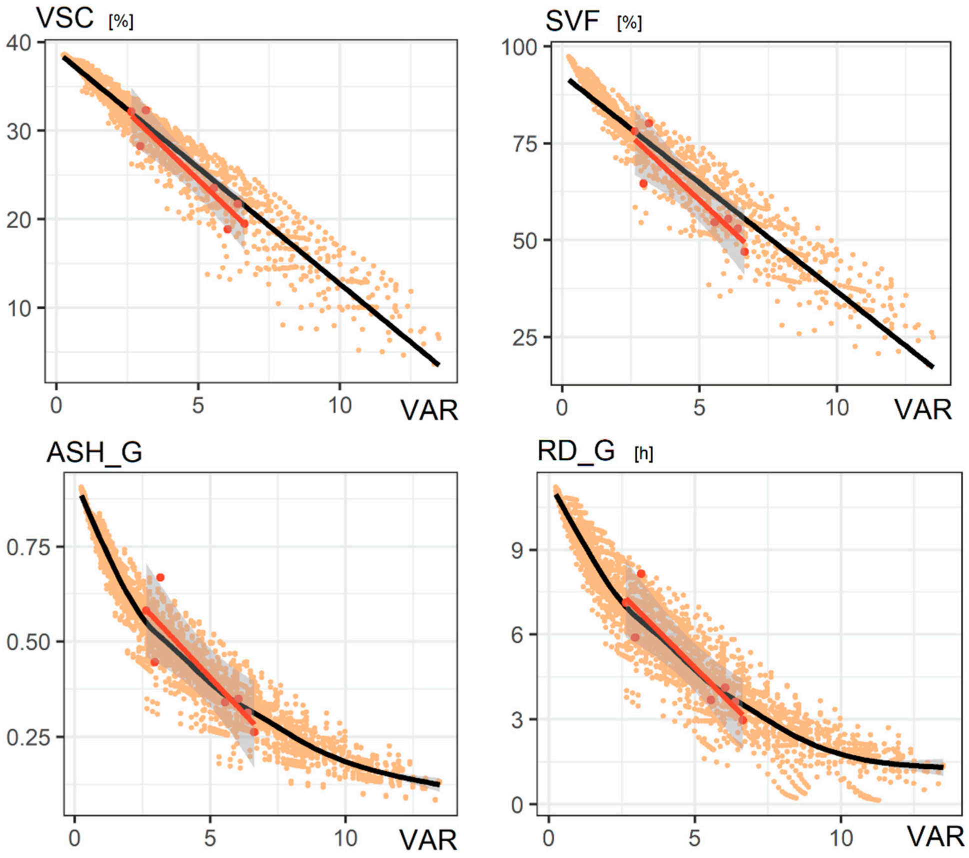
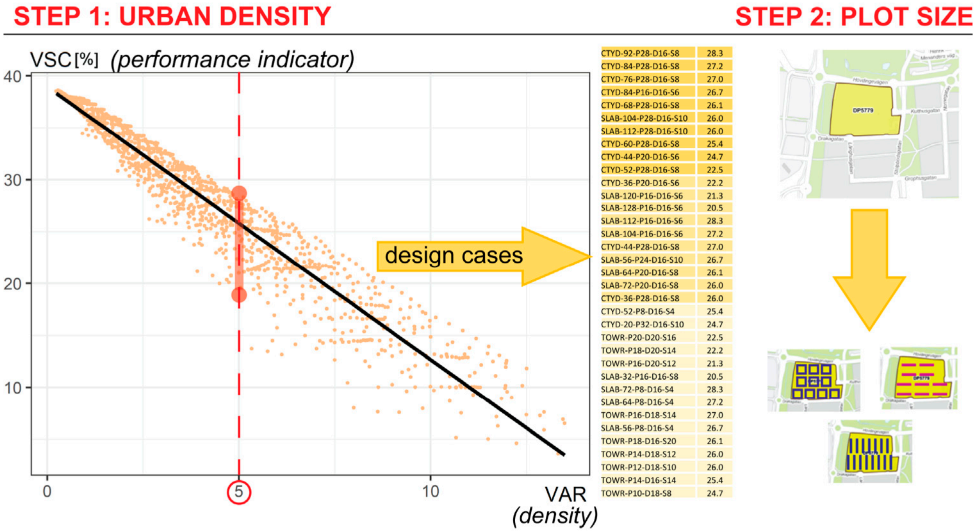


Figure 16
Linear (top) and non-linear (bottom) regression curves showing the relationship of potential solar access indicators to urban density metric, VAR. The black line represents the iteration-based neighbourhood cases, while the red line represents the case studies. The iteration-based regression curves fall within the confidence intervals (grey areas) of the case study regression lines.

3.5. Suggested assessment methods

The urban planning stage of building design lacks many of the inputs necessary for performing detailed performance assessments. As such, this design stage is also driven by political actions and development needs. The prevailing inputs for the early planning phase are the projected number of inhabitants, land size, and urban density.

This analysis suggests two ways in which to apply the validated metric datasets generated in this study. Both methods require the analyst to select a target urban density of the planned development and decide which objective to consider, i.e., which metric to use as performance indicator (see Table 3). In the first suggested method, the analyst applies the urban density value to the performance indicator dataset and may preview the best-performing examples of neighbourhood layouts (Figure 17). This could be further developed into a planning tool that would generate suggestions for urban designs with high solar access. With the alternative method, the analyst may instead look at the reference values for metric ranges based on the simulated neighbourhood cases and use the range as a guideline for assessing their own urban design proposals (Figure 18). The analyst will then know whether their design falls into the high or low range of metric values, in order to identify the room for improvement.



CTYD-92-P28-D16-S8	28.3
CTYD-84-P28-D16-S8	27.2
CTYD-76-P28-D16-S8	27.0
CTYD-84-P16-D16-S6	26.7
CTYD-68-P28-D16-S8	26.1
SLAB-104-P28-D16-S10	26.0
SLAB-112-P28-D16-S10	26.0
CTYD-60-P28-D16-S8	25.4
CTYD-44-P20-D16-S6	24.7
CTYD-52-P28-D16-S8	22.5
CTYD-36-P20-D16-S6	22.2
SLAB-120-P16-D16-S6	21.3
SLAB-128-P16-D16-S6	20.5
SLAB-112-P16-D16-S6	28.3
SLAB-104-P16-D16-S6	27.2
CTYD-44-P28-D16-S8	27.0
SLAB-56-P24-D16-S10	26.7
SLAB-64-P20-D16-S8	26.1
SLAB-72-P20-D16-S8	26.0
CTYD-36-P28-D16-S8	26.0
CTYD-52-P8-D16-S4	25.4
CTYD-20-P32-D16-S10	24.7
TOWR-P20-D20-S16	22.5
TOWR-P18-D20-S14	22.2
TOWR-P16-D20-S12	21.3
SLAB-32-P16-D16-S8	20.5
SLAB-72-P8-D16-S4	28.3
SLAB-64-P8-D16-S4	27.2
TOWR-P16-D18-S14	27.0
SLAB-56-P8-D16-S4	26.7
TOWR-P18-D16-S20	26.1
TOWR-P14-D18-S12	26.0
TOWR-P12-D18-S10	26.0
TOWR-P14-D16-S14	25.4
TOWR-P10-D18-S8	24.7

Figure 17
A suggestion for using the metric datasets in solar assessments in urban planning. Assuming target urban density and using the plot as a design input, urban planners may receive suggestions for the best design options.

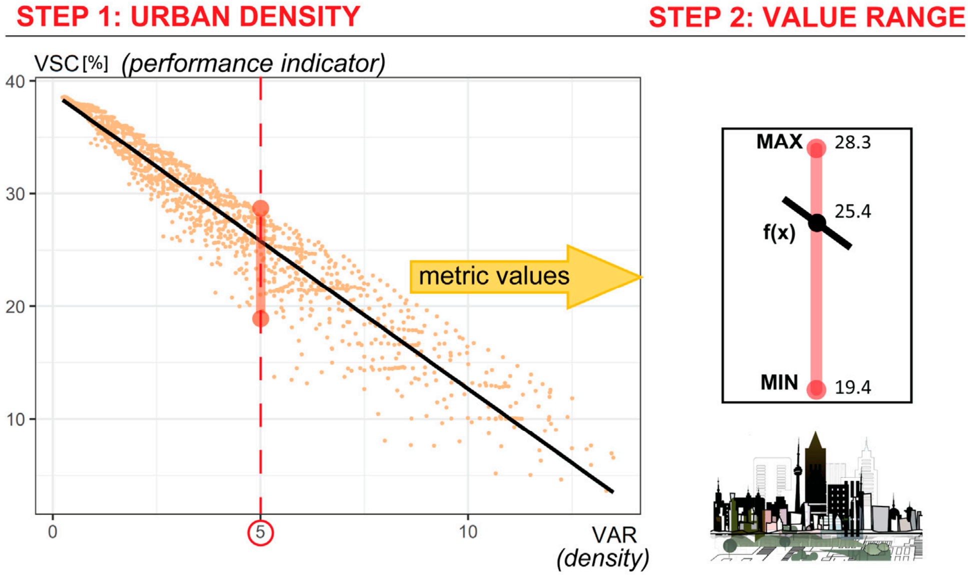


Figure 18
An alternative suggestion for using the metric datasets in solar assessments in urban planning. Assuming target density, urban planners are presented with the expected range of metrics as a reference to be compared with metric results of their own design proposals.

4. Discussion

4.1. Research questions

This section discusses the importance of this thesis work by addressing the research questions stated in the beginning of the thesis.

> **RQ:** Which metrics are suitable as performance indicators of solar access in assessments of urban plans?

The main research question of the thesis work was answered, as suitable metrics were suggested (see Table 3). Each metric is intended to address a specific solar access objective: 1) daylighting indoors – VSC, 2) daylighting outdoors – SVF, 3) sunlighting indoors – ASH_F, and 4) sunlighting outdoors – RD_G. The validity of the methods used for the metric identification was ensured by a) using a large dataset of simulated neighbourhood models, b) statistical comparisons of regression lines of iteration-based models with case studies, and c) checking for high correlation to urban density.

This thesis emphasised that metrics intended for use in early planning assessments must be simple, comparative, and easy to obtain and understand. The resulting metrics (VSC, SVF, ASH_F, RD_G) fulfil these prerequisites.

It should be noted that the suggested metrics are only numeric. In the design process, it may be of value to produce spatial graphical versions of results with coloured surfaces and appropriate legends for visual assessment and detection of critical points. This thesis recommends that the analyst perform initial assessments using the suggested numeric metrics, and potentially in the next steps, produce visual representations of results for further design inspection. All four of the proposed metrics for performance indicators are well-suited for visual grid-based assessments.

Importantly, the next step towards establishing functional performance indicators for solar access studies is to determine thresholds of the suggested metrics. Further research must define the upper and lower benchmarks based on a multitude of factors, including more complex and qualitative aspects such as microclimate, wellbeing, and subjective perception of solar access.

> **Q1:** How are metrics developed depending on the purpose of assessment?

Metric formulation principles, metric functions, and methods of metric communication were defined in this thesis. These outline the basic characteristics of metrics that must be considered when developing a metric for the purpose of measuring something. Further, the purposes of assessments were indicated by metric functions, which may be classified as either comparative, conforming, or quantified.

A metric that is consciously developed to serve its purpose may become a valuable performance indicator. On the contrary, a metric that is poorly developed may be misinterpreted or ill-suited for its intended application. The proposed formulation principles aim to help the analyst to develop useful metrics that would suit the intended function within performance assessments. The formulation principles may also help to interpret existing metrics to establish their purpose and correct applications.

> **Q2:** How can metrics related to solar access research be classified based on the complexity of data inputs?

Solar access metrics were classified into a taxonomy, and four metric classes were identified based on the complexity of data inputs needed for obtaining metrics. The classes consist of 1) geometrical, 2) latitudinal, 3) external climatic, and 4) internal climatic. The input complexity increases for each higher class, as seen in Table 2.

Additionally, metric groups within the four classes were identified. Unlike the classes, the metric groups were not bound by complexity, but rather by the means of obtaining them. Thus, the coverage of groups is open to new additions; there might be more relevant groups of metrics that fall under the defined metric classes.

> **Q3:** Are the legislated solar access metrics well-correlated?

The legislated solar access metrics in the Swedish context currently consist of daylight and exposure-to-sunlight stipulations (SSI & CEN, 2021), which pertain to indoor solar access by daylighting and sunlighting. This thesis looked at the sunlighting metric only, as the daylighting metric relies on internal building features. The sunlighting metric is a threshold-based metric, which means that in order to comply, the calculated metric must score above a certain performance threshold. The sunlighting metric is also calculated for one selected reference day (typically 21 March).

The findings of this thesis suggest that the threshold-based sunlighting stipulation may not perform well as a solar access metric. In general, threshold-based metrics did not correlate well with other metrics nor with density indicators. It is suggested to therefore avoid applying threshold-based metrics in comparative studies involving various design proposals. Thresholds are important in assessments as they communicate levels of performance, but to confidently apply conforming metrics, the selected thresholds must be meticulously verified to prove high correlation with performance.

The results also showed that assessing sunlighting levels on façades is better done with an annual metric (ASH_F) rather than an equinox-based metric (RD_F). The annual metric showed better correlation scores and smoother relationship graphs. The reason for this is that façades are sensitive to orientation because they are directional. On the equinox, the sun moves only on one half of the sky dome, which leaves the north façade orientation with zero-hour potential for direct sunlight.

> **Q4:** Can simpler metrics substitute more complex ones in measuring solar access?

It seems that simpler metrics can not only substitute more complex ones, but they are in fact even more suitable for the early assessment phase where a lot of the building design details are still unknown. Simple metrics, considered to be those of classes G and L, demonstrated good correlation with urban density and with the EC radiation metric.

> **Q5:** How can solar access metrics be applied in solar neighbourhood assessments at the urban planning level?

This thesis suggested two methods of applying the produced metric datasets into assessments of urban plans. The datasets can be used in two ways. The first provides an analyst with ready suggestions for urban designs, which exhibit high levels of solar access (Figure 17). The second would have the analyst assess the solar access potential of bespoke urban designs by comparing the design's metric score with the provided metric ranges for a given urban density (Figure 18).

The main difference between the two suggested assessment methods is the level of design autonomy of the analyst. The first method tends towards automation of the design process, suggesting possible urban layout solutions for a specific density and high solar access. The second method simply gives the analyst a value reference to assess solar access in the given urban design and to discern the potential for improvement.

Both of the suggested methods should be revised once metric thresholds are established. Setting solar access level benchmarks will improve solar assessment methods. The thresholds should instate boundaries for the recommended minimum and maximum solar access levels.

4.2. Limitations

This thesis outlined the scope of solar access objectives and goals (see Figure 4), but some relevant goals were neglected. For instance, the thesis did not consider urban heat island issues. There were two main reasons for this: a) microclimate simulations are complex and sensitive to unique and detailed designs, and this thesis assumed simplified models; and b) vegetation plays a major role in the heat balance of cities, but in this thesis, it was a conscious choice to disregard the surface types of the ground plane. However, the SVF metric has previously been associated with urban heat island mitigation (Theeuwes et al., 2017); thus, a small link to urban heat studies exists in this thesis, but it is not a main concern. Similarly, the thesis did not focus on solar access for food production purposes. However, the ASH_G metric could be useful for ensuring good direct solar access for vegetation growth, and future studies should investigate this potential.

There were further limitations in the selection of metrics:

- The analysed metrics were all numeric without considering visual metrics.
- The metrics were calculated in such a way as to express a single value for any given neighbourhood case, using the arithmetic average. This was to ensure comparability of metrics and design cases.
- Metrics were correlated to each other and to urban density, but a correlation analysis with the late design (IC) metrics was not performed due to high level of uncertainty and the need for many assumptions. This should, however, be further examined.
- The selection of metrics was based on the literature. Potentially, further metrics could be relevant for solar access and could be tested. The metric datasets from this thesis were published with open access online (Czachura & Lund University, 2022), so anyone can reuse this data and further contribute to this research.

Furthermore, there were limitations to the modelling of the neighbourhood cases:

- The LoD was set to a low value, which provides a very simplified building form, without realistic shapes, design details, or other elements of the city fabric, such as vegetation and infrastructure.
- Some assumptions about the neighbourhood cases such as the homogeneity, typology limitation, and size constraints might have restricted the ranges and variances of metric databases and might have influenced the observed relationships. More urban forms, including hybrid examples, should be studied.

5. Conclusions

This thesis studied solar metrics with the aim of increasing knowledge and improving assessment routines of solar access evaluations of neighbourhoods at the urban planning level. The main findings encompassed:

- Metric characteristics and formulation principles;
- Solar access metric taxonomy;
- Potential performance indicators of solar access at urban planning level; and,
- Suggested methods of solar access assessment at the early urban planning stage.

The overall metric characteristics and solar metric taxonomy provide a structured foundation for the process of selection, creation, and procurement of assessment metrics. A systematic way of selecting or creating metrics for specific assessment purposes, using the metric formulation principles, can facilitate design evaluations and aid decision-making. Correct metric formulation can improve the metric's design-descriptive power, which in turn leads to highly informed design decisions with strong emphasis on performance. Furthermore, assisted by the metric taxonomy, navigating solar access metrics and their different classes may prove easier and more transparent.

The thesis identified four solar access indicators (metrics (VSC, SVF, ASH_F, and RD_G) for assessments at the urban planning stage. This represents an important contribution towards establishing reliable solar assessment workflows and validating the associated methods. This thesis assessed the suitability of a range of commonly used metrics and proposed potential performance indicators. Each indicator was aimed at one of four different solar access objectives, which are a combination of the solar access goal (daylighting or sunlighting) with the target environment (indoor or outdoor). Matching validated indicators with specific solar access objectives should improve the usability of early-stage solar access evaluations and increase confidence in applying assessment metrics.

The metric datasets resulting from this thesis can be used as a practical reference and analytical support in solar access assessments at the urban planning level. Two methods of applying the proposed solar access indicators were suggested. Both the indicators and the methods are of suitably low complexity for the intended design intervention phase. The analyst may choose between a method of higher or lower degree of intervention. These methods are the result of initial attempts to develop assessment workflows and should be further improved. For this purpose, performance thresholds for the proposed indicators should be established.

6. Future work

The present work focussed on the identification of metrics as suitable performance indicators for urban planning assessments of neighbourhood solar access.

As a continuation of this research, future work aims to establish performance thresholds for the proposed solar access metrics (Figure 19). The work intends to apply quantitative and qualitative methods to establish evidence for solar access levels and associate performance with specific metric values. Metric thresholds must be further examined to assess their predictive power. The end goal would be to establish validated performance indicators and develop reliable assessment methods for early-stage solar access evaluations.

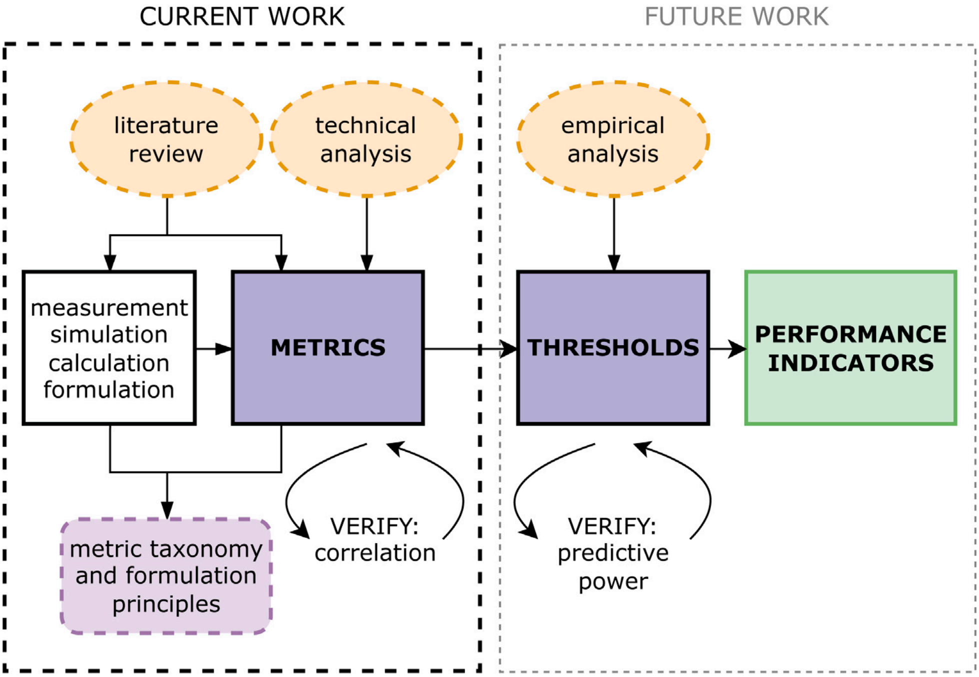


Figure 19
Simplified workflow diagram outlining current and future work of the present research.

Currently, out of the four solar access objectives presented here, only two – daylighting indoors and sunlighting indoors – are legislated. While daylighting standards are supported with extensive research, the sunlighting recommendations need more empirical evidence. Future work should focus on establishing performance thresholds for sunlighting indoors and outdoors and for daylighting outdoors. The performance criteria should be translated into design benchmarks for the solar access indicators in the urban planning assessment workflows.

References

Angel, S., Lamson-Hall, P., Blei, A., Shingade, S., & Kumar, S. (2021). Densify and Expand: A Global Analysis of Recent Urban Growth. *Sustainability, 13*(7), 3835. https://doi.org/10.3390/SU13073835

Bournas, I., & Dubois, M.-C. (2019). Daylight regulation compliance of existing multi-family apartment blocks in Sweden. *Building and Environment, 150,* 254–265. https://doi.org/10.1016/j.buildenv.2019.01.013

Boverket. (2011). Boverkets byggregler (BFS 2019:2) – föreskrifter och allmänna råd.

Cambridge University Press. (2022). METRIC | English meaning - Cambridge Dictionary. Cambridge Advanced Learner's Dictionary & Thesaurus. https://dictionary.cambridge.org/dictionary/english/metric

Chatzipoulka, C., Compagnon, R., Kaempf, J., & Nikolopoulou, M. (2018). Sky view factor as predictor of solar availability on building façades. *Solar Energy, 170,* 1026–1038. https://doi.org/10.1016/j.solener.2018.06.028

Chatzipoulka, C., & Nikolopoulou, M. (2018). Urban geometry, SVF and insolation of open spaces: London and Paris. *Building Research and Information, 46*(8), 881–898. https://doi.org/10.1080/09613218.2018.1463015

Chokhachian, A., Perini, K., Giulini, S., & Auer, T. (2020). Urban performance and density: Generative study on interdependencies of urban form and environmental measures. *Sustainable Cities and Society, 53,* 101952. https://doi.org/10.1016/j.scs.2019.101952

Czachura, A., & Davidsson, H. (2021). Integrated Daylight and Energy Evaluation of Passive Solar Shadings in a Nordic Climate. ISES EuroSun 2020 Conference, 32–40. https://doi.org/10.18086/eurosun.2020.01.01

Czachura, A., & Lund University. (2022). Mätvärden för soltillgång simulerade för stadsdesigniterationer och fallstudier. Svensk nationell datatjänst. https://doi.org/https://doi.org/10.5878/jf63-ay82

de Luca, F., & Dogan, T. (2019). A novel solar envelope method based on solar ordinances for urban planning. *Building Simulation, 12*(5), 817–834. https://doi.org/10.1007/s12273-019-0561-1

Dimoudi, A., & Nikolopoulou, M. (2003). Vegetation in the urban environment: microclimatic analysis and benefits. *Energy and Buildings, 35*(1), 69–76. https://doi.org/10.1016/S0378-7788(02)00081-6

D'Ippoliti, D., Michelozzi, P., Marino, C., De'Donato, F., Menne, B., Katsouyanni, K., Kirchmayer, U., Analitis, A., Medina-Ramón, M., Paldy, A., Atkinson, R., Kovats, S., Bisanti, L., Schneider, A., Lefranc, A., Iñiguez, C., & Perucci, C. A. (2010). The impact of heat waves on mortality in 9 European cities: Results from the EuroHEAT project. *Environmental Health: A Global Access Science Source, 9*(1), 1–9. https://doi.org/10.1186/1476-069X-9-37/FIGURES/2

Elsevier. (2020). Scopus Content Coverage Guide. https://www.elsevier.com/__data/assets/pdf_file/0007/69451/Scopus_ContentCoverage_Guide_WEB.pdf

EnergyPlus. (2021). U.S. Department of Energy's (DOE) Building Technologies Office (BTO) |EnergyPlus | Weather Data. https://www.energyplus.net/weather

European Commission. (2019). The European Green Deal (Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions). https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission Department of Energy. (2020). In focus: Energy efficiency in buildings.

Eurostat. (2022, January 26). Renewable energy on the rise: 37% of EU's electricity. Products Eurostat News. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220126-1

Fahimipour, A. K., Hartmann, E. M., Siemens, A., Kline, J., Levin, D. A., Wilson, H., Betancourt-Román, C. M., Brown, G., Fretz, M., Northcutt, D., Siemens, K. N., Huttenhower, C., Green, J. L., & van den Wymelenberg, K. (2018). Daylight exposure modulates bacterial communities associated with household dust. *Microbiome, 6*(1). https://doi.org/10.1186/s40168-018-0559-4

Grandjean, E., & Gilgen, A. (1976). Environmental factors in urban planning. Taylor & Francis.

Holick, M. F. (2004). Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. *The American Journal of Clinical Nutrition, 80*(6), 1678S-1688S. https://doi.org/10.1093/ajcn/80.6.1678s

Kanters, J., Gentile, N., & Bernardo, R. (2021). Planning for solar access in Sweden: routines, metrics, and tools. *Urban Planning and Transport Research, 9*(1), 348–368. https://doi.org/10.1080/21650020.2021.1944293

Kanters, J., & Wall, M. (2018). Experiences from the urban planning process of a solar neighbourhood in Malmö, Sweden. *Urban, Planning and Transport Research, 6*(1), 54–80. https://doi.org/10.1080/21650020.2018.1478323

Ladybug Tools. (2021). Ladybug Tools | Home Page. https://www.ladybug.tools/

Littlefair, P. (2001). Daylight, sunlight and solar gain in the urban environment. *Solar Energy, 70*(3), 177–185. https://doi.org/10.1016/S0038-092X(00)00099-2

Littlefair, P. J., King, S., Howlett, G., Ticleanu, C., & Longfield, A. (2022). Site layout planning for daylight and sunlight (BR 209) (3rd ed.). S&P Global.

Ljubojević, M. (2021). Horticulturalization of the 21st century cities. *Scientia Horticulturae, 288,* 110350. https://doi.org/10.1016/J.SCIENTA.2021.110350

Mattson, K., Hägglund, E., & Bokliden, K. B. (2015). Förtätning av städer. Trender och utmanningar. https://skr.se/download/18.583b3b0c17e40e30384ae1a7/1643282557706/5381.pdf

McNeel, R., & Associates. (2021). Rhinoceros 3D, version 7. https://www.rhino3d.com/

McNeel, R., & Associates. (2022). Grasshopper - algorithmic modeling for Rhino. https://www.grasshopper3d.com/

Nault, E., Peronato, G., Rey, E., & Andersen, M. (2015). Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs. *Building and Environment, 92,* 679–691. https://doi.org/10.1016/j.buildenv.2015.05.012

Rosenthal, N. E., Sack, D. A., Gillin, J. C., Lewy, A. J., Goodwin, F. K., Davenport, Y., Mueller, P. S., Newsome, D. A., & Wehr, T. A. (1984). Seasonal Affective Disorder: A Description of the Syndrome and Preliminary Findings With Light Therapy. *Archives of General Psychiatry, 41*(1), 72–80. https://doi.org/10.1001/archpsyc.1984.01790120076010

RStudio Team. (2021). RStudio: Integrated Development Environment for R. PBC. http://www.rstudio.com/

Seto, K. C., Fragkias, M., Güneralp, B., & Reilly, M. K. (2011). A Meta-Analysis of Global Urban Land Expansion. *PLOS ONE, 6*(8), e23777. https://doi.org/10.1371/JOURNAL.PONE.0023777

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104,* 333–339. https://doi.org/10.1016/J.JBUSRES.2019.07.039

Šprah, N., & Košir, M. (2020). Daylight provision requirements according to EN 17037 as a restriction for sustainable urban planning of residential developments. *Sustainability (Switzerland), 12*(1). https://doi.org/10.3390/su12010315

SSI, & CEN. (2021). SS-EN 17037:2018+A1:2021 Daylight in buildings. European Committee for Standardization (CEN).

Theeuwes, N. E., Steeneveld, G.-J. J., Ronda, R. J., & Holtslag, A. A. M. M. (2017). A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe. *International Journal of Climatology, 37*(1), 443–454. https://doi.org/10.1002/joc.4717

United Nations. (2019). World Urbanization Prospects. The 2018 Revision. United Nations. https://doi.org/https://dx.doi.org/10.18356/b9e995fe-en

Victoria, M., Haegel, N., Peters, I. M., Sinton, R., Jäger-Waldau, A., del Cañizo, C., Breyer, C., Stocks, M., Blakers, A., Kaizuka, I., Komoto, K., & Smets, A. (2021). Solar photovoltaics is ready to power a sustainable future. *Joule, 5*(5), 1041–1056. https://doi.org/10.1016/J.JOULE.2021.03.005

World Bank. (2022). Urban population (% of total population) - European Union | Data. United Nations Population Division. World Urbanization Prospects: 2018 Revision. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=EU

Paper I

buildings

Review

Solar Performance Metrics in Urban Planning: A Review and Taxonomy

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Abstract: Metrics are instrumental in design assessments. Solar performance metrics help designers to evaluate solar access in cities. Metrics should be used early in the urban planning stages in order to enable sustainable urban development with greater access to solar energy. Currently, solar assessments at this design stage are limited in practice; established methods or routines are lacking, and so are suitable metrics. This paper reviews the relevant literature to provide a critical overview of solar metrics commonly used in building performance assessments. The review defines key metric formulation principles—valuation, time constraint, and normalisation—which should be considered when designing a performance indicator. A new taxonomy of solar performance metrics is provided. Metric definitions, suitability, and limitations are discussed. The findings highlight the need for reliable, low-complexity metrics and adequate methods for early solar assessments for urban planning.

Keywords: solar access; daylight access; passive solar; active solar; urban planning; taxonomy

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1. Introduction

Sustainable buildings should employ solar strategies to reduce the use of primary energy and to produce renewable energy on site. The European directive 210/31/EU on energy performance of buildings [1] requires all new buildings to be nearly zero-energy buildings (nZEB)—namely, exhibiting high energy performance with increased contribution in locally sourced renewable energy. Adequate solar access in urban environments supports energy-efficient strategies which are instrumental in achieving nZEB [2]. Sunlight affects key aspects of the building performance—heating, cooling, lighting, and on-site energy production. Balancing the benefits (reduced energy use for heating and lighting, electricity generation) with adverse effects of sunlight (urban heat island, increased need for cooling) is a difficult task for architects and urban planners [3].

Decisions made in the early stages of building life are most impactful [4]. Solar access is defined at the level of urban planning when street layouts and building masses are shaped. At this design stage, often called massing [5], the building form and spatial layout constitute the only design variables [6], since there is limited knowledge about more sophisticated building properties, while the climate and built context are given. Hence, the task of planning new neighbourhoods with high performance and quality objectives meets several challenges, among which appropriate assessment methods and informed selection of suitable metrics are imperative [7–10].

Several metrics and performance indicators exist to quantify, describe, and assess an urban design, but there is no consensus yet as to which metrics are the most appropriate in solar access evaluations and which could be used as performance indicators in the urban planning stages. Furthermore, the metrics and respective thresholds applied in legislation seem inconsistent [11]. In Europe, there is no standard dedicated to solar access in urban planning; the daylighting provisions included in the EN 17037 standard [12] are the closest yet to solar access stipulation, but they focus primarily on the conditions indoors, hence require more advanced design inputs, which are unknown at the urban planning stage. At this level, little is known about the floor layouts of buildings, thus the European daylighting standard appears inadequate for early design phases. Nault et al. [13] conducted the first comprehensive review of early design evaluation metrics and indicated that there is a need to further explore the potential of simple and computationally light metrics as performance indicators. Because of limited expertise and high computational load, solar design assessments are sporadically performed in the urban planning practice [14,15]. Thus, many researchers have advocated easy, efficient, and comprehensible evaluation metrics for the early planning stages; metrics that must prove adequate for the size of urban area and the limited level of detail with few established design parameters [13,16–18].

This paper presents an overview and a critical assessment of solar design metrics for urban planning applications. A new taxonomy of solar urban design metrics is proposed. It can assist practitioners and researchers in the selection of metrics for solar design assessments.

The goal of this review is to systemise the knowledge on how metrics can be constructed, formulated, and presented to effectively communicate design evaluation results. Metrics which are formulated in a systematic way and whose relation to the performance is validated might ultimately become performance indicators.

This review stands as a part of a larger research on solar access in neighbourhoods. International experts of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 63 "Solar Neighbourhood Planning" [10] collaborate with local urban planners in effort to find suitable solar design methods. The main goal of this review is to compile the state-of-the-art knowledge on metrics used in solar assessments of urban designs. The present paper focuses predominantly on metrics used in the northern latitudes, while the wider research targets the local Swedish context.

2. Method

A review of literature was conducted using an integrative narrative-based approach [19]. Scopus was the selected database for citation searches as it contains an extensive catalogue of indexed peer-reviewed publications and provides a broad coverage in relevant disciplines [20].

The search keywords and concepts used in citation searching are presented in Table 1. Each concept consists of synonymous keywords. Initially, a narrow search, aiming for low recall and high precision, was conducted to find the most relevant publications that could be used and to help further formulate a more complete search query. It included only the underlined keywords from concepts 1 and 2 from Table 1. Then, a refined search query was developed using relevant keywords and synonyms forming concepts 1–3, which were based on the reviewed citations retrieved by the initial search. The first listed word in each concept is the main keyword for that concept, and the rest are inclusive synonyms, which were added to the string with a Boolean operator 'OR'. The query excluded 'power plant' to cull articles related to large scale energy generation. The search was limited to peer-reviewed journal articles and returned the total of 135 documents of which 40% were deemed relevant. Papers focusing on the following areas were excluded: (i) systems and technologies; (ii) materials and/or building components; (iii) driven by country-specific regulations; (iv) aspects other than solar access and solar performance, for instance, socioeconomic issues.

The final collection of articles for the review included shortlisted publications from the conducted database searches supplemented by additional selection of relevant articles found through backwards and forwards citation searching. The starting point was the shortlisted article collection, and the citation library grew in a snowballing process. Furthermore, in order to place the review of metrics for urban solar assessments into a legislative context, examples of regulations for solar access in urban planning focussing on the Swedish context are also discussed in this paper. For this purpose, additional information available in grey literature and legislative documents was retrieved by direct searches via a web browser search engine.

Table 1. Concepts and keywords that were used in a citation search query string in Scopus. The first item of each concept (in bold) is the main keyword, followed by its synonyms and similar keywords. The underlined keywords were used in the initial database scoping.

	Concept 1	Concept 2	Concept 3
↑ OR ↓	**solar access**	**metric**	**neighbourhood**
	solar potential	indicator	urban
	solar performance	requirement	public
	solar availability	recommendation	building
	solar envelope	ordinance	city
	solar planning	legislation	cities
	solar design		district
← AND →			

Keywords in bold capture the main distinct concepts, of which the rest of the keywords are synonymous. Keywords that are underlined were used in initial scoping of a citation database.

3. Results

The first three subsections (Section 3.1. Use of metrics; Section 3.2. Formulation of metrics; Section 3.3. Taxonomy) consist of a general overview on the construction and types of metrics for design assessment purposes. The fourth subsection (Section 3.4) presents a more detailed report on the types of metrics used for assessing urban designs. Several metrics were further discussed to review their suitability, and validity.

3.1. Use of Metrics

Metrics can be classified in respect to their functions, presentation methods, and characteristics (Figure 1).

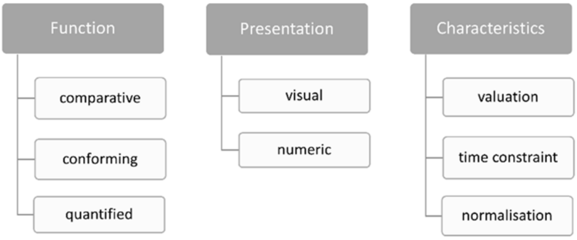


Figure 1. Identification of metric functions, presentation methods, and characteristics.

Metrics were found to fulfil one of three functions, which are here categorised as:

- Comparative;
- Conforming;
- Quantified.

The comparative function is used to evaluate multiple design proposals aiming to find the option with the best score of a selected metric. Comparative metrics can benefit from normalisation, as this enables fair numeric comparisons between different designs and projects. For instance, a radiation total can be divided over the usable building floor area to provide a normalised value and a comparative function.

The conforming function requires that a metric of a given design meets a certain threshold; for that, it is not only crucial to know which metrics can be used to assess a neighbourhood design, but also what benchmarks should be applied to reach certain solar performance criteria. Conforming function may be obtained by using performance benchmarks, which pertain to, e.g., the economic feasibility of a solution. An example of that can be a planned implementation of active solar systems on building surfaces. Surfaces that receive less radiation than a given feasibility threshold would be rejected. Such a metric would typically be expressed as area quantity or a fraction of the total area.

Lastly, the quantified function may be used when it is imperative to know the absolute value of simulated parameters, for example, the total roof irradiation for a photovoltaic (PV) system. For a quantified function, the metric might be given as a total incident radiation for a given analysed surface.

Furthermore, we identify two distinct ways of presentation that are frequently used to convey the results of metric-based analyses (Figure 1):

- Visual;
- Numeric.

In visual assessments, the results are typically communicated using some graphical aids. Examples could be printouts with spatial grid-based images containing model geometry with resulting metrics presented in a numeric form or as a coloured hatch. Such visualisations usually include a legend and a suitable colour scheme. The respective 3D model must be presented in a carefully chosen view; for instance, top view may be good for showing results on the ground surface, but a perspective view may be suitable to display facades. In the numeric method, the design receives one number for a given metric or indicator. Floor Area Ratio (FAR) is an example of a purely numeric indicator because it provides a single record for a given design variant, and the results cannot be presented spatially. The opposite example of a purely visual metric is the sun path diagram [21]. Yet, most metrics can be presented using either of these methods. The advantages of the visual assessment method include better spatial understanding of the solar access potential and the ability to spot critical areas that may need improvement. On the other hand, a numeric analysis can be advantageous as it is easier to apply design criteria thresholds and to compare different designs. However, potential numerical metrics for early design urban planning must prove to be valid predictors of solar access for the final design, which is currently not the case [13,22,23].

3.2. Formulation of Metrics

The characteristics of metrics identified in Figure 1 are further explored in this section (Figure 2). Metrics are characterised by the way in which they are valuated, which time constraint is considered in calculations, and which method of normalisation that is used, if any. The metric characteristics should thus be viewed as prescribed metric formulation principles. A non-exhaustive list of examples of the metric characteristics can be found in Figure 2. One or more characteristics can be relevant, e.g., valuation can be based on the mean value principle and also be given a criterion threshold.

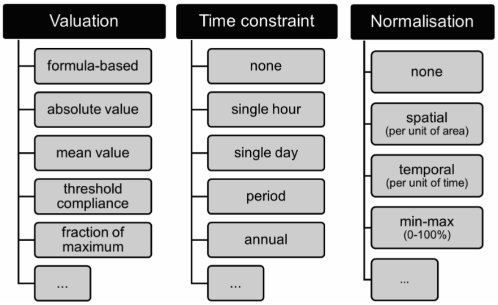
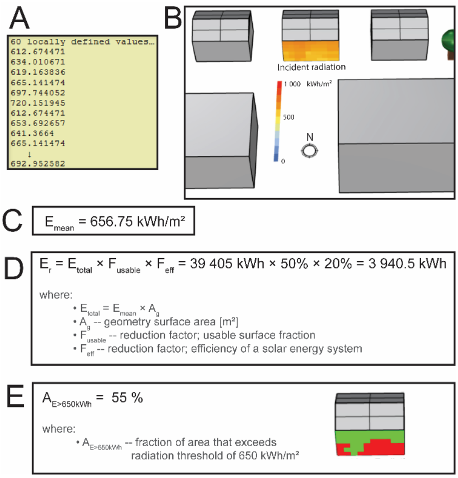


Figure 2. The three metric characteristics that should constitute the metric formulation principles, including commonly found examples.

A design metric is not just simply a result of steady-state calculations or time-based simulations; it is rather created based on the resulting data and by informed decisions, applying the aforementioned formulation principles that are shown in Figure 2. In that sense, there may be many metrics that convey the same information but in different ways.

For example, data received from an annual solar radiation simulation on building surfaces typically consists of a list of cumulative radiation values—one for each grid point—which is given in kWh per square meter surface area of the analysed geometry (Figure 3A), and which can be presented in a visual form (Figure 3B). The first choice concerns the time constraint, and sometimes it must be made even before the simulation begins. The simulation in this example (Figure 3) returned cumulative values for the entire simulation year, so the preselected time constraint was set to annual. However, the simulation could have been set to return cumulative values for only a selected period of time, or it could return a list of hourly irradiation values for every hour of the analysis period per each analysis grid point. The next choice is related to the post-processing of the data. In order to quantify surface irradiation with a metric, depending on the purpose of the analysis, i.e., what kind of information the metric is intended to convey, it may be desired to formulate the result as a mean value for the whole analysed geometry given in kWh/m^2 [24] as shown in Figure 3C; or as a total, using for instance a special formula with a variety of assigned design factors or reduction factors [25], as shown in Figure 3D. Formulas, such as the one in the example, may be used to compensate for a low level of detail in the model and to provide a more accurate result. As a matter of fact, a metric based on radiation simulations does not necessarily need to have an energy unit. For instance, performance thresholds can be applied to consider only the parts of a surface that receive the desired amount of radiation [26]. A numeric metric can thus be formulated as a percentage of the entire surface area that meets or exceeds an irradiation threshold cumulatively over one year, or visualised using the model, as seen in Figure 3E. In such a case, the metric valuation is based on threshold compliance, with min-max normalisation applied to the area, and the time constraint of the whole simulation year.



```
60 locally defined values…
612.674471
634.010671
619.163836
665.141474
697.744052
720.151945
612.674471
653.692657
641.3664
665.141474
    ↓
692.952582
```

$E_{mean} = 656.75\ \mathrm{kWh/m^2}$

$E_r = E_{total} \times F_{usable} \times F_{eff} = 39\,405\ \mathrm{kWh} \times 50\% \times 20\% = 3\,940.5\ \mathrm{kWh}$

where:
- $E_{total} = E_{mean} \times A_g$
- A_g -- geometry surface area [m²]
- F_{usable} -- reduction factor; usable surface fraction
- F_{eff} -- reduction factor; efficiency of a solar energy system

$A_{E>650kWh} = 55\ \%$

where:
- $A_{E>650kWh}$ -- fraction of area that exceeds radiation threshold of 650 kWh/m²

Figure 3. Example of creating different metrics from the same annual solar radiation simulation data. The model was drawn in Rhinoceros [27], and the simulation was performed with Ladybug 1.3.0 [28]. (**A**) list of values for every analysis grid point resulting from the annual solar radiation computation; (**B**) visual presentation of solar radiation metric; (**C**) radiation metric computed as an average; (**D**) radiation metric based on a formula; (**E**) normalised radiation metric based on threshold compliance.

Using the principles of metric formulation in a purposeful way can ensure effective communication of analysis results. Metrics must have the ability to capture the quality and performance potential of a design, but they also have a certain design assessment function: comparative, conforming, or quantifying. The way a metric is constructed, using the formulation principles of valuation, time constraint, and normalisation, must match the intended communicative function of the metric. For example, average values and spatial normalisation methods enable straightforward comparisons between different designs and projects, whereas the metric valuation and normalisation method presented in Figure 3E is appropriate for the conforming function. The quantifying function, on the other hand, is often used as a purely technical outcome that may help to calculate system performance, but it does not directly communicate design quality. The selection of time constraint usually concerns the kind of design consequence the metric is supposed to communicate. For example, a common strategy is to use a reference day or a period that can help assess the yearly extremes, e.g., solstices. Annual metrics are usually adopted to provide an overall view on the solar performance using a typical meteorological year [29].

3.3. Taxonomy

When an evaluation metric is acknowledged and validated in terms of its good correlation to the performance, it becomes a performance indicator. Some metrics may be used to merely characterise a design, for example, FAR which communicates built density of a design. However, the metric must prove that it corelates well with the performance goal (for example, high façade irradiation) to become a performance indicator. Usually, it is the higher complexity metrics, such as a climate-based heating demand, which are used as performance indicators. The simpler metrics lack validation to be recognised as performance indicators because their use comes with higher risk of uncertainty and inaccuracy [13]. Studies about energy systems in district applications tend to use key performance indicators (KPIs) to evaluate and select best system proposals [30,31]. In a study of open spaces in cities, the mean ground sky view factor (SVF) was applied as an environmental performance indicator [32]. Another study looked at implications of urban density and used façade area with sky exposure factor between 20% and 40% as a performance indicator which was normalised by gross floor area [33]. Chen and Norford [6] used five performance indicators, including solar, ventilation, and connectivity potential. All five performance indicators were normalised by the gross floor area of the massing designs. Another optimisation study considering energy and daylight performance of neighbourhood typologies used load match index and spatial daylight autonomy as performance indicators and applied respective benchmarks in design evaluations [34]. Previous applications show that metrics used as performance indicators are typically formulated using a normalisation technique and valuated based on performance thresholds.

Building on a previous review by Nault et al. [13] and considering the complexity of data inputs, four main classes of metrics are identified:

- Geometrical (G);
- Latitudinal (L);
- External climatic (EC);
- Internal climatic (IC).

From the conducted literature review on metrics used in urban planning assessments and critical analysis thereof, the most common solar performance metrics were identified and grouped into metric categories. The results are presented in Table 2.

Table 2. Taxonomy of metrics in solar urban design. Metrics were divided in classes: G, L, EC, and IC. Each class consists of metric groups (underlined) and includes a few commonly used metrics that are further discussed in this paper. Other metrics exist but are used less frequently.

Geometrical (G)	Latitudinal (L)	External Climatic (EC)	Internal Climatic (IC)
Morphological ratio - FAR (floor area ratio) - VAR (volume area ratio) - S/V ratio (surface to volume ratio) - H/W ratio (height to width ratio) - OSR (open space ratio)	Direct sunlight hours - APS (area of permanent shadow) - Two-hour area - Sunlight exposure	Weather-data-based - APSH (annual probable sunlight hours) - UHI (urban heat intensity)	Energy use * Daylighting * Thermal comfort * Visual comfort *
View of the sky dome - SVF (sky view factor) - VSC (vertical sky component) - DF (daylight factor)	Sun path diagram - Shading mask	Solar irradiation	

COMPLEXITY OF DATA INPUT →

* These metric groups do not fit in the context of this review thus were not discussed here.

Groups of metrics were developed based on metric input information such as the simulation type and other parametrical similarities of the metrics, whereas the classes distinction (i.e., the four main metric categories) was based on the overall complexity of the site and climate input information. Site and climate inputs indicate information such as building geometry details, location, sun path, annual solar radiation, and other specific climate-related factors. Each higher metric class builds on information input of the previous class; thus, the complexity increases.

Typically, the level of detail of the modelled geometry would have to increase for the higher complexity metric classes, but there are exceptions. For example, daylight factor (DF) is a relatively simple G metric that does not need climate nor location information; however, it requires high level of detail in modelling of the façade and window elements, and of the interior spaces, including the information about surface reflectance [35]. Conversely, energy use can be simulated for a very basic geometry model, as many inputs are typically simplified anyway [36]. In this case, the geometry level of detail does not need to be sophisticated, but there is an added input complexity in the additional operational information that is required, including operational schedules and internal loads.

3.4. Description and Critical Analysis of Selected Metrics

In this section, selected metrics of the four classes (see Table 1), which were frequently used in research according to the conducted literature review, are presented and discussed.

3.4.1. Geometrical Metrics

G metrics are calculated using information about the urban and site layout and form, without any location-specific information such as latitude or climate. They are sun-less, meaning they do not account for insolation, radiation, or local sunpath; hence, they have been used for a variety of urban design purposes and not only for solar access analysis. G metrics are, furthermore, isotropic, which means that for a given design they will remain the same regardless of orientation and geographical location. Consequently, the time constraint attribute does not apply to these metrics.

Some G metrics, such as VSC, SVF, or DF, have been grouped as 'View of the sky dome' metrics (see Table 2) because their calculations are based on the spatial relation of the geometry to the open sky, and for that, they use a digital model of a standardised sky dome. The sky dome is divided into several sky patches, the number of which depends on the selected sky density. The commonly used sky subdivisions are the low resolution Tregenza sky [37] and higher resolution divisions based on the continuous sky concept [35] including the Reinhart model [38]. The division of the sky dome enables time-efficient simulations. VSC and DF metrics use the standard CIE overcast sky [39]. The luminance distribution of the standard CIE overcast sky model is such that the zenith sky patch gives three times the illuminance level at the horizon [40]; this sky represents the worst-case scenario, and it is hardly found in reality. The SVF metric uses a special weighing function for sky patches instead of the overcast sky model and assigns more weight to sky patches closer to the zenith, according to the projection of the sky view onto a plane [41]. The weights of the sky patches for SVF calculations are isotropic but change with altitude.

The European daylighting standard (EN 17037) states three-fold compliance criteria for levels of view out quality, one of which is associated with morphological spacing and massing, namely the outside distance of view [12]. In a dense urban setting, neighbouring buildings might restrict the view distance from a window. The standard recommends three view distance thresholds: 6 m for minimum, 20 m for maximum, and 50 m for high view out level. This morphological constraint can be applied in the urban planning stages, and although it is not strictly a metric, it can be viewed as an important geometrical restriction that should be considered early in the design. The remaining two criteria, however, come at later stages of the design process, as they refer to the layers of the view and the view width which are inherently reliant on the exact window placement and room layout.

- FAR

Floor Area Ratio (FAR), illustrated in Figure 4a, is a G metric expressing compactness or urban density as a ratio of gross floor area of buildings to their site area [42]. It has also been called floor space index [43] or plot ratio [44]. It has been widely used as a measure of density in various urban studies [26,33,34,45–47]. Figure 4b displays some possible variations in building shape and height for two example values of FAR.

Many studies investigated FAR performance correlations. The relationship of FAR to daylight penetration in neighbourhoods was found to be strongly negative in respect to vertical daylight factor, also known as vertical sky component (VSC) [48]. Due to possible variations in site coverage and building heights and forms, the same FAR of multiples designs received different level of solar availability, varying up to 30% [49], which may indicate that FAR is not a good standalone metric to be used as a performance indicator. There is, however, an indication of strong correlation between FAR and solar potential [24]. FAR has also been widely used in studies about microclimate [50–52]. It has been seen to correlate well with food self-sufficiency measures in cities [44]. In urban planning practice, there are some cities that use FAR as a control variable to regulate maximum density and prevent congestion [53,54]. The relevance of FAR in performance assessments has been acknowledged in research, which implies a good potential for future application, possibly in conjunction with other metrics.

- VAR

Volume Area Ratio (VAR) is a morphological G metric that is very similar to FAR. It is a ratio of the volume of buildings to the site area (Figure 4a). The VAR metric has also been known as a built urban density measure [16,55,56]. Studies showed that VAR has good association with indoor daylight availability [56], and that it correlates with irradiation levels on facades [55]. Morganti et al. demonstrated that VAR correlated with solar performance, understood as cloudless annual irradiation of facades, with level of $R^2 = 0.53$ [43]. There is an indication that the VAR metric has a promising potential as an early-stage design indicator in urban assessments [24]. Its function as a control value or density recommendation is still debatable, because if we assume a fixed VAR but modify other morphological parameters (i.e., shape), a better solar performance can be achieved [55]. Its potential use in conjunction with other metrics should be further investigated.

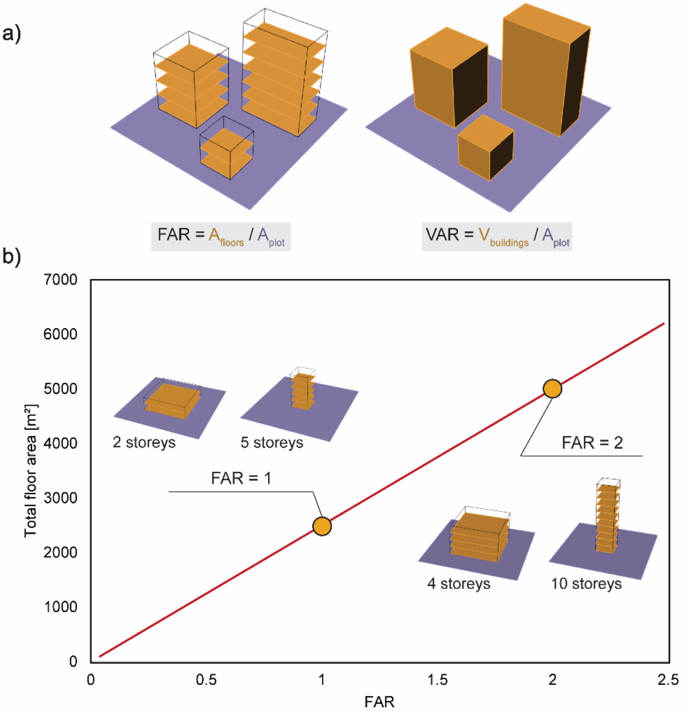


Figure 4. (**a**) Visualization of two twin morphological metrics, FAR and VAR, and their calculation methods. (**b**) Relationship between FAR and total floor area for an assumed plot size 50 × 50 m^2. The graph contains examples of single building forms that can be created on the plot to abide by FAR equal to 1 and 2.

- S/V ratio

Surface-to volume (S/V) ratio has been used in research as a measure of building compactness [57–59]. It may also be called building aspect ratio [43]. The metric was originally introduced as an inverse (V/S) [60]. Example values of the metric can be found in Figure 5. For high compactness levels, smaller values of the metric are desired, while large values express low compactness. The S/V ratio metric showed low correlation with PV-generated electricity from building envelope and with energy use [18]. A common implication of the S/V ratio metric for the building design performance is the reduced heat loss from the building envelope the higher the compactness. However, the S/V ratio is never used as a lone performance indicator, because if the sole design objective would be to maximise compactness, then a significant loss of daylight and sunlight indoors would occur [59]. It can be seen in Figure 5 that bigger volumes with larger edge dimensions yield lower S/V values, i.e., higher compactness, as the centre of gravity of the forms moves further away from their external boundaries.

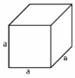
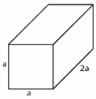
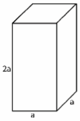
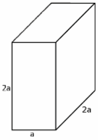
				
Dimension *a*	S/V ratio			
10	0.6	0.5	0.5	0.4
15	0.4	0.33	0.33	0.27
20	0.3	0.25	0.25	0.2

Figure 5. Exemplary values of surface to volume (S/V) ratio for different building shapes and sizes.

Ratti et al. [59] advocated the use of a passive to non-passive zone ratio instead of the S/V ratio, where a passive zone is the floor area immediately next to the external building perimeter, equal (in buffer thickness) to twice the ceiling height; and the non-passive zone is the remaining inner floor area of the building. A passive zone is assumed to have a possibility to be passively daylit and ventilated, making it more energy efficient. The proposed zone ratio remains in conflict with the compactness advantage as understood by the S/V ratio metric.

As demonstrated, building compactness in terms of S/V ratio may not be effective in urban planning studies. Instead, what might be interesting, especially in terms of solar access optimisation, could be to look at the relation between the exposed surface area and site area, following the concept of FAR and VAR metrics. Chiatzipoulka et al. [55] used a metric called 'complexity', which expressed the ratio of total façade surface area to the gross site area. It was shown to have a negative impact on solar availability. However, it should be noted that the metric representing solar availability lacked normalisation per used floor area, and because of that, the effect might have been inflated. Suitable morphological metrics involving external surface area should be further explored as they can potentially bring valuable of information to the early-stage urban design assessments.

- H/W ratio

Building height to open space width (H/W) ratio [46,61] or its inverse [57] have been used in studies of urban form, particularly of urban canyon, and its influence on energy consumption and/or solar potential. It can also be called aspect ratio, for instance, when it refers to courtyard spaces [62]. It is a widely used metric in courtyard microclimate studies [63–65]. Notably, the studies focussing on microclimate advocate for higher H/W [65], whereas those that looked at façade solar potential support lower values for increased solar access [46]. Evidently, there is a conflict between the two objectives. The H/W metric has been also linked with indoor daylighting; DeKay [54] demonstrated a relationship between the H/W metric and DF which suggested that the H/W ratio of 0.6 can lead to a mean DF of 3%, and H/W = 1.5 gives a DF average of 1%. However, the findings were limited to urban canyon design typologies and certain test room dimensions. While the H/W metric is easily applied in studies of courtyard and street canyons, it has lower applicability in studies of hybrid and more complex urban districts. It is because the metric is only two-dimensional and assumes that the buildings are of the same height. It may be sufficient for analysis of a single building, but it falls short in application in larger neighbourhoods.

- OSR

Open Space Ratio (OSR) is a G metric that expresses a ratio of site open space area (excluding footprints) to gross floor area [66]. OSR has been seen in urban morphology research investigating the impact of urban typology on solar potential [67], energy use [26], and microclimate [50]. This metric could be a relevant substitute for H/W ratio metric in urban studies of larger areas, as it combines the ratio of outside area and building morphology, and is three-dimensional. It has also an added meaning; in residential neighbourhood analysis, it communicates how much of outdoor public space is available for residents and occupants per unit of indoor floor area.

- SVF

Sky View Factor (SVF) measures, at a given point on a horizontal surface, the 'fraction of the overlying hemisphere occupied by sky' [68]. An open flat field has a SVF equal to 100%. SVF can be obtained using simulation software where the hemisphere or the sky dome is usually divided into a number of sky patches. There are a few methods of calculating the SVF, assuming different weights of the sky patches [41,69]. A common method is the cosine-weighted SVF definition [33], in which the sky patches closer to the zenith have more weight than those closer to the horizon.

Studies have indicated relevance of SVF in urban design evaluations. A correlation of $R^2 = 0.79$ to solar availability on facades was demonstrated in a study which simulated solar radiation assuming cloudless annual conditions [43]. Findings from another study concurred that SVF correlates well with solar irradiation of facades, especially considering only the diffuse solar radiation component that showed a nearly perfectly linear correlation to SVF [16]. Furthermore, SVF has shown to have a significant effect on urban microclimate and has been closely associated with urban heat intensity (UHI) [70–72]. In fact, the SVF metric originated from urban climatology studies [68]. The connection of SVF to daylight, sunlight, and microclimate is evident, which suggests that it has a high potential for urban planning applications. For the metric to become a reliable indicator of urban design performance, further investigation into SVF and suitable benchmarks is necessary.

- VSC

Vertical Sky Component (VSC) is a simple G metric that is calculated for a vertical façade surface and is used to predict the daylight penetration indoors, without having to introduce information about the interior layout and properties. It is calculated at a single point on a façade as a ratio of illuminance that arrives at the given point to the total illuminance received by an unobstructed horizontal surface, assuming the CIE overcast sky conditions and no reflections [73].

Good correlation between VSC and DF has been demonstrated [74]. VSC is given as a predictor of daylight in Building Research Establishment (BRE) daylighting guide [73]. Bournas [56] studied VSC among some geometric attributes that may affect indoor daylighting scores and found that VSC had a significant effect on compliance to the reviewed daylighting criteria. The correlation between VSC and DF is perhaps unsurprising since both metrics are in fact geometry-based; they both use the CIE overcast sky model, except that VSC measure stops at the façade level and thus does not account for window properties and internal layout. Due to the lack of model complexity required, VSC could be a prospective choice for early design assessments with focus on daylighting.

- DF

Daylight factor (DF) is a measure that expresses a ratio of illuminance at a point located on a horizontal plane indoors to the total illuminance of an unobstructed horizontal plane located outside, assuming the CIE overcast sky [75]. When it forms a metric, it is often presented as an average DF per room, or as a point value for a standardised control point location within a room [76]. Both metrics (average DF and point DF) require knowledge about window placement on facades, window properties (e.g., transmittance), internal layout (room boundaries), and surface reflectances. Although site and climate inputs for the DF metric calculation are relatively simple, the complexity of aforementioned input information, which is typically unknown in the urban planning stages, implies that the metric might not be suitable for early design assessments. A relevant substitute metric for the early-stage assessments might be the VSC metric, as it was seen to correlate well with DF [56,74].

3.4.2. Latitudinal Metrics

L metrics are created from the information about the site geometry and the position of the sun in the sky due to the latitude location, and thus, they typically reflect the solar access aspects of a design. Building orientation matters for L metrics, and it is imperative for passive solar design [77]. The metrics remain relatively simple, as clouds and radiation are neglected. The calculation is based on the spatial relation between urban geometry and solar vectors, which represent the direction of the solar rays when the sun is up, assuming a theoretical cloudless sky condition. The analysis checks if selected sun vectors are intercepted by an obstruction before they reach a given point in the analysed geometry grid. Solar vectors are calculated based on a geographical reference. The conditions governing sun positions and sun vectors are perpetual; this type of information is not subject to temporal modifications or external influence, e.g., climate change.

Calculating solar access in a 3D modelling space has multiple analysis purposes. The simulation of direct sunlight hours group of L metrics can be used to determine building masses with the solar envelope method [78,79]. It has been used in estimation of solar energy potential [80]. Architects often use point-in-time shadow plots to visually assess shadowing and solar access of an urban area [4].

The time constraint of L metrics is usually either a certain period or a selected reference date. According to the BRE guide, the so-called 'shadow plots', which can result from L metric calculations, should be performed for 21 March—spring equinox [73]. Equinoxes are special in a way that the daytime duration is the same everywhere on Earth (12 h), which makes this reference date suitable for design comparisons across the globe. Equinoxes also give an averaged solar access information for a given location, as the date falls exactly in between the two winter and summer extremes: the solstices. However, 8 February, 21 February, and 21 December have also been used as standard reference dates in previous research [81]. Some of these dates also appear in many of the present solar access regulations [11].

- Shading mask

Shading mask is a visual type of metric that is presented on a stereographic projection of a sky dome and the local sunpath—commonly known as the sunpath diagram [82]. Shading mask is drawn for a single point looking upward. The sky dome projection is shaded by surrounding obstructions, which are projected onto the image in a fisheye perspective. Thus, shading masks have also been known as fisheye catchments [83]. They can be either generated using a computer 3D model or captured directly on site. The sunpath lines that are covered by obstructions in a shading mask image represent the times in a year when solar access to the analysis point is restricted. This method is commonly used to display shading of a single point located on the ground or on the façade [12,21].

The shading mask metric is advantageous in being able to display shading over the entire year, but the downside is that it is carried out only for a single point. Multiple shading masks for different points on an analysis surface can be combined into a single multishading mask [84,85], which provides the benefit of assessing shading of the whole area in the whole year. It indicates which times of the year the space can be overlit or overshaded and is computed by superimposing shading masks taken from many points on the analysis grid.

Stereographic sunpath projections have also been used as sunlight availability protractors [82,86]. They display probabilities of sunshine marked on the sunpath as average sunlight duration. However, because the metric provides probability of sun shining at certain times in a year, it involves climate-dependent data and therefore, should be considered an EC metric.

- APS

Area of Permanent Shadow (APS) is a metric that was first introduced in an older version of the BRE guide: 'Site layout planning for daylight and sunlight: a guide to good practice' [87]. The recommendation stated the following 'It is suggested that, for it to appear adequately sunlit throughout the year, no more than two-fifths and preferably no more than a quarter of any garden or amenity area should be prevented by buildings from receiving any sun at all on 21 March'. Naturally, the term 'permanent' refers to areas that are completely shaded during the entire winter season (from equinox to equinox). It proved problematic in application because points which receive only minutes of sunlight can still comply, yet are not sufficiently sunlit. Therefore, the recommendation was removed from the following and latest version of the guide, and instead of APS, BRE now suggests using a threshold of two hours of direct sunlight on ground (see 'Two-hour area').

An example analysis of the APS metric in an enclosed square courtyard ground surface (Figure 5) reveals an intrinsic relationship: for a given building geometry, the value assumed by the metric is different depending on the orientation of the courtyard building, and follows an exponential function shown in Figure 6, as $\text{APS}_{45^\circ} = (\text{APS}_{0^\circ})^2$. It occurs because solar access to a courtyard, which is here expressed by APS area, is dictated by the highest position of the sun on the reference day, i.e., solar altitude at noon. Concurrently, it was found that the orientation of the same courtyard geometry does not affect cumulative solar radiation received by the facades of the courtyard. It is, therefore, indeed questionable whether the metric is adequate for quantifying solar access. Moreover, the metric has not been found in scientific literature.

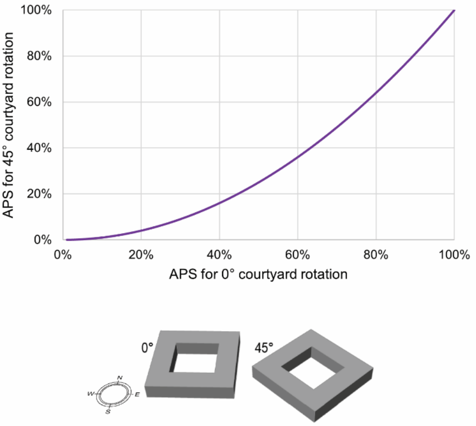


Figure 6. The graph presents a universal relationship between the values of the area of permanent shadow (APS) metric depending on the orientation of a square closed building courtyard. The 0° orientation has facades facing the cardinal directions.

- Two-hour area (ground)

The latest edition of the BRE guide 'Site layout planning for daylight and sunlight: a guide to good practice' recommends that 'at least half of a garden or amenity area should receive at least two hours of sunlight on 21 March' [73]. The metric is based on threshold compliance, and the results are normalised by min-max fraction of the analysis area that complies. BRE advise to draw a two-hour sun contour on the analysed surface for further visual examination. The metric is based on a single reference day, the spring equinox, which consists of twelve sun vectors in an hourly-based computer simulation. The metric has not been found in scientific literature. In general, little attention has been paid so far to the evaluation of cloudless direct sunlight access on ground surfaces.

- Sunlight exposure (façade)

Façade sunlight exposure quantifies the connectedness of building apertures to the sunpath, and when formulated into a metric, it may, for example, express information about the proportion of the façade area that receives certain duration of cloudless direct sunlight on an approved reference day. Such a measure is used in the Swedish and European daylighting standard SS EN 17037 [12] under the recommendation for exposure to sunlight in dwellings. The stipulation reads that at least one habitable room in a dwelling should receive a minimum of 1.5 h of direct sunlight (assuming cloudless sky) on any one date between 1 February and 21 March. It suggests that the European authorities issuing the directive considered sunlight important for ensuring pleasant indoor quality of dwellings.

Indeed, there are multiple benefits of sunlight, including positive impact on health [88], wellbeing [89,90], and hygiene [91]. Residents have indicated therapeutic benefits of sunlight as the most liked effects of sunlight [92].

There are also adverse effects of sunlight to consider, namely glare and overheating [93]. Negative effects of sunlight indoors can be accounted for by the metric called Annual Sunlight Exposure [94], which expresses a percentage of analysed indoor area that receives over 1000 lux for more than 250 h in a simulation year. However, ASE is rather an IC metric as it involves full climate-based annual simulations and requires internal modelling and thus is less suitable for urban planning purposes (see Section 3.4.4).

3.4.3. External Climatic Metrics

Adding on to the information about the geometry and location, EC metrics also use information provided in a local weather data file. It is typically carried out in a simple and selective way, hence their distinction from more advanced IC metrics that often use multiple weather parameters at a time. EC metrics are also limited to external assessment of surfaces and conditions, whereas the IC metrics describe the performance from a more complex indoor perspective. EC metrics assume simplified weather data, boiling it down to a model or to an equation, whereas IC metrics use a time-based (typically hourly) simulation. Thus, the computations of IC metrics are much more sophisticated and require late design variables, such as system schedules or material properties. Furthermore, weather parameters used for EC metrics can be translated into simple climate models, e.g., a cumulative radiance sky model, where every patch of the sky dome is assigned a cumulative radiance value from a given period of time [95]. Weather parameters can be also used in a static formula, like in the calculation of maximum urban heat island (UHI) temperatures [96].

- APSH

Annual Probable Sunlight Hours (APSH) is a metric used to evaluate the sunlight availability of a façade surface at a single point. It was used in the BRE guide [73] and the British code of practice [97]. APSH checks for availability of sunlight considering the average cloudiness of the local climate. The 1999 BRE guide [98] introduced a graphical method of calculating the APSH involving the use of sunlight availability indicators. An indicator was marked with 100 points, each representing 1% of annual probable sun. The sunshine duration values could be obtained from a reference book [99]. Calculation and graphical interpretation methods were introduced. The number of unobstructed dots on the sunlight indicator make up the percentage score for the APSH metric. The method of calculating and plotting the sunlight availability indicator was originally manual; however, an automated APSH calculation method has been developed as a plugin for SketchUp [100]. The British code [97] recommends that a window surface receives at least a quarter of all APSH, and that at least 5% fall on the geometry during the winter months (21/9–21/3).

- UHI

Urban heat intensity (UHI) is a metric that pertains to the unwanted effect of abundant sunlight access and overheating of urban spaces (known as the urban heat island effect). The UHI equation (Equation (1)) derived by Theeuwes et al. [96] calculates the severity of temperature increase in an urban space in relation to the rural area with a zero-level increase using (i) view of the sky dome G-metric—SVF, (ii) vegetation coverage of the area—veg, (iii) selected weather parameters—M_{rural}. The meteorological rural weather variable (M_{rural}) is calculated using parameters from a simulation weather data file: wind velocity, solar radiation, and air temperature.

$$UHI_{max} = M_{rural} \times (2 - SVF - veg) \tag{1}$$

In the UHI equation, only SVF and vegetation coverage can be modified by means of design, as site-specific climate cannot be altered. SVF accounts for the ability of an area to undergo radiative cooling, and it can only really be manipulated in the planning (massing) stages of new developments. Vegetation coverage is equally important in heat dissipation of urban spaces because of the cooling benefit in transpiration of foliage. Unlike SVF, vegetation fraction of an area can be increased at a later stage of development, for instance by dedicating more urban spaces to greenery or by turning regular roof finishes into green roofs.

Urban microclimate is affected by urban heat island effect, which can be exacerbated by urban morphology. Microclimate analysis using simulations can be complicated and time-consuming. The UHI metric enables a quick and simple method to assess overheating issues in an urban area and to perform initial design assessments.

- Solar irradiation

Irradiance appears to be the most common type of information used to quantify solar access in built environments. It has been widely used in solar potential research [25,83,101–103] and in validations of other simpler metrics [16,24,45,55]. It is a reliable measure of solar potential because it connects to real time-based climate; yet it does not require complex simulations nor is it computationally intensive. The computation ceases at the external surface layer of the built environment, therefore in the taxonomy (Table 2), irradiation-based metrics fall under the EC metric class.

Irradiance is a measure of solar radiation flux coming directly from the sun beams and indirectly as diffused light on the sky dome. It is implemented in solar radiation simulations using solar information from a weather data file. When a surface is exposed to irradiance over a period of time, then the geometry receives certain amount of irradiation. Prior to simulations of surface irradiation, a computer-based sky model must be generated. It contains either hourly or cumulative period-based values of irradiance (W/m^2) or radiation (J/m^2), which are then used to compute the solar radiation amount that reaches a given analysis point in a 3D model. Cumulative radiative sky models contain for each of the sky dome points (sky patches) an aggregate solar radiation energy value for the entire analysis period. The use of such models in simulations can save computational power and reduce simulation time. Furthermore, it is imperative to set a desired level of computational accuracy for modelling and for radiance simulations. It is done by adjusting various simulation settings such as sky model division, number of ambient bounces, or surface grid resolution. Normally, the models are created from climate data which includes realistic values with a mix of sunny, intermediate, and cloudy skies. However, it is possible to assume artificial sky conditions such as the cloudless sky [43]. Though, a metric based on such initial conditions would be closer in principle to the G- or L-metric class.

Metrics formulated from solar radiation simulations have a good suitability and usability in evaluations driven by solar design objectives, as irradiation is directly linked to solar performance aspects. This is especially true in the case of estimating solar energy potential for on-site electricity generation [104,105]. For this purpose, performance thresholds are often used, which have to do with financial feasibility aspects of solar installations. Commonly used target values for annual irradiation are 600 kWh/m^2 [16,106] or 800 kWh/m^2 [13,17,24] for facades, and 1000 kWh/m^2 [17,24,34,107] for roofs. The benchmark values tend to be lower for solar thermal applications [13,17]. Furthermore, reduction factors can be applied to account for window-to-wall ratio or fenestration design (e.g., balconies) when precise information about surface elements is unknown or insufficient [25].

Surface irradiation results can be presented directly in a visual form, but to form a numeric metric, the results must be transformed using the aforementioned formulation principles: normalisation, time constraint, and valuation. There are infinite ways of presenting and formulating the results depending on the purpose, which can be for instance: passive solar heating [24,108], active solar systems [109–111], urban heat island [112], or food and energy self-sufficiency [44]. The previous example in Figure 3 illustrates some possible ways of constructing an irradiance-based metric. The challenge of the analyst lies in the selection of suitable formulation characteristics to generate the metric which should communicate the simulation results adequately to the design evaluation aims. Spatial normalisation is a common strategic choice in irradiance-based metric formulation [3,6,26]. It has the advantage of making the metric comparable across different designs and projects. Additionally, normalising the irradiance by the living space floor area gives a metric a better communicative power, with the potential of expressing self-sufficiency.

3.4.4. Internal Climatic Metrics

IC metrics often serve as performance indicators as they pertain directly to the quantifiable design objectives or criteria used in energy, daylighting, and comfort assessments. There is certainly a direct link between the performance and the IC simulated metrics due to their level of simulation complexity and realism of expression. However, they may not be suitable for early design stages as they require much more sophisticated inputs than the simpler metrics presented in this paper [13]. The latter do not require the design to reach a high level of external and internal modelling detail, and instead stop at the exterior level of buildings.

IC metrics are computationally demanding; therefore, they often come into design considerations late in the development process. Moreover, they require the input of internal layouts and other scheduled or non-scheduled inputs that have a great impact on the IC metrics but are not yet established during the massing stages, whereas the context-dependent solar access is. It is usually after the massing stages are concluded and the context geometries are established that the internal layouts undergo further planning.

4. Discussion

This review proposed a taxonomy with four classes of solar performance metrics in urban planning. Amongst those, the internal climatic (IC) metrics may not be suited for urban planning stages despite their accuracy in performance assessments. As an example, we can look at the Swedish Planning and Building Act [113], which regulates the detailed development plan (DDP). Swedish municipalities are responsible for producing such a DDP, which contains initial massing of future developments and is setting spatial constraints for urban areas. In the plan, a municipality must determine the extent and function of public spaces and of planned neighbourhoods (including building footprints and roof shapes). They may also state the planned proportion and size of the apartments. To ensure good solar access in the massing stages within the scope of a DDP, decisions should be informed and driven by solar performance assessments. The DDP, however, does not provide enough internal geometry information and other building properties needed for complex performance assessments using IC metrics; yet, the DDP may provide sufficient geometry constraints to calculate the less complex metrics pertaining to the solar access of the neighbourhood areas, allowing to make early urban planning inferences. The present review showed that for that purpose, the lower complexity metrics appear to be more appropriate.

Such metric(s) are not yet available, although efforts are being made. For instance, a new aperture-based daylight modelling approach was recently proposed [114]. Instead of assessing metrics calculated for internal building grid, the method looks at the size of building apertures. This simple geometrical information provides an understanding of the connection between the building interior and the view out (sky, ground, and obstructions), linking the G metrics to the IC ones. While the approach is of great interest, its validation is still missing.

Urban planners have a limited expertise in solar evaluations and lack relevant methods, tools, and indicators [14,22]; thus, they urgently need reliable, yet simple methods that can be integrated into their planning routines. Urban planners have also shown a preference for visual methods of metrics presentation and expressed the need for simple evaluation techniques that would yield fast and accurate results.

However, it is important to mark that there is no clear indication of adaptable metrics which could be applied consistently in assessments of different neighbourhood typologies. For example, there is an important distinction between neighbourhoods comprising of low-rise and/or high-rise buildings. Many types of neighbourhoods are potentially possible [115], and different geometric variations may yield deviating results. The scope of this paper, however, is not limited to a specific neighbourhood type, size, or density; the presented solar metrics can be applied to any kind of urban design. Nonetheless, this review advocates further validation of solar performance metrics using multiple design patterns. Previous studies have typically used one of two methods to evaluate performance metrics with respect to different densities and urban typologies: assuming artificial design cases [26,49,67], or using real case studies [6,24,55].

This review showed that efforts had been made to establish simple solar metrics as urban planning phase performance indicators; however, consistent methods and prescribed indicators for solar performance evaluations at the urban planning level are still lacking. Despite promising correlations to complex IC metrics, simple metric benchmarks have not yet been defined. It is also not clear how the simpler metrics correlate with each other. Future research should focus on this knowledge gap and aim at expanding the understanding of suitable solar metrics as well as demonstrating their application methods in solar evaluations of urban designs. This knowledge will further assist urban planners in their efforts and might also promote regulatory consensus in solar access legislation.

5. Conclusions

In this paper, a review of metrics used in solar performance assessments in the urban planning and early design stages was presented. Aiming to systematise the knowledge on metrics, we identified and discussed:

- The main assessment functions of metrics (comparative, conforming, and quantified);
- The metric formulation principles (valuation, time constraint, and normalisation);
- The presentation methods (visual and numeric) with examples;
- The metric taxonomy, containing classes (G, L, EC, and IC) and groups of metrics;
- Popular metrics used for solar urban planning assessment purposes.

The information provided here can be further used by practitioners and researchers alike as the review offers guidelines on the use of metrics in design evaluations. It was indicated that using the principles of metric formulation in a purposeful and appropriate way can ensure effective communication of analysis results.

Systematically formulated metrics, which have been validated in relation to performance, may be used with confidence as KPIs. The review showed that performance indicators are typically formulated using a normalisation technique and valuated based on performance thresholds. Potentially, multiple metrics might be aggregated to form a single performance index using bespoke weighing factors. However, such methodology should be applied cautiously as reducing the data to one index hides important information, which can weaken comprehension. To increase reliability of metric-based assessment methods, potential metrics must be validated and further studied. Indeed, there is a need to find ways of incorporating simple numeric metrics as well as visual display methods into early design assessments.

Future work should aim to fill this gap in order to increase the confidence in the use of metrics for design evaluations. It is imperative to unveil the relationship between various complexity metrics and to analyse the feasibility and consequences of using the lower complexity metrics for decision making purposes in the urban planning stages. Building on the present research, future work should aim to (a) evaluate solar metrics for neighbourhood assessments to increase understanding about their role and correlations; (b) establish metric thresholds and solar performance criteria; (c) establish workflows and assessment method for solar access evaluations in early planning stages.

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References

1. European Union. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings*; European Union: Brussels, Belgium, 2010.
2. Bucking, S.; Zmeureanu, R.; Athienitis, A. A methodology for identifying the influence of design variations on building energy performance. *J. Build. Perform. Simul.* **2013**, *7*, 411–426. [CrossRef]
3. Kanters, J.; Wall, M. The impact of urban design decisions on net zero energy solar buildings in Sweden. *Urban Plan. Transp. Res.* **2014**, *2*, 312–332. [CrossRef]
4. Lechner, N. *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*, 4th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2015.
5. Building and Construction Authority. *Building Planning and Massing*; The Centre for Sustainable Buildings and Construction, Building and Construction Authority: Singapore, 2010.
6. Chen, K.W.; Norford, L. Evaluating Urban Forms for Comparison Studies in the Massing Design Stage. *Sustainability* **2017**, *9*, 987. [CrossRef]
7. Delsante, I. Urban environment quality assessment using a methodology and set of indicators for medium-density neighbourhoods: A comparative case study of Lodi and Genoa. *Ambiente Construído* **2016**, *16*, 7–22. [CrossRef]
8. Garau, C.; Pavan, V.M. Evaluating Urban Quality: Indicators and Assessment Tools for Smart Sustainable Cities. *Sustainability* **2018**, *10*, 575. [CrossRef]
9. IEA SHC Task 51. *Solar Energy in Urban Planning. Approaches, Methods and Tools for Solar Energy in Urban Planning*; IEA SHC Task 51: Karachi, Pakistan, 2018. [CrossRef]
10. Wall, M.; Hachem-Vermette, C.; Vettorato, D.; Croce, S.; Kanters, J.; Florio, P. SHC Task 63: Solar Neighbourhood Planning, Annex Plan. Available online: https://task63.iea-shc.org/supporting-documents (accessed on 13 December 2021).
11. De Luca, F.; Dogan, T. A novel solar envelope method based on solar ordinances for urban planning. *Build. Simul.* **2019**, *12*, 817–834. [CrossRef]
12. *SS-EN 17037:2018*; Daylight in Buildings. Swedish Standards Institute: Stockholm, Sweden, 2018.
13. Nault, E.; Peronato, G.; Rey, E.; Andersen, M. Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs. *Build. Environ.* **2015**, *92*, 679–691. [CrossRef]
14. Kanters, J.; Wall, M. Experiences from the urban planning process of a solar neighbourhood in Malmö, Sweden. *Urban Plan. Transp. Res.* **2018**, *6*, 54–80. [CrossRef]
15. Kanters, J.; Horvat, M.; Dubois, M.C. Tools and methods used by architects for solar design. *Energy Build.* **2014**, *68*, 721–731. [CrossRef]
16. Chatzipoulka, C.; Compagnon, R.; Kämpf, J.; Nikolopoulou, M. Sky view factor as predictor of solar availability on building façades. *Sol. Energy* **2018**, *170*, 1026–1038. [CrossRef]
17. Compagnon, R. Solar and daylight availability in the urban fabric. *Energy Build.* **2004**, *36*, 321–328. [CrossRef]
18. Natanian, J.; Wortmann, T. Simplified evaluation metrics for generative energy-driven urban design: A morphological study of residential blocks in Tel Aviv. *Energy Build.* **2021**, *240*, 110916. [CrossRef]
19. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
20. Elsevier. Scopus Content Coverage Guide. Available online: https://www.elsevier.com/__data/assets/pdf_file/0007/69451/Scopus_ContentCoverage_Guide_WEB.pdf (accessed on 7 February 2022).
21. Littlefair, P.J.; Santamouris, M.; Alvarez, S.; Dupagne, A.; Hall, D.; Teller, J.; Coronel, J.F.; Papanikolaou, N. *Environmental Site Layout Planning: Solar Access, Microclimate and Passive Cooling in Urban Areas*; Building Research Establishment: London, UK, 2000; Volume 380, p. 151.
22. Kanters, J.; Gentile, N.; Bernardo, R. Planning for solar access in Sweden: Routines, metrics, and tools. *Urban Plan. Transp. Res.* **2021**, *9*, 347–368. [CrossRef]
23. Nault, E.; Moonen, P.; Rey, E.; Andersen, M. Predictive models for assessing the passive solar and daylight potential of neighborhood designs: A comparative proof-of-concept study. *Build. Environ.* **2017**, *116*, 1–16. [CrossRef]

24. Mohajeri, N.; Upadhyay, G.; Gudmundsson, A.; Assouline, D.; Kämpf, J.; Scartezzini, J.-L. Effects of urban compactness on solar energy potential. *Renew. Energy* **2016**, *93*, 469–482. [CrossRef]
25. Lobaccaro, G.; Lisowska, M.M.; Saretta, E.; Bonomo, P.; Frontini, F. A Methodological Analysis Approach to Assess Solar Energy Potential at the Neighborhood Scale. *Energies* **2019**, *12*, 3554. [CrossRef]
26. Zhang, J.; Xu, L.; Shabunko, V.; Tay, S.E.R.; Sun, H.; Lau, S.S.Y.; Reindl, T. Impact of urban block typology on building solar potential and energy use efficiency in tropical high-density city. *Appl. Energy* **2019**, *240*, 513–533. [CrossRef]
27. Robert McNeel and Associates. Rhinoceros 3D, Version 7. Available online: https://www.rhino3d.com/ (accessed on 6 December 2021).
28. Ladybug Tools. Ladybug Tools | Home Page. Available online: https://www.ladybug.tools/ (accessed on 11 October 2021).
29. Wilcox, S.; Marion, W. *Users Manual for TMY3 Data Sets*; Technical Report NREL/TP-581-43156; National Renewable Energy Laboratory: Golden, CO, USA, 2008.
30. Prabatha, T.; Hager, J.; Carneiro, B.; Hewage, K.; Sadiq, R. Analyzing energy options for small-scale off-grid communities: A Canadian case study. *J. Clean. Prod.* **2020**, *249*, 119320. [CrossRef]
31. Li, Y.; O'Donnell, J.; García-Castro, R.; Vega-Sánchez, S. Identifying stakeholders and key performance indicators for district and building energy performance analysis. *Energy Build.* **2017**, *155*, 1–15. [CrossRef]
32. Chatzipoulka, C.; Nikolopoulou, M. Urban geometry, SVF and insolation of open spaces: London and Paris. *Build. Res. Inf.* **2018**, *46*, 881–898. [CrossRef]
33. Zhang, J.; Heng, C.K.; Malone-Lee, L.C.; Hii, D.J.C.; Janssen, P.; Leung, K.S.; Tan, B.K. Evaluating environmental implications of density: A comparative case study on the relationship between density, urban block typology and sky exposure. *Autom. Constr.* **2012**, *22*, 90–101. [CrossRef]
34. Natanian, J.; Aleksandrowicz, O.; Auer, T. A parametric approach to optimizing urban form, energy balance and environmental quality: The case of Mediterranean districts. *Appl. Energy* **2019**, *254*, 113637. [CrossRef]
35. Mardaljevic, J. Daylight Simulation: Validation, Sky Models and Daylight Coefficients, Loughborough University. Available online: /articles/thesis/Daylight_simulation_validation_sky_models_and_daylight_coefficients/9460817/1 (accessed on 22 February 2021).
36. Baker, C.; Goel, S.; Wang, N.; Rosenberg, M.; Wolf, D.; Henderson, P. A simplified energy modeling approach for buildings. In Proceedings of the ASHRAE and IBPSA-USA Building Simulation Conference, Chicago, IL, USA, 26–28 September 2018; pp. 53–59.
37. Tregenza, P.R. Subdivision of the sky hemisphere for luminance measurements. *Light. Res. Technol.* **1987**, *19*, 13–14. [CrossRef]
38. Subramaniam, S.; Mistrick, R. A More Accurate Approach for calculating Illuminance with Daylight Coefficients. In Proceedings of the Illuminating Engineering Society Annual Conference 2017, Portland, OR, USA, 8–10 August 2017; Available online: http://sarith.in/papers/2017-IES.pdf (accessed on 15 November 2021).
39. *ISO-15469:2004 (E)/CIE S 011/E:2003*; Spatial Distribution of Daylight–CIE Standard General Sky. ISO-CIE: Geneve, Switzerland, 2004.
40. Darula, S.; Kittler, R. Standard sky calculations for daylighting design and energy performance purposes. *Fiz. Budowli Teor. Prakt.* **2009**, *4*, 23–28.
41. Johnson, T.G.; Watson, I.D. The Determination of View-Factors in Urban Canyons. *J. Clim. Appl. Meteorol.* **1984**, *23*, 329–335. [CrossRef]
42. Metropolitan Council. *Calculating Floor Area Ratio—Local Planning Handbook*; Metropolitan Council: Saint Paul, MN, USA, 2015.
43. Morganti, M.; Salvati, A.; Coch, H.; Cecere, C. Urban morphology indicators for solar energy analysis. *Energy Procedia* **2017**, *134*, 807–814. [CrossRef]
44. Tablada, A.; Zhao, X. Sunlight availability and potential food and energy self-sufficiency in tropical generic residential districts. *Sol. Energy* **2016**, *139*, 757–769. [CrossRef]
45. Wu, Z.; Ren, Y.; Chen, L. Evaluating Urban Geometry Impacts on Incident Solar Radiation on Building Envelopes. *Environ. Model. Assess.* **2021**, *26*, 113–123. [CrossRef]
46. Curreli, A.; Roura, H.C. Urban layout and façade solar potential: A case study in the Mediterranean Region. *Arch. City Environ.* **2013**, *7*, 117–132. [CrossRef]
47. Chokhachian, A.; Perini, K.; Giulini, S.; Auer, T. Urban performance and density: Generative study on interdependencies of urban form and environmental measures. *Sustain. Cities Soc.* **2020**, *53*, 101952. [CrossRef]
48. Šprah, N.; Košir, M. Daylight Provision Requirements According to EN 17037 as a Restriction for Sustainable Urban Planning of Residential Developments. *Sustainability* **2019**, *12*, 315. [CrossRef]
49. Lee, K.S.; Lee, J.W. Feasibility study on the relation between housing density and solar accessibility and potential uses. *Renew. Energy* **2016**, *85*, 749–758. [CrossRef]
50. Wei, R.; Song, D.; Wong, N.H.; Martin, M. Impact of Urban Morphology Parameters on Microclimate. *Procedia Eng.* **2016**, *169*, 142–149. [CrossRef]
51. Yahia, M.W.; Johansson, E.; Thorsson, S.; Lindberg, F.; Rasmussen, M.I. Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania. *Int. J. Biometeorol.* **2018**, *62*, 373–385. [CrossRef]
52. Maiullari, D.; Esch, M.P.-V.; Van Timmeren, A. A Quantitative Morphological Method for Mapping Local Climate Types. *Urban Plan.* **2021**, *6*, 240–257. [CrossRef]

53. Joshi, K.K.; Kono, T. Optimization of floor area ratio regulation in a growing city. *Reg. Sci. Urban Econ.* **2009**, *39*, 502–511. [CrossRef]
54. DeKay, M. A comparative review of daylight planning tools and a rule-of-thumb for street width to building height ratio. In Proceedings of the 17th National Passive Solar Conference, Cocoa Beach, FL, USA, 15–18 June 1992; Available online: https://www.academia.edu/908120/a_comparative_review_of_daylight_planning_tools_and_a_rule_of_thumb_for_street_width_to_building_height_ratio (accessed on 18 November 2021).
55. Chatzipoulka, C.; Compagnon, R.; Nikolopoulou, M. Urban geometry and solar availability on façades and ground of real urban forms: Using London as a case study. *Sol. Energy* **2016**, *138*, 53–66. [CrossRef]
56. Bournas, I. Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density. *Build. Environ.* **2020**, *185*, 107276. [CrossRef]
57. Vartholomaios, A. A parametric sensitivity analysis of the influence of urban form on domestic energy consumption for heating and cooling in a Mediterranean city. *Sustain. Cities Soc.* **2017**, *28*, 135–145. [CrossRef]
58. Ko, Y. Urban Form and Residential Energy Use: A Review of Design Principles and Research Findings. *J. Plan. Lit.* **2013**, *28*, 327–351. [CrossRef]
59. Ratti, C.; Baker, N.; Steemers, K. Energy consumption and urban texture. *Energy Build.* **2005**, *37*, 762–776. [CrossRef]
60. Knowles, R.L. The solar envelope: Its meaning for energy and buildings. *Energy Build.* **2003**, *35*, 15–25. [CrossRef]
61. Mangan, S.D.; Oral, G.K.; Kocagil, I.E.; Sozen, I. The impact of urban form on building energy and cost efficiency in temperate-humid zones. *J. Build. Eng.* **2021**, *33*, 101626. [CrossRef]
62. Forouzandeh, A.; Richter, T. Accurate prediction of heating energy demand of courtyard's surrounding envelopes using temperature correction factor. *Energy Build.* **2019**, *193*, 49–68. [CrossRef]
63. Martinelli, L.; Matzarakis, A. Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones. *Sustain. Cities Soc.* **2017**, *29*, 97–106. [CrossRef]
64. Nasrollahi, N.; Hatami, M.; Khastar, S.R.; Taleghani, M. Numerical evaluation of thermal comfort in traditional courtyards to develop new microclimate design in a hot and dry climate. *Sustain. Cities Soc.* **2017**, *35*, 449–467. [CrossRef]
65. Rodríguez-Algeciras, J.; Tablada, A.; Chaos-Yeras, M.; De la Paz, G.; Matzarakis, A. Influence of aspect ratio and orientation on large courtyard thermal conditions in the historical centre of Camagüey-Cuba. *Renew. Energy* **2018**, *125*, 840–856. [CrossRef]
66. Berghauser-Pont, M.; Haupt, P.A. The Spacemate: Density and the typomorphology of the urban fabric. In *Urbanism Laboratory for Cities and Regions*; IOS Press: Amsterdam, The Netherlands, 2007; pp. 11–26.
67. Zhu, D.; Song, D.; Shi, J.; Fang, J.; Zhou, Y. The Effect of Morphology on Solar Potential of High-Density Residential Area: A Case Study of Shanghai. *Energies* **2020**, *13*, 2215. [CrossRef]
68. Oke, T.R. Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations. *J. Clim.* **1980**, *1*, 237–254. [CrossRef]
69. Brown, M.J.; Grimmond, S.; Ratti, C. *Comparison of Methodologies for Computing Sky View Factor in Urban Environments*; Los Alamos National Lab: Los Alamos, NM, USA, 2001.
70. Dirksen, M.; Ronda, R.; Theeuwes, N.; Pagani, G. Sky view factor calculations and its application in urban heat island studies. *Urban Clim.* **2019**, *30*, 100498. [CrossRef]
71. Hämmerle, M.; Gál, T.; Unger, J.; Matzarakis, A. Comparison of models calculating the sky view factor used for urban climate investigations. *Theor. Appl. Climatol.* **2011**, *105*, 521–527. [CrossRef]
72. Lau, K.K.-L.; Lindberg, F.; Rayner, D.; Thorsson, S. The effect of urban geometry on mean radiant temperature under future climate change: A study of three European cities. *Int. J. Biometeorol.* **2014**, *59*, 799–814. [CrossRef]
73. Littlefair, P. *Site Layout Planning for Daylight and Sunlight: A Guide to Good Practice (BR 209)*; Building Research Establishment: Watford, UK, 2011.
74. Olina, A.; Zaimi, N. Daylight Prediction Based on VSC-DF Relation: A Guideline for Daylight in Urban Planning. Master's Thesis, Lund University, Lund, Sweden, 2018.
75. Moon, P.; Spencer, D.E. Illumination form a non-uniform sky. *Illum. Eng.* **1942**, *37*, 707–726.
76. Bournas, I.; Dubois, M.-C. Daylight regulation compliance of existing multi-family apartment blocks in Sweden. *Build. Environ.* **2019**, *150*, 254–265. [CrossRef]
77. Morrissey, J.; Moore, T.; Horne, R. Affordable passive solar design in a temperate climate: An experiment in residential building orientation. *Renew. Energy* **2011**, *36*, 568–577. [CrossRef]
78. Capeluto, I.G.; Yezioro, A.; Shaviv, E. Climatic aspects in urban design-a case study. *Build. Environ.* **2003**, *38*, 827–835. [CrossRef]
79. Capeluto, I.G.; Plotnikov, B. A method for the generation of climate-based, context-dependent parametric solar envelopes. *Arch. Sci. Rev.* **2017**, *60*, 395–407. [CrossRef]
80. Yousuf, M.U.; Siddiqui, M.; Rehman, N.U. Solar energy potential estimation by calculating sun illumination hours and sky view factor on building rooftops using digital elevation model. *J. Renew. Sustain. Energy* **2018**, *10*, 13703. [CrossRef]
81. Grandjean, E.; Gilgen, A. *Environmental Factors in Urban Planning*; Taylor & Francis: London, UK, 1976.
82. Littlefair, P. Passive solar urban design: Ensuring the penetration of solar energy into the city. *Renew. Sustain. Energy Rev.* **1998**, *2*, 303–326. [CrossRef]

83. Desthieux, G.; Carneiro, C.; Camponovo, R.; Ineichen, P.; Morello, E.; Boulmier, A.; Abdennadher, N.; Dervey, S.; Ellert, C. Solar Energy Potential Assessment on Rooftops and Facades in Large Built Environments Based on LiDAR Data, Image Processing, and Cloud Computing. Methodological Background, Application, and Validation in Geneva (Solar Cadaster). *Front. Built Environ.* **2018**, *4*, 14. [CrossRef]
84. Compagnon, R.; Goyette-Pernot, J. Multishading masks: A new method for assessing solar penetration in open spaces. In Proceedings of the PLEA2013—29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany, 10–12 September 2013.
85. Compagnon, R.; Chatzipoulka, C. A Simple Tool for Assessing Solar and Daylight Access in Urban Canyons. In Proceedings of the EuroSun 2018, International Solar Energy Society, Freiburg, Germany, 10–13 September 2018; pp. 1–8. [CrossRef]
86. Ne'Eman, E.; Light, W.; Hopkinson, R. Recommendations for the admission and control of sunlight in buildings. *Build. Environ.* **1976**, *11*, 91–101. [CrossRef]
87. Littlefair, P. *Site Layout Planning for Daylight and Sunlight: A Guide to Good Practice*; Building Research Establishment: Watford, UK, 1991.
88. Holick, M.F. Sunlight and vitamin D for bone health and prevention of autoimmune diseases, cancers, and cardiovascular disease. *Am. J. Clin. Nutr.* **2004**, *80*, 1678S–1688S. [CrossRef] [PubMed]
89. Bilu, C.; Einat, H.; Zimmet, P.; Vishnevskia-Dai, V.; Kronfeld-Schor, N. Beneficial effects of daytime high-intensity light exposure on daily rhythms, metabolic state and affect. *Sci. Rep.* **2020**, *10*, 19782. [CrossRef] [PubMed]
90. Rosenthal, N.E.; Sack, D.A.; Gillin, J.C.; Lewy, A.J.; Goodwin, F.K.; Davenport, Y.; Mueller, P.S.; Newsome, D.A.; Wehr, T.A. Seasonal Affective Disorder: A Description of the Syndrome and Preliminary Findings with Light Therapy. *Arch. Gen. Psychiatry* **1984**, *41*, 72–80. [CrossRef]
91. Fahimipour, A.K.; Hartmann, E.M.; Siemens, A.; Kline, J.; Levin, D.A.; Wilson, H.; Betancourt-Román, C.M.; Brown, G.Z.; Fretz, M.; Northcutt, D.; et al. Daylight exposure modulates bacterial communities associated with household dust. *Microbiome* **2018**, *6*, 175. [CrossRef]
92. Ne'Eman, E.; Craddock, J.; Hopkinson, R. Sunlight requirements in buildings—I. Social survey. *Build. Environ.* **1976**, *11*, 217–238. [CrossRef]
93. Czachura, A. Integrated Daylight and Energy Evaluation of Passive Solar Shadings in a Nordic Climate. In Proceedings of the 13th International Conference on Solar Energy for Buildings and Industry, Online, 1–3 September 2020; pp. 32–40.
94. Illuminating Engineering Society. *IES LM-83-12 Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*; Illuminating Engineering Society: New York, NY, USA, 2012.
95. Robinson, D.; Stone, A. Irradiation modelling made simple: The cumulative sky approach and its applications. In Proceedings of the 21st PLEA Conference, Eindhoven, The Netherlands, 19–21 September 2004; pp. 19–22.
96. Theeuwes, N.E.; Steeneveld, G.-J.; Ronda, R.J.; Holtslag, B. A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe. *Int. J. Clim.* **2017**, *37*, 443–454. [CrossRef]
97. BSI. Lighting for Buildings. Code of Practice for Daylighting. BS 8206-2:2008—BSI British Standards, London. Available online: https://shop.bsigroup.com/ProductDetail/?pid=000000000030157088 (accessed on 17 May 2021).
98. Littlefair, P.; Aizlewood, M. *Calculating Access to Skylight, Sunlight and Solar Radiation on Obstructed Sites in Europe*; Construction Research Communications; Building Research Establishment: Watford, UK, 1999.
99. Palz, W.; Greif, J. *European Solar Radiation Atlas: Solar Radiation on Horizontal and Inclined Surfaces*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2016.
100. Annual Probable Sun Hours. Available online: https://deluminaelab.com/docs/dl-light/en/apsh.html (accessed on 3 December 2021).
101. Liao, W.; Heo, Y.; Xu, S. Simplified vector-based model tailored for urban-scale prediction of solar irradiance. *Sol. Energy* **2019**, *183*, 566–586. [CrossRef]
102. Sarralde, J.J.; Quinn, D.J.; Wiesmann, D.; Steemers, K. Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London. *Renew. Energy* **2015**, *73*, 10–17. [CrossRef]
103. Freitas, S.; Catita, C.; Redweik, P.; Brito, M. Modelling solar potential in the urban environment: State-of-the-art review. *Renew. Sustain. Energy Rev.* **2015**, *41*, 915–931. [CrossRef]
104. Lukač, N.; Seme, S.; Žlaus, D.; Štumberger, G.; Žalik, B. Buildings roofs photovoltaic potential assessment based on LiDAR (Light Detection and Ranging) data. *Energy* **2014**, *66*, 598–609. [CrossRef]
105. Cronemberger, J.; Martin, M.E.C.; Sanchez, S.V. Assessing the solar irradiation potential for solar photovoltaic applications in buildings at low latitudes—Making the case for Brazil. *Energy Build.* **2012**, *55*, 264–272. [CrossRef]
106. Saretta, E.; Bonomo, P.; Frontini, F. A calculation method for the BIPV potential of Swiss façades at LOD2.5 in urban areas: A case from Ticino region. *Sol. Energy* **2020**, *195*, 150–165. [CrossRef]
107. Naboni, E.; Natanian, J.; Brizzi, G.; Florio, P.; Chokhachian, A.; Galanos, T.; Rastogi, P. A digital workflow to quantify regenerative urban design in the context of a changing climate. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109255. [CrossRef]
108. Zirnhelt, H.E.; Richman, R.C. The potential energy savings from residential passive solar design in Canada. *Energy Build.* **2015**, *103*, 224–237. [CrossRef]
109. Lobaccaro, G.; Carlucci, S.; Croce, S.; Paparella, R.; Finocchiaro, L. Boosting solar accessibility and potential of urban districts in the Nordic climate: A case study in Trondheim. *Sol. Energy* **2017**, *149*, 347–369. [CrossRef]

110. Huang, Z.; Mendis, T.; Xu, S. Urban solar utilization potential mapping via deep learning technology: A case study of Wuhan, China. *Appl. Energy* **2019**, *250*, 283–291. [CrossRef]
111. Peronato, G.; Rastogi, P.; Rey, E.; Andersen, M. A toolkit for multi-scale mapping of the solar energy-generation potential of buildings in urban environments under uncertainty. *Sol. Energy* **2018**, *173*, 861–874. [CrossRef]
112. Terjung, W.H.; Louie, S.S.-F. Solar Radiation and Urban Heat Islands. *Ann. Assoc. Am. Geogr.* **1973**, *63*, 181–207. [CrossRef]
113. Boverket. *Planning and Building Act (2010:900) Planning and Building Ordinance (2011:338)*; Swedish National Board of Housing, Building and Planning; Boverket: Karlskrona, Sweden, 2018.
114. Mardaljevic, J. The implementation of natural lighting for human health from a planning perspective. *Light. Res. Technol.* **2021**, *53*, 489–513. [CrossRef]
115. Mehaffy, M.W.; Kryazheva, Y.; Rudd, A.; Salingaros, N.A. *A New Pattern Language for Growing Regions: Places, Networks, Processes*; Sustasis Press: Portland, OR, USA, 2019.

Paper II

Selection of Weather Files and Their Importance for Building Performance Simulations in the Light of Climate Change and Urban Heat Islands

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Abstract

Building performance predictions and their reliability rely heavily on weather data inputs. Climate is affected by spatial and temporal differences related to climate change and urban heat island effects, but the weather files used in building performance simulations (BPS) often remain unchanged and may represent weather observations generated from inadequate space and time for their application. This study investigated Swedish weather data using statistical methods and analysed i) the local differences related to rural and urban microclimates and ii) the country-wide differences linked to climate change; by comparing recent observation data to the respective EnergyPlus Weather (EPW) files. The findings reveal that there are significant differences between rural and urban temperature means, and that outdated model years of weather data files make them unsuitable for BPS. The impact of using an inadequate weather file based on changes in recent climate in Sweden can lead to an overestimation of heating demand by 6.5 % on average, while the impact is higher for warmer climates – up to 12 %. The combined impact including climate change and urban heat island effects can lead to a heating energy overestimation by 12 % to 19 %, based on the Stockholm example. On the other hand, it was found that although the global radiation means saw a slightly increasing trend, its impact on the BPS remains inconclusive. The study highlights the importance of selection of adequate weather data for BPS keeping in mind the spatial and temporal influencing factors.

Keywords: weather data, EPW, statistical analysis, urban heat island, climate change, building performance simulations

1. Introduction

Weather data is a central input in building performance simulations (BPS) and sustainable urban planning. It defines the output of simulations relating to daylighting, energy use, and solar potential, and ultimately influences the decision-making process in the urban planning and building design practice. In a typical BPS process, a weather file selection is fixed to a single available weather file which is used repetitively in studies of a given geographical or administrative area and contains hourly values representing a typical meteorological year (TMY). One of the common weather file extensions used in building simulation software based on EnergyPlus and Radiance is the EPW (EnergyPlus Weather) file format. International EnergyPlus database is a large repository of EPW files from many different weather sources (EnergyPlus, 2021). It is often not possible to pick and choose between different weather files for a given location; there is usually only one that is the nearest available hence deemed the most suitable. For some locations and some data repositories it may also be difficult to obtain files with updated TMY with observation from the most recent years. In other terms, available weather file might not be fully representative due to spatial (location of the weather station) and temporal (years of observation included in the TMY) differences.

There are two key factors that drive the local spatial and temporal, as well as short-term and long-term, weather observation differences: urban heat island and climate change. Their effects on BPS have been previously studied, see e.g., (Burleyson et al., 2018; Crawl, 2008; de Wilde and Coley, 2012; Moazami et al., 2019). Studies also investigated the impact of future climate scenarios on BPS (Baglivo et al., 2022; de Masi et al., 2021; Moazami et al., 2019). Nik and Sasic Kalagasidis (2013) showed that the heating demand of Stockholm's residential buildings might expect a potential decrease of 30 % under a future climate scenario. On the other hand, a study by Guattari et al. (2018) investigating urban climate of Rome demonstrated that the average cooling need was 30 % higher, pertaining to urban heat island effects alone.

The urban heat island effect drives climate differences on a local scale. The phenomenon occurs due to conducive urban characteristics such as high build-up density, scarce vegetation, thermal waste, and the extensive use of heat-

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storing materials and dark surface colours; all of which causes the city centres to reach higher ambient and radiant temperatures, meanwhile possessing a decreased ability for radiative cooling due to a limited openness to the sky. Since the weather files are commonly built from stations located outside of the cities e.g., at rural airports, they typically do not account for this effect. In Sweden, six city locations are covered by the EnergyPlus database of EPW files, five of which come from rural airport-based weather stations outside of the city (Table 1). The source of the presented Swedish weather data files is IWEC (International Weather for Energy Calculations), which was developed by ASHRAE (ASHRAE, 2001).

Table 1. The available Swedish EPW file locations and the observation time spans they are generated from.

City and weather file name	Weather station location	TMY time period
Copenhagen (DK; also used in Malmö, SE)	Kastrup Airport	1983 to 1999
Gothenburg (SE)	Landvetter Airport	1983 to 1995
Karlstad (SE)	Sommarro area	1984 to 1996
Kiruna (SE)	Kiruna Airport	1982 to 1993
Östersund (SE)	Åre (Frösön) Airport	1982 to 1999
Stockholm (SE)	Arlanda Airport	1984 to 1993

While the heat island phenomenon triggers spatial microclimate differences, climate change alters the long-term weather patterns. The available EPW files in Sweden contain data based on real weather observations taken within a similar time span, ranging from 1982 to 1999, as shown in Table 1. Climate change is affecting locations globally in varying magnitudes, and it is important to understand how different places around the world are impacted. While future climate scenarios were previously applied in BPS studies in Sweden (Moazami et al., 2019; Nik and Sasic Kalagasidis, 2013), the disparities between recent weather observations and common Swedish weather files have not yet been studied.

To investigate the impact of the selection of weather files, a statistical analysis of Swedish weather data was conducted. The main objective of the research was to study the differences between the EPW weather data sets and recent weather observations, which might adversely impact future solar and thermal building performance predictions. The goal was to investigate firstly, whether there are significant statistical differences between the rural and the urban weather observations based on Stockholm's urban agglomeration, and secondly, whether the available EPW files for Swedish locations remain representative of the most recent weather patterns. The study looked at both hygrothermal as well as solar weather parameters (global radiation, sun duration) and analysed their potential impact on BPS. Since the impact of climate change on clouds is still largely unknown (Ceppi et al., 2017), it is important to study the solar aspects of climate. Lastly, the outcomes of the study address a key question for BPS: Is it important to continuously update the simulation weather files?

2. Methodology

2.1. Rural and urban differences - Stockholm

The first part of this study analysed dry bulb air temperature records measured in six selected stations located in Stockholm County. The analysis area was of a 35 km radius with Central Stockholm at its centre. The measured temperature data was obtained from SMHI (Sweden's Meteorological and Hydrological Institute) (SMHI, 2021a). Thirteen years of data records spanning between year 2008 and 2020 were extracted for the selected weather stations. The prerequisites for selecting suitable weather stations were: 1) the data was recorded hourly, 2) the station was active in years 2008-2020, and 3) the station was located in the Greater Stockholm area. The following weather stations were selected: Stockholm (A), Adelsö, Arlanda, Bromma, Tullinge, and Skarpö. To study their location on the map of Greater Stockholm area, see Figure 3. For each station and each annual hourly temperature data set, an annual temperature mean was calculated.

There were missing records in the retrieved data sets. Following the statistical significance level rule of 5 %, the annual data sets which had more than 5 % of data records missing were considered as significant loss of data and thus were removed from the analysis. There were four such data sets: Adelsö 2016, Arlanda 2008, and Skarpö 2014 and 2015.

A statistical analysis on the annual mean temperatures was conducted in RStudio (RStudio Team, 2021). A general linear model was used, and analysis of variance (ANOVA) as well as post hoc comparison tests (Tukey's method) were performed. Test assumptions regarding normality and homoscedasticity of the residuals were checked.

Weather data files used in BPS were introduced to assess their likeness to the measured data and to evaluate their ability to digitally represent the analysed climate of the recent time period in computer-based modelling. The weather data was obtained from two databases: EnergyPlus (EP) (EnergyPlus, 2021) with data source IWEC (ASHRAE, 2001), and OneBuilding (OB) (OneBuilding Climate, 2021). The former is a widespread source of weather data for BPS. Ladybug Tools (Ladybug Tools, 2021) users can connect directly via a web browser to a Ladybug interactive map providing many EP files to download, including IWEC files (Roudsari and Peng, 2021). As previously indicated, those files are often based on old measurements (Table 1). OB, on the other hand, is a free repository of TMY weather data that is updated continuously and covers many more locations. For this study, there was only one EP file available for the analysed area, while there were twelve different OB files – two for each of the stations, containing two different sets of model years on which the TMY data was based.

2.2. Spatial and temporal differences - Sweden

The second part of this study investigated weather data measurements from six Swedish locations: Stockholm, Gothenburg, Malmö, Östersund, Karlstad, and Kiruna (Fig. 1). The data was retrieved from SMHI's database (SMHI, 2021a), from weather stations that were located closest to the available IWEC weather file for a given city, and for eleven consecutive years: 2010-2020. The following weather parameters were analysed: air temperature (°C), relative humidity (%), global solar irradiance (W m^{-2}), and sunlight duration as fraction of an hour. Annual averages from the measured hourly-based data were calculated: for temperature and humidity – taking all data items, and for irradiance and sunlight duration – taking only data for those hours when the sun is up, which differs per location. Additionally, yearly temperature extremes were also investigated.

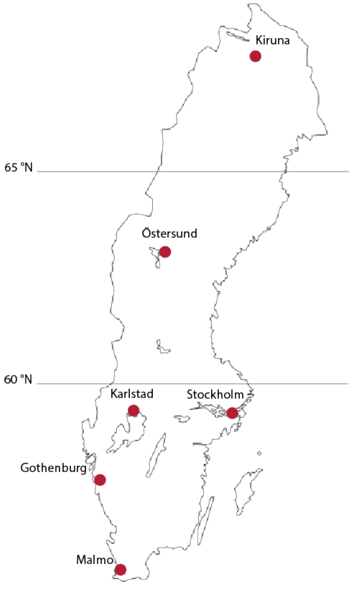

Figure 1. Locations of the weather stations for the analysis of Swedish weather.

The sunlight duration parameter was accounted for differently in the measured data and in the weather file data. SMHI uses a threshold of above 120 W m^{-2} in measured global radiation to determine that a given second was sunny (sunlight was present) and gives the results of these measurements hourly with maximum value of 3600 per hour (SMHI, 2021b). The SMHI sunlight duration data was normalised for this study, and all values were divided by the maximum to give a range between 0 and 1. The weather data from EPW files, on the other hand, provided information about the cloud coverage of the sky for every hour of the year, the invert of which was taken as sunlight duration.

There were some difficulties encountered during data extraction. Relative humidity data was missing or was of inadequate quality (category yellow by SMHI) for all locations for measurements in years 2010, 2011, 2012, and 2020: thus, only seven measurement years were considered for this parameter, except for Malmö where year 2020 records were available. Solar stations, those that measure global radiation and sunlight duration, were positioned in different locations than the weather stations which recorded the temperature and relative humidity; however, they were still located within the same precincts, except for Malmö, as the closest solar measuring station was in the nearby town of Lund.

Climatic differences between the selected Swedish locations but also differences between recent weather measurements and respective TMY data for these locations were investigated. The weather data files for all locations were sourced from EnergyPlus IWEC database. For Malmö, the Copenhagen file was used, as it was the nearest available location from IWEC.

Each parameter was first analysed separately using an additive linear model design. The assumptions for the ANOVA were checked for each data set. Temperature, relative humidity, and sun duration data sets proved normality and homoscedasticity on residuals; however, tests on radiation data set rejected the normality hypothesis. In order to be able to conduct further statistical tests, outliers of the radiation data were identified and removed. To ensure data normality, it was sufficient to remove just one radiation record, for Malmö 2017, which was the biggest outlier. ANOVA of every weather parameter data set showed that the locations and years had significant differences with high significance p-value levels. Post hoc comparisons were conducted on each weather parameter separately.

3. Results and discussion

3.1. Rural and urban differences - Stockholm

The annual temperature averages are shown in Figure 2. The parallel appearance of the lines indicated a block effect in the data; hence, a linear additive model with blocking was used. Next, one-way ANOVA was used to test whether the block design was appropriate. The ANOVA indicated that there was a significant ($p<0.001$) difference in the data corresponding to the year and the location, and that the grouping of data into blocks was adequate. The assumptions for ANOVA were tested using the Shapiro-Wilk and Levene tests, which did not reject normal distribution and homoscedasticity of the residuals, so the assumptions were met.

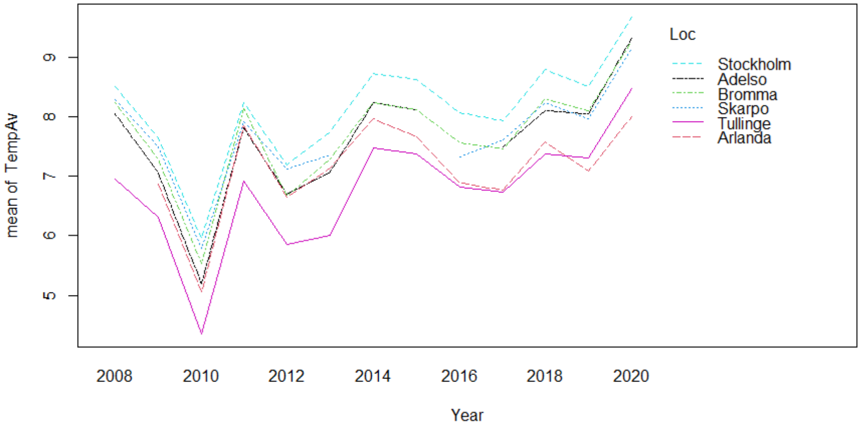

Figure 2. Interaction plot with Stockholm weather stations temperature means. Some lines appear broken because of missing data.

The Tukey's post hoc comparison test results with the level of significance $\alpha = 0.05$ are presented in Table 2. There are small standard errors and many degrees of freedom. The comparison of the location means showed that there are four groups of stations with significantly different temperature means, while three stations, Skarpö, Bromma, and Adelsö, did not have significantly different means according to the Tukey's test. The table also includes an annual temperature mean for the IWEC weather file from Stockholm Arlanda which was added to contrast the statistical means with the TMY mean.

Table 2. Tukey's post hoc test results with statistical grouping of means (descending order).

Location	emmean (estimated marginal mean)	SE (standard error)	DF (degrees of freedom)	Lower CL (confidence level)	Upper CL	Group
Stockholm	8.12	0.0540	56	8.01	8.23	A
Skarpö	7.76	0.0597	56	7.64	7.88	B
Bromma	7.71	0.0540	56	7.60	7.82	B
Adelsö	7.59	0.0567	56	7.47	7.70	B
Arlanda	7.16	0.0567	56	7.05	7.27	C
Tullinge	6.76	0.0540	56	6.66	6.87	D
IWEC (Arlanda)	6.49					

The weather station located in the Stockholm's city centre, named 'Stockholm', resulted in the highest estimated temperature mean. It was also significantly different from other stations. The result confirms the initial hypothesis that the air temperatures are higher in city centres, closer to the densely built and populated urban areas (Fig. 3), which might be ascribed to the known heat island effect.

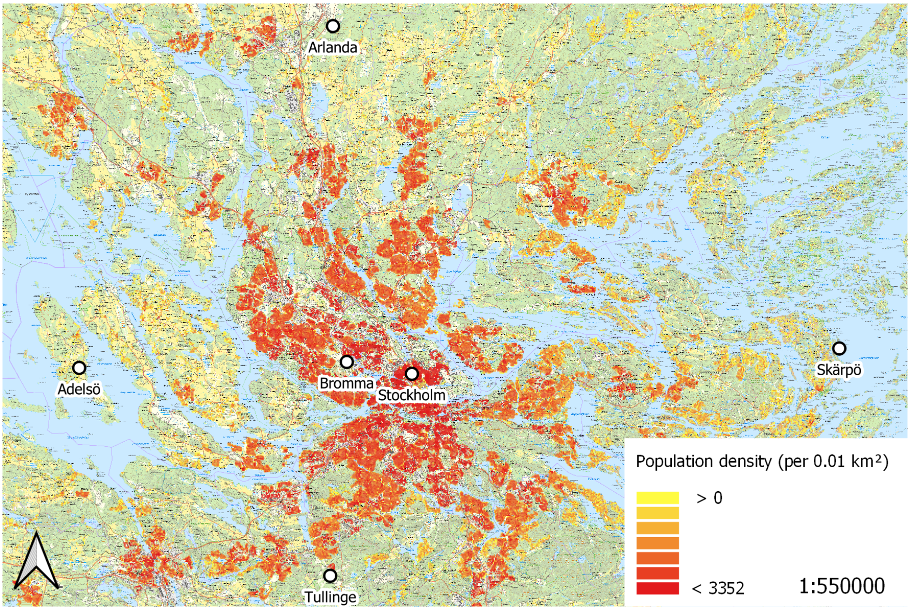

Figure 3. Stockholm's weather stations and population density (source: Lantmäteriet).

Weather stations of Bromma, Skarpö, and Adelsö were placed together in one group, which was the second highest group by temperature means. This means that there is no significant difference between these station's temperature means. While Bromma was located close to the agglomeration's centre, the other two were located outside of the strict city centre. The reason the means are not different could be attributed to the geographical and topographical location of the two rural stations. Skarpö and Adelsö are located close to large sea reservoirs, which might affect local climate and cause milder temperatures. The results might also be affected by the reduced data samples for the two said stations.

Arlanda and Tullinge were identified as the coldest locations within the analysed area. There was also a significant difference between them, with Tullinge being the colder station. It was noted that these two stations are located inland, further away from large water bodies than the warmer stations of Adelsö and Skarpö. This might again indicate the coastal effect on temperature averages, because all four of these stations were located far away from the city centre of Stockholm in rural locations that are not densely populated (Fig. 3).

The temperature means for all investigated weather stations and for all data sources (SMHI used this paper's statistical analysis, and IWEC and OB from online databases) were placed together in Table 3 and sorted by the ascending temperature mean. There was only one IWEC file available for the Greater Stockholm area, and its location was Arlanda. The OB weather files database offered two files for each station. The one which had the addition of '2004-2018' in the name was generated using this exact time period or shorter time span within it, while the other version was generated using an unspecified time span. The IWEC file's average of model years was the oldest.

The comparison table (Table 3) shows that for three out of six investigated locations the SMHI sourced temperature mean for the most recent years 2008-2020 expressed higher temperature mean than the weather files. In case of Skarpö and Bromma, the latest model years resulted in higher temperature means when comparing all three means for each location. The difference is especially pronounced for the temperature means that were modelled using larger time spans dating back to the 1980s, such as Bromma (OB) and Arlanda (OB). Their means were about 0.5 K lower than the two other respective means. It is noteworthy that the lowest temperature mean was obtained from the Arlanda IWEC file data, which is still a commonly used source of weather data for simulations.

Table 3. Weather station temperature data from different sources sorted by ascending temperature mean.

Weather station (source)	T mean /°C	Years
Stockholm (OB)	8.19	2002 - 2019
Stockholm (SMHI)	8.12	2008 - 2020
Stockholm 2004-2018 (OB)	7.98	2005 - 2017
Adelsö (OB)	7.78	2002 - 2019
Skarpö (SMHI)	7.76	2008 - 2020
Skarpö 2004-2018 (OB)	7.75	2004 - 2018
Bromma (SMHI)	7.71	2008 - 2020
Bromma 2004-2018 (OB)	7.70	2004 - 2018
Skarpö (OB)	7.66	1999 - 2018
Adelsö (SMHI)	7.59	2008 - 2020
Adelsö 2004-2018 (OB)	7.41	2004 - 2017
Arlanda 2004-2018 (OB)	7.27	2005 - 2018
Arlanda (SMHI)	7.16	2009 - 2020
Bromma (OB)	7.09	1980 - 2011
Tullinge (SMHI)	6.76	2008 - 2020
Arlanda (OB)	6.69	1981 - 2013
Tullinge (OB)	6.66	2002 - 2019
Tullinge 2004-2018 (OB)	6.66	2004 - 2016
Arlanda (IWEC)	6.49	1984 - 1993

The order of the Table 3 is similar to the post hoc classification from Table 2, with some exemptions which were discussed above. The overall difference between the lowest (Arlanda OB) and the highest (Stockholm OB) temperature mean from Table 3 is 1.7 K, which for an annual average difference of a relatively small geographical area is substantial. Based on simple hand calculations of building heat balance using a degree hours method (Letherman and Al-Azawit, 1986), such a discrepancy in annual average temperature could have a 12 % to 19 % incremental impact on the predicted heating energy use, depending on the indoor temperature setpoint through independently of the rate of heat loss. Miscalculated heat balance and mismatched energy performance predictions can lead to poor design and planning. This can, for instance, result in excessive and redundant insulation added onto the building envelopes in order to meet energy requirements, which may further cause potential overheating issues in the summertime (Porritt et al., 2012).

2.2. Spatial and temporal differences – Sweden

The temperature estimated means based on measurement data from SMHI and the corresponding TMY temperature averages from IWEC data were contrasted in Table 4 and sorted in a descending order by the emmeans. IWEC's temperature averages were between 0.65 K and 1.3 K lower than the mean based on the recent 11 years of measured data. There were significant differences between the locations, which resulted in 5 distinct statistically different groups (see also Fig. 4). Comparing the years instead, only year 2010 was colder than the IWEC TMY. Comparing relative humidity means in the same manner, the differences between SMHI and IWEC data means were negligible and inconclusive; there were very small differences between the investigated locations.

The temperature means from the recent weather observations were higher for all locations in respect to the IWEC weather files. Table 4 shows the impact of the difference on heating demand predictions; the percentages were calculated using the same simple degree hours method as previously (Letherman and Al-Azawit, 1986). An overestimation between 4 % and 12 % is expected, depending on the location. Colder locations are less affected by the rising annual temperatures, because the difference constitutes a smaller fraction of the temperature differential when considering the same heating setpoint temperature.

Table 4. Annual temperature means for SMHI observations for years 2010-2020 and IWEC weather files.

Location	Group	emmean (SMHI) /°C	IWEC average /°C	Difference /K	Heating energy difference
Malmö / Copenhagen	A	9.40	8.32	1.08	8-12%
Gothenburg	B	7.28	6.53	0.75	5-7%
Stockholm	BC	7.14	6.49	0.65	4-6%
Karlstad	C	6.75	5.92	0.83	5-7%
Östersund	D	3.86	3.15	0.71	4-5%
Kiruna	E	0.21	-1.09	1.30	6-7%

The comparison of annual maximum and minimum temperatures was presented in Table 5. All recent observations show higher maximum annual temperatures than those of the IWEC files, which may introduce overheating issues in buildings. The temperature minima, on the other hand, were both higher and lower depending on the location. Thus, no clear trend was observed, and the impact that the changes in temperature minimum might have on the heating peak load is smaller than of the heating energy difference - up to 7 % only.

Table 5. Annual temperature extremes for SMHI observations for years 2010-2020 and IWEC weather files.

Location	T_{max} emmean /°C	IWEC T_{max} /°C	Difference /K	T_{min} emmean /°C	IWEC T_{min} /°C	Difference /K	Heating power difference
Gothenburg	28.3	27.1	1.2	-14.1	-15.9	1.8	- 7 %
Karlstad	28.3	26.3	2	-18.3	-19.5	1.2	5 %
Kiruna	25.4	22.7	2.7	-31.6	-29.2	-2.4	- 4 %
Malmö / Cph.	29.6	26.8	2.8	-11.5	-9.6	-1.9	3 %
Östersund	26.7	26.5	0.2	-23.5	-25.7	2.2	5 %
Stockholm	29.1	27.1	2	-18.3	-17	-1.3	- 5 %

Radiation data from SMHI calculated emmeans and IWEC weather files was compared in Table 6. The recent SMHI measurements recorded higher averages than the older TMY model years with up to 10 % increase. This does not yet indicate a trend, but it is worth noting that for all locations there was an increase in the global radiation average. This phenomenon could be related to the potential discrepancy between the estimate-based radiation data, typically used in the weather file generation, and ground-based measurements. IWEC files are based on estimates from cloud coverage and other weather parameters (ASHRAE, 2001), while OneBuilding radiation estimates use satellite-based models (OneBuilding Climate, 2021). Satellite-based data allows to generate sky models and calculate surface irradiance at virtually any location, which increases data accessibility and improves applications promoting solar energy implementation (Huld et al., 2012), but the models can suffer accuracy loss (Psiloglou et al., 2020).

Similar comparison could not have been performed for the sunlight duration data, because SMHI and the TMY data had different ways of accounting for the direct sunlight duration.

Table 6. Annual global radiation means for SMHI observations for years 2010-2020 and IWEC weather files.

Location	Group	emmean (SMHI) /Wm^{-2}	IWEC average /Wm^{-2}	Difference / Wm^{-2}	Change
Malmö / Copenhagen	A	233	219.8	13.2	6.0 %
Karlstad	AB	227	221.4	5.6	2.5 %
Stockholm	B	226	204.7	21.3	10.4 %
Gothenburg	B	223	219.9	3.1	1.4 %
Östersund	C	201	196.4	4.6	2.3 %
Kiruna	D	177	163.7	13.3	8.1 %

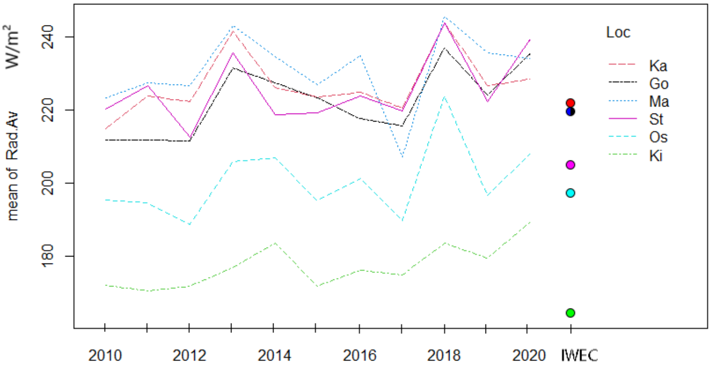

Figure 4. Annual global radiation average over measurement years and the IWEC year.

The graph presenting global solar radiation means from the last eleven years data in Figure 4 does not suggest that there are trends or changes in the means over time. What can be seen, however, is that the weather file IWEC radiation mean is generally quite low in comparison to the annual measurements. This increase may potentially have an effect on solar potential, energy, and daylight simulations; however, a previous study on weather data for daylight simulations showed that the impact is quite insignificant (Iversen et al., 2013).

All the individual post hoc comparisons of the Swedish weather locations were combined in one chart in Figure 5. This method of presentation is proposed for the purpose of comparing multi-parameter post-hoc comparisons. The graph can be read in multiple ways. First, it can be noticed that the order of locations by temperature as well as by solar parameters, particularly by radiation, roughly follows the latitude order from southernmost (Malmö) to northernmost (Kiruna) location. Special attention might be paid then to those locations which deviate from the latitude order in those parameters. One can also read the graph by looking at a certain location in respect to others. Gothenburg, for instance, is warm, but not exceptionally warm for its latitude as it does not deviate in respect to the latitudinal order. It is also rather humid and often cloudy since the radiation and sun duration are below latitudinal expectations for Gothenburg's latitude. It can be also assessed from the graph that Stockholm, Karlstad, and Gothenburg share similar climates. We think that this method for comparing climates proved easy to interpret and hence was chosen over the PCA biplots presentation method.

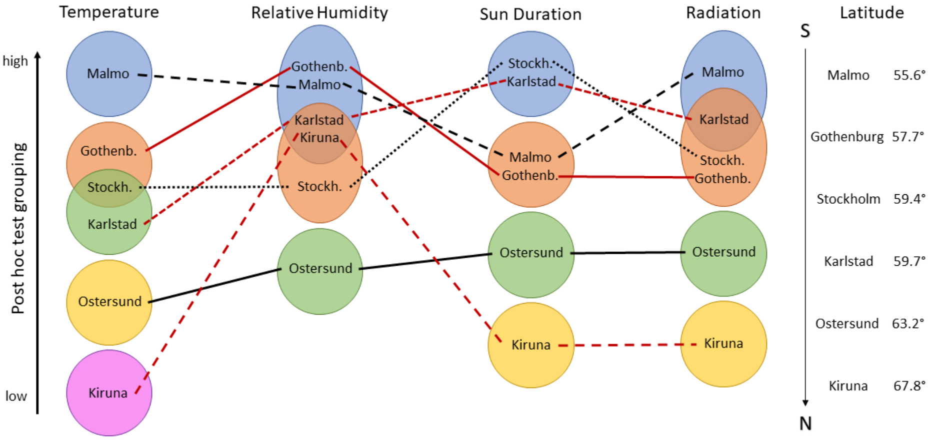

Figure 5. Combined post-hoc comparisons (data included IWEC yearly averages) and latitudes.

4. Conclusions

This paper analysed difference in weather files based on location of the weather stations and observations reference period on the example of the Swedish capital city agglomeration and Sweden as a country. The scope was to understand how the selection of weather files might affect BPS. The analysis showed the importance of keeping weather data for BPS updated, as it was seen that inadequate time and location that a weather file was generated from may have significant consequences on BPS.

The study brought to the attention of BPS analysts that there might be a substantial deviation in urban temperature from the respective rural-based weather data. Choosing an incorrect weather file for BPS can have a significant impact on simulation accuracy. BPS practitioners should be aware of the type of the location (rural/urban) that the selected weather file is from. In case of a mismatch in building site and weather station location type (e.g., a urban development and a rural weather file), adjustments may be advised to reduce the discrepancy. To transform a rural EPW file into a more accurately morphed urban file, one can use the Urban Weather Generator (UWG) (Nakano et al., 2015). Future studies should investigate the precision of the UWG transformations in relation to the actual rural-urban differences observed in real life.

There was a clear indication of potential impact from the temperature differences in different weather data sets and the implications they may have on heating and cooling. Climate change and urban heat islands contribute to higher average outdoor temperatures than those recorded in some weather files, which may lead to misestimation of the energy balance. For the heating demand of buildings in Sweden, poor selection of weather files may lead to an overestimation of up to 19 %. While there is a strong tendency for the yearly maximum to increase carrying potential consequences on cooling in buildings, the yearly minimum temperatures saw neither increasing nor decreasing trends, and thus, the impact on dimensioning of building heating systems is inconclusive.

Regarding solar weather parameters, it is uncertain whether the observed increase in average global radiation can be perceived as a trend. Previous research suggests that the impact on daylighting BPS is thus far limited and possibly negligible. Solar weather observations and the potential temporal differences due to climate change should be continuously inspected, and the consequences on BPS should be further investigated. Future work should examine the impact of the weather data differences on solar, thermal, and daylighting building performance using full-scale BPS.

5. Acknowledgements

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6. References

ASHRAE, 2001. International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-

ROM.

Baglivo, C., Congedo, P.M., Murrone, G., Lezzi, D., 2022. Long-term predictive energy analysis of a high-performance building in a mediterranean climate under climate change. Energy 238.

Burleyson, C.D., Voisin, N., Taylor, Z.T., Xie, Y., Kraucunas, I., 2018. Simulated building energy demand biases resulting from the use of representative weather stations. Applied Energy 209, 516–528.

Ceppi, P., Brient, F., Zelinka, M.D., Hartmann, D.L., 2017. Cloud feedback mechanisms and their representation in global climate models. Wiley Interdisciplinary Reviews: Climate Change.

Crawl, D.B., 2008. Estimating the impacts of climate change and urbanization on building performance. Journal of Building Performance Simulation 1, 91–115.

de Masi, R.F., Gigante, A., Ruggiero, S., Vanoli, G.P., 2021. Impact of weather data and climate change projections in the refurbishment design of residential buildings in cooling dominated climate. Applied Energy 303.

de Wilde, P., Coley, D., 2012. The implications of a changing climate for buildings. Building and Environment 55.

EnergyPlus, 2021. U.S. Department of Energy's (DOE) Building Technologies Office (BTO) |EnergyPlus | Weather Data [WWW Document]. URL https://www.energyplus.net/weather (accessed 3.16.21).

Guattari, C., Evangelisti, L., Balaras, C.A., 2018. On the assessment of urban heat island phenomenon and its effects on building energy performance: A case study of Rome (Italy). Energy and Buildings 158, 605–615.

Huld, T., Müller, R., Gambardella, A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. Solar Energy 86, 1803–1815.

Iversen, A., Svendsen, S., Nielsen, T., 2012. The effect of different weather data sets and their resolution on climate-based daylight modelling. Lighting Research and Technology 4, 305-316.

Ladybug Tools, 2021. Ladybug Tools | Home Page [WWW Document]. URL https://www.ladybug.tools/ (accessed 10.11.21).

Letherman, K.M., Al-Azawit, M.M.J., 1986. Predictions of the Heating and Cooling Energy Requirements in Buildings using the Degree Hours Method. Building and Environment 21, 171–176.

Moazami, A., Nik, V.M., Carlucci, S., Geving, S., 2019. Impacts of future weather data typology on building energy performance-Investigating long-term patterns of climate change and extreme weather conditions. Applied Energy 238, 696-720.

Nakano, A., Bueno, B., Norford, L., Reinhart, C.F., 2015. Urban Weather Generator - A Novel Workflow for integrating urban heat island effect within urban design process, in: Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association. Hyderabad.

Nik, V.M., Sasic Kalagasidis, A., 2013. Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties. Building and Environment 60, 291–304.

OneBuilding Climate, 2021. Repository of free climate data for building performance simulation [WWW Document]. URL http://climate.onebuilding.org/default.html (accessed 10.11.21).

Porritt, S.M., Cropper, P.C., Shao, L., Goodier, C.I., 2012. Ranking of interventions to reduce dwelling overheating during heat waves. Energy and Buildings 55, 16–27.

Psiloglou, B.E., Kambezidis, H.D., Kaskaoutis, D.G., Karagiannis, D., Polo, J.M., 2020. Comparison between MRM simulations, CAMS and PVGIS databases with measured solar radiation components at the Methoni station, Greece. Renewable Energy 146, 1372–1391.

Roudsari, M., Peng, M., 2021. GitHub - ladybug-tools/epwmap: map of available .epw weather files [WWW Document]. GitHub. URL https://github.com/ladybug-tools/epwmap (accessed 10.11.21).

RStudio Team, 2021. RStudio: Integrated Development Environment for R.

SMHI, 2021a. Data och analyser för väder samt Sveriges klimat och miljö | SMHI [WWW Document]. URL https://www.smhi.se/data (accessed 3.16.21).
SMHI, 2021b. Hur mäts solskenstid? | SMHI [WWW Document]. URL https://www.smhi.se/kunskapsbanken/meteorologi/stralning/hur-mats-solskenstid-1.5206 (accessed 10.11.21).

Paper III

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Identifying Potential Indicators of Neighbourhood Solar Access in Urban Planning

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Abstract: Solar access describes the capacity of urban spaces to receive sunlight and daylight. Rapid urbanization and unbridled densification pose a threat to sustainable solar access, reducing the penetration of sunlight and daylight into cities. To effectively assess solar access at such an early design stage, at the urban planning level, it is critical that evaluation metrics are simple and reliable. This paper examines a cross section of solar metrics, from simple to more complex ones, to find potential solar performance indicators for urban planning evaluations. The metric datasets were created based on iterations of homogeneous neighbourhood designs, based on the three commonest typologies in the Swedish context: courtyard, slab, and tower. The results were validated using case studies sampled from districts of Malmö. The findings indicate that simple geometrical and latitudinal metrics may be suitable for assessing the solar access of urban designs due to high correlation with built density. Potential performance indicators aimed at indoor and outdoor evaluation of daylighting (VSC, SVF) and sunlighting (ASH_F, RD_G) in urban planning stages were suggested. Possible methods of applying the provided metric database into assessments were proposed. Future work should find evidence-based thresholds for the metric values to establish performance benchmarks.

Keywords: solar access; daylight; sunlight; Kendall correlation; regression analysis; urban planning; performance indicator; neighbourhood scale

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1. Introduction

Sunlight is a valuable resource in cities, as it contributes to multiple sustainability and wellbeing goals. Solar energy impacts the building heat and energy balance, plays a major role in energy conservation strategies [1–3], and is essential for integrating on-site solar energy systems [4–6]. Furthermore, sunlight has the potential to improve mood [7,8], increase immune response [9], and kill germs [10], contributing to good health and the wellbeing of residents. The amount of sunlight reaching urban areas is commonly known as solar access. It defines the capacity of outdoor and indoor living spaces to receive sunlight.

The United Nations (UN) predicts that, by 2050, two-thirds of world's population will live in cities [11]. Cities will have to accommodate future inhabitants through new developments and densification projects, which has been observed in the past few decades already [12]. The rapid urbanization and increased densification of inhabited land pose a threat to sustainable solar access, reducing the availability of sunlight and daylight in cities. A study investigating daylighting in Swedish multi-family dwellings demonstrated that houses built in the years 1940–1960 received the highest solar access, which in later decades decreased due to an evident densification trend [13]. These authors also showed that increased urban density reduces chances to comply with daylight regulation.

Urban planners decide the form and layout of urban environments which define urban density and the amount of solar access. Studies have shown that urban planners often lack the expertise to carry out daylight assessments [14,15]. At such an early design stage, they also have insufficient data input for advanced simulation methods, missing crucial information about, for example, window placements, material properties, roofscapes, balconies, and internal layouts. There is a need for simpler methods and assessment metrics that could be implemented in early planning and massing stages when available input data is limited [16,17].

A previous review on solar performance metrics for urban planning indicated that simpler metrics are more suited for early design stages due to their lower complexity and level of data input required [18]. The review identified relevant metrics and found those metric classes that may be adequate for urban planning purposes: geometrical, latitudinal, and external climatic. While the metrics' suitability was assessed based on literature, little is still known about the metrics' relationships, impact, and correlations. Many previous studies focused on examining differences between urban design typologies rather than metrics and their best application [19–22].

Research into the domain of solar performance metrics for urban planning focuses mainly on: (a) evaluation of metrics and their relationships to increase confidence and knowledge in their application in solar performance assessments, (b) benchmarking metric values to establish performance criteria that can be used in design evaluations, and (c) establishing working paradigms for urban solar assessment methods with the use of multiple metrics and relevant criteria. The present paper deals with the first objective (a) and provides a database foundation for the second objective (b). Finding suitable metrics will help in establishing solar assessment paradigms for urban planning practice. Because metrics that are suitable for urban planning tend to be simple (carrying limited information), assessment workflows might need to integrate a combination of several metrics into the method.

The purpose of this paper is to analyse a selection of existing and newly developed solar metrics as potential candidates as performance indicators in design assessments. Metric datasets were evaluated for their relationship to each other and their suitability for early design assessments. The question to be addressed is whether simpler metrics can substitute for more complex ones in measuring solar access, and how can these metrics be applied in solar neighbourhood assessments. This paper focuses on metrics which are numeric and whose function is designated as comparative [18], meaning that they can provide reduced bias in the assessments of multiple different designs.

2. Methods

A selection of solar performance metrics was calculated using a large dataset of homogenous computer-based neighbourhood design iterations and a small set of existing neighbourhood case studies, which were used for the purpose of validating the outcomes based on the larger virtual design dataset. The methodology section consists of four parts: (a) modelling the neighbourhood design iterations, (b) selection of case studies, (c) solar performance metrics, and (d) data analysis. Previous work on solar performance metrics used in urban morphology studies provided grounding to the present study and informed the selection of solar metrics for the analysis [18]. The scope of this study was limited to residential multi-family neighbourhoods in the northern latitudes with a focus on the Swedish context.

2.1. Neighbourhood Design Iterations

The selection of typical Swedish neighbourhood typologies for this study was conducted based on the existing Swedish residential stock of multi-family apartment blocks. Most of the Swedish residential stock (52%) consists of multi-dwelling buildings, and their proportion is increasing [23]. In the years 2011–2020, there were three times as many dwellings built as multi-family buildings than those of single- or double-dwelling building type. A survey into Swedish urban morphology revealed that the most prevalent multi-family building types can be reduced to courtyard, slab, and tower typologies [24]. In Malmö, slab and courtyard typologies appear to be the most dominant (Figure 1); other forms such as tower, L-shaped, and U-shaped exist but are less common. Although towers were found less frequently in Malmö, they appear more frequently in higher density cities, including the Swedish capital city, Stockholm. Thus, for this study, three neighbourhood typologies were selected for generating design iterations and further solar performance analysis: courtyard, slab, and tower (Figure 2A–C).

Figure 1. Examples of existing urban neighbourhoods and building types in Malmö, where slab and courtyard typologies prevail. Imagery ©2022 Google, Imagery ©2022 Lantmäteriet/Metria, Maxar Technologies, Map data ©2022.

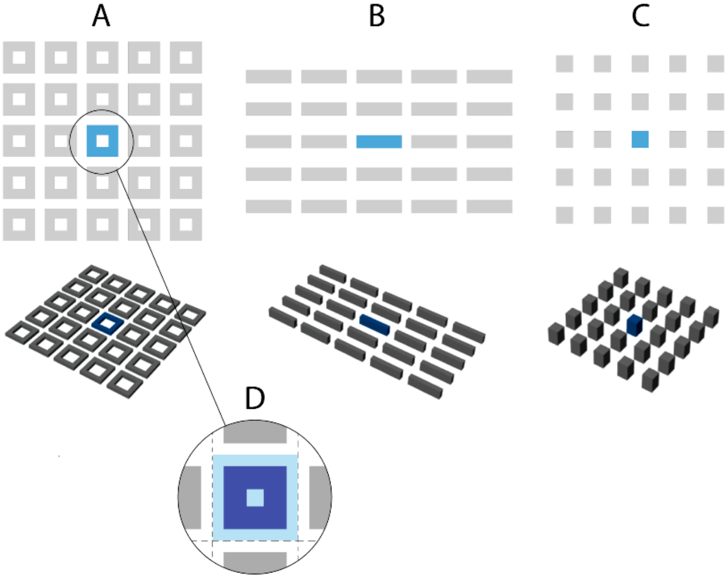


Figure 2. Exemplary iterations of the three studied neighbourhood typologies in top and perspective views: (**A**)—courtyard grid, (**B**)—slab grid, (**C**)—tower grid, and (**D**)—example of an analysed representative unit, comprising of one building and its plot (top view).

In order to facilitate the iterative modelling process, the neighbourhoods were modelled as homogeneous. Buildings within a neighbourhood were evenly spaced and arranged in a large, 5 × 5 unit orthogonal grid to include context shading (Figure 2A–C). Since the neighbourhoods were modelled homogenously, only the central building unit and the immediate area around it were analysed for solar access i.e., the middle unit was considered representative of the entire neighbourhood (Figure 2D). Vegetation and urban infrastructure were not included. Buildings were modelled without roof or façade details, which in digital city modelling is known as Level of Detail 1 (LoD1) [25]. The 3D models of design iterations were generated using Rhinoceros 7 [26] with Grasshopper [27].

Neighbourhood design iterations were created assuming ranges of geometrical design constraints. The dimensional constraints of the modelled neighbourhood geometries were intended to provide an adequate representation of the typical Swedish residential stock and a reasonable framework for the metric datasets. The discrete (countable) parameters are listed in Table 1, and the corresponding dimensions are marked in Figure 3. The number of design iterations changes in respect to the taxonomical class of calculated metrics; geometrical (G-) metrics have a smaller number of individual iterations because the building orientation variable is unapplicable for these metrics. Wall thickness (0.5 m) and storey height (3.0 m) were set as fixed values to calculate floor areas and space volumes. The plot offset was the distance from building façade edge facing outwards to the plot edge. For slab iterations, the offset distance was measured from the longer façade edge, and the distance from the short edge to the plot edge was equal to half the offset. This was found to be a common spatial feature in real slab neighbourhood cases.

Table 1. Range (X-Y) and number (N, in brackets) of discrete variables used in neighbourhood design iterations and the total number of iterations.

Typology	**Variables**					**Total No. of Design Iterations [G-Metrics/Other Metrics]**
	Dimension, B [m]	**Plot Offset [m]**	**Building Depth, D [m]**	**Storeys**	**Rotations [°]**	
Courtyard	12–92 (11)	8–32 (7)	16 (1)	2–10 (5)	0–45 (2)	385/770
Slab	32–128 (13)	8–32 (7)	16 (1)	2–10 (5)	0–90 (3)	455/1365
Tower	16–20 (3)	4–32 (15)	=B	2–20 (10)	0–45 (2)	450/900

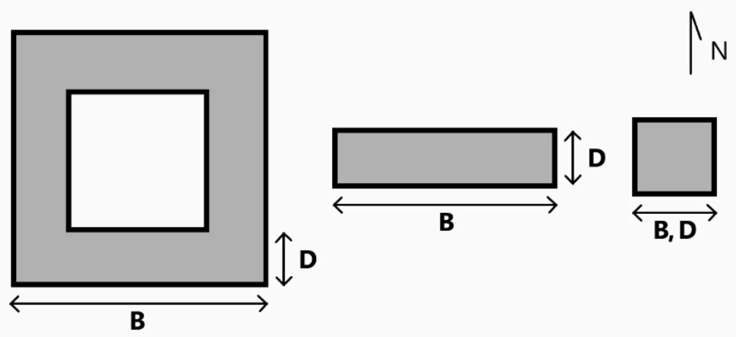


Figure 3. Courtyard, slab, and tower typologies (from left to right) presented in top view at 0° rotation: The letters 'B' and 'D' denote the dimension variables specified in Table 1.

The original dataset included more extreme cases (e.g., towers having 20 storeys and only 8 m span between buildings). However, iteration cases with a density indicator and a floor area ratio (FAR), larger than 4 were removed, as they represented highly unrealistic urban scenarios [28,29]. Even in the high-density city of New York, the maximum FAR averages 2.4 [30]. The FAR distribution of the original dataset is highly skewed (Figure 4). Neighbourhood design iterations with FAR above 4 were outliers of the dataset, as seen from the box plot in Figure 4. Removing the outliers provides a more balanced dataset.

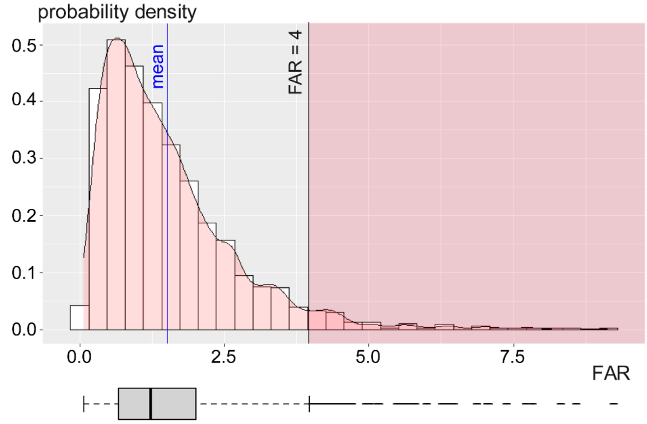


Figure 4. Population density of the FAR metric with original mean line (blue) and removed portion of iteration cases (where FAR > 4). A box plot of the FAR dataset is included at the bottom.

2.2. Case Studies

Case studies of seven existing neighbourhoods situated in Malmö, Sweden, were used to validate the iterative design datasets that were generated from hypothetical neighbourhoods (Section 2.1). The case studies were comprised of the same typologies as the iterations and included three courtyard neighbourhoods, three slab neighbourhoods, and one tower neighbourhood. The tower typology is underrepresented in the urban context of Malmö, therefore only one tower neighbourhood was included. The selected case studies are presented in Figures 5 and 6.

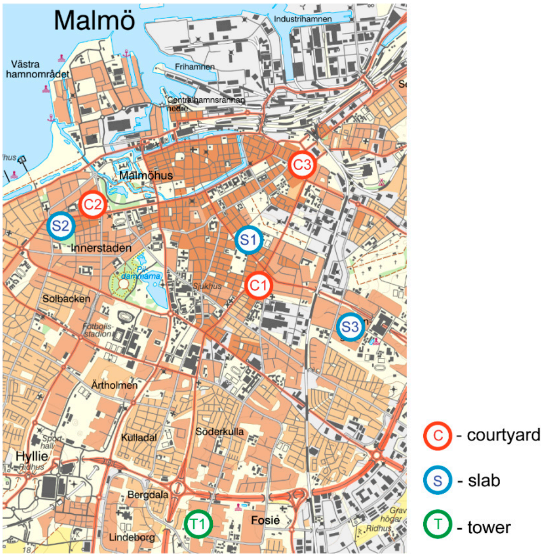


Figure 5. Map of Malmö with neighbourhood case study locations. Background map (1:50,000, raster) © Lantmäteriet (2022).

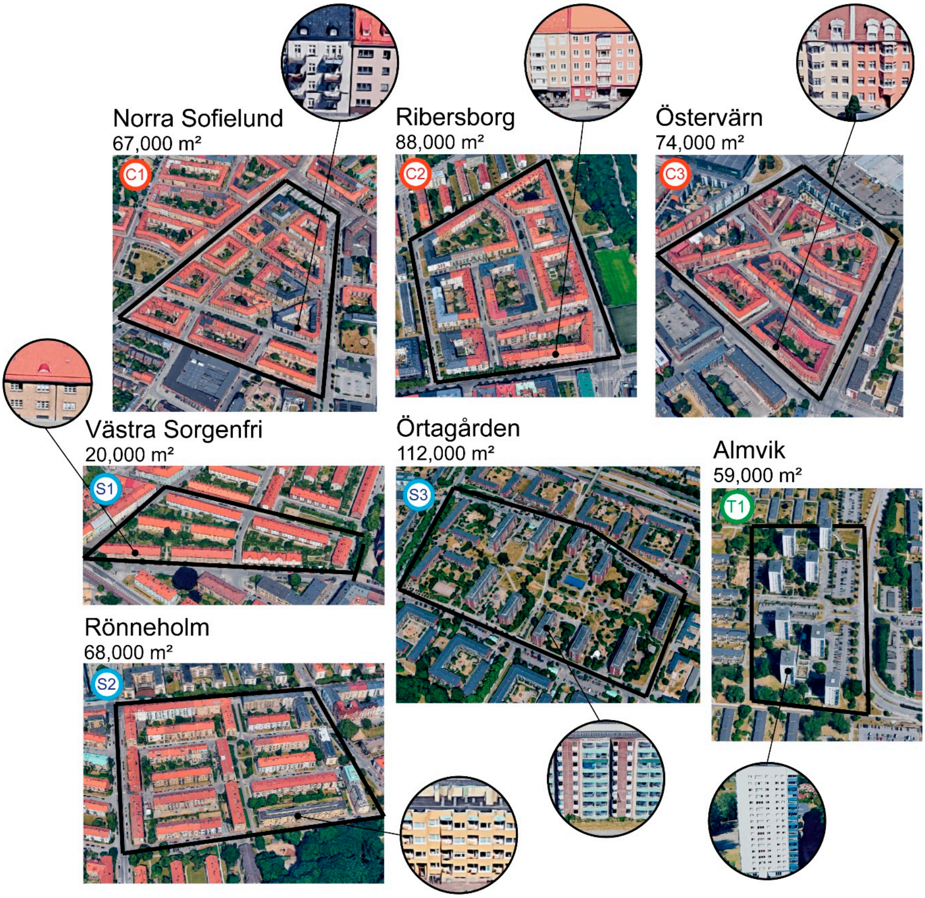


Figure 6. Malmö neighbourhood case studies used in analysis. Case study codes link to markings in the map in Figure 5. Imagery ©2022 Google, Imagery ©2022 Lantmäteriet/Metria, Maxar Technologies, Map data ©2022.

The identification of suitable neighbourhood areas for case studies was governed by preassigned selection criteria. The definition of a neighbourhood is vague; many varying neighbourhood concepts exist, and the classification of the extents of one neighbourhood tends to be blurry. The concept of a "neighbourhood unit" was used in this paper as a framework for the identification of neighbourhood boundaries [31–33]. However, the factors that define a neighbourhood should remain flexible, diverse, and sensitive to the local context [34,35]. Swedish cities differ slightly from the West European cities as they developed in a more decentralized fashion, and they tend to be less densely populated [36]. They also seem to lack a precise definition of a neighbourhood [37]. The selection criteria were thus adapted to reflect the understanding of a neighbourhood in the Swedish context. The criteria were also intended to match the attributes assigned to the hypothetical neighbourhood design iterations in order to provide a suitable validation framework for the solar metrics. The following selection criteria were used:

- The neighbourhood shall not be intersected by large traffic roads,
- The neighbourhood must be comprised of residential multi-storey buildings and include one of the three analysed typologies (courtyard, slab, tower),
- The neighbourhood shall be nearly homogenous (composed of the same typology),
- The neighbourhood shall be surrounded by built context of similar height,
- The case studies shall come from different administrative districts (sv: delområde).

The neighbourhoods were modelled in Rhinoceros 7. Geodata used for generating 3D models was obtained from Lantmäteriet [38]. The modelling details were similar to those of the iteration dataset: the geometries were simplified to LoD1, which means that roof and ground surfaces were horizontal and flat. Façade details, such as windows and balconies, were not included in the model, and neither were the vegetation and urban infrastructure elements.

2.3. Solar Performance Metrics

The selection of metrics for the analysis was based on an earlier review [18], and the metrics are listed in Table 2. All metrics belong to one of three classes of metrics: geometrical (G-metrics), latitudinal (L-metrics), and external climatic (EC-metrics). These three classes appear most suitable for solar assessments in urban planning stages due to the lower level of complexity compared with internal climatic metrics [18]. Only metrics with comparative and conforming functions [18] were used. Most of the metrics were sourced from previous literature, though there were also new metrics generated for this study; these were marked in Table 2 with an asterisk. Two types of urban surfaces were analysed for solar access depending on the assumed outdoor or indoor performance perspective, i.e., ground and facades (Figure 7). The analysis surfaces are given in the 'Subject' column of Table 2 and indicated with 'G' or 'F' suffix in metric acronyms. Roofs were not considered in this study because of their flat horizontal shape and the homogeneity of neighbourhood building heights in the iteration cases, which means that the roofs are receiving maximal solar access, and little variation due to design choices can be achieved. Metrics were simulated using Ladybug and Honeybee [39] in Grasshopper for Rhinoceros 7 [26].

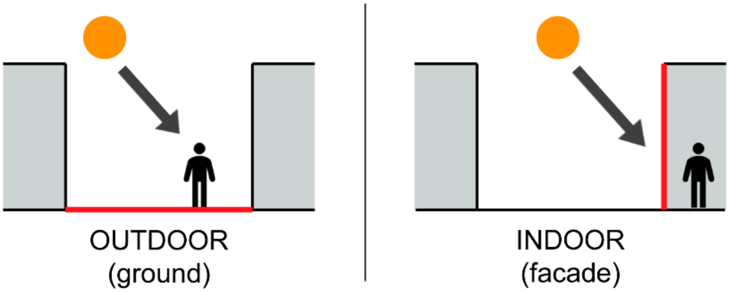


Figure 7. Two types of analysis surfaces (ground—**left**, façade—**right**) used to assess the outdoor and indoor environment.

G and L metrics that were calculated on façades (VSC, TH_F, ASH_F, RD_F) were simulated for a single string of points located on the façade at the height of 1.4 m and spaced 1 m apart (Figure 8), as solar access at the ground floor guarantees even better solar access at upper levels. Façade-based EC metrics measure surface irradiation, which affects the building's overall thermal balance and solar energy potential, and thus, assessing the entire surface was deemed necessary to assess the radiation aspects. The radiation metrics were simulated for the entire façade surfaces (Figure 8).

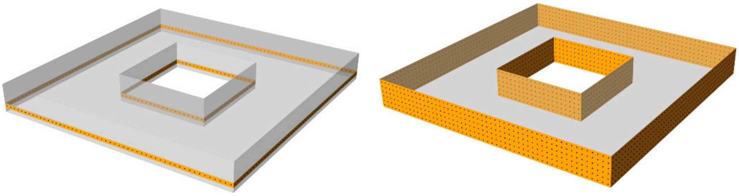


Figure 8. Two kinds of simulation point grids for façade-based metrics. **Left**: single string of points at 1.4 m height. **Right**: the whole façade made into a point grid.

Table 2. List of metrics selected for analysis. Metrics that were not sourced from literature were marked with an asterisk.

	Acronym	Name	Subject	Calculation or Simulation Method [Unit]
G-metrics	FAR	Floor Area Ratio	whole	Ratio of gross floor area to plot area [m^2/m^2; used as unitless]
	VAR	Volume Area Ratio	whole	Ratio of gross building volume to plot area [m^3/m^2; used as unitless]
	SAR *	Surface Area Ratio	whole	Ratio of gross external building surface area to plot area [m^2/m^2]
	OSR	Open Space Ratio	whole	Ratio of open space area to gross floor area [m^2/m^2]
	SVF	Sky View Factor	ground	Grid-based (1 m), 145 sky patches, cosine-weighted sky dome [%]
	VSC	Vertical Sky Component	façade (string)	At 1.4 m height, 1024 sky patches, CIE overcast sky [%]
L-metrics	APS	Area of Permanent Shadow	ground	Grid-based (1 m), ray intersection, fraction of the grid open to no direct sunshine on 21 March
	TH_G	Two-Hour area	ground	Grid-based (1 m), ray intersection, fraction of the grid open to 2 or more hours of direct sunshine on 21 March
	TH_F *	Two-Hour area	façade (string)	Grid-based (1 m), ray intersection, fraction of the grid open to 2 or more hours of direct sunshine on 21 March
	ASH_G *	Annual Sunlight Hours	ground	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors
	ASH_F *	Annual Sunlight Hours	façade (string)	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors
	RD_G *	Reference Day (Sunlight Hours)	ground	Grid-based (1 m), ray intersection, average hours of direct sunshine on 21 March [h]
	RD_F *	Reference Day (Sunlight Hours)	façade (string)	Grid-based (1 m), ray intersection, average hours of direct sunshine on 21 March [h]
EC-metrics	APSH	Annual Probable Sunlight Hours	façade (string)	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors (relative to cloud coverage: e.g., 40% cloudiness for a given hour gives 0.6 h of direct sun)
	RAD_F	Solar radiation (mean)	façade	Grid-based (1 m), annual solar radiation mean per façade area [kWh/m^2]
	nRAD_F	Solar radiation (norm.)	façade	Grid-based (1 m), total annual radiation normalized by gross floor area [kWh/m^2]
	nPV_F	PV potential	façade	Grid-based (1 m), surface area with solar radiation above 600 kWh/m^2 normalised by floor area [m^2/m^2]

There are different levels of site and layout factors that influence metrics, depending on their class, which are presented in Table 3. Location has impact on L- and EC-metrics; G-metrics are unaffected by location. Two European climates were investigated in the iterations analysis: Stockholm (59.65° N, 17.95° E) and Frankfurt (50.05° N, 8.60° E). Both locations belong to the transitional temperate zone of warm climate according to the classification by the European Environment Agency [40] yet are located at the northern and southern end of its reaches, which affects the amount of potential solar access. The case studies were simulated for the same locations. IWEC (international weather for energy calculations) EPW (energy plus weather) annual weather files were used for both Stockholm and Frankfurt [41].

Table 3. The main influencing factors of each solar metric class.

G-Metrics	L-Metrics	EC-Metrics
geometrical dimensions	geometrical dimensions latitude orientation	geometrical dimensions latitude orientation insolation (climate)

2.4. Data Analysis

Metric datasets were analysed for correlations. The analysis method was two-fold: first, a Kendall correlation analysis was performed to assess the strength of associations based on its τ_B value, and then a pairwise graphical evaluation of metric relationships was conducted to assess the functions' linearity and variance.

The datasets did not meet the necessary conditions for linear regression and Pearson correlation analyses. However, for those cases of pairwise metric relationships that resembled a linear function, Pearson correlation (r value) and linear regression analyses were conducted. These analyses were carried out for illustrative purposes and should be treated with caution since required assumptions were not met. Statistical analyses were performed in RStudio [42].

The suitability iteration-based datasets were validated by comparing them with case study datasets for each metric pair. The test hypothesis was that the slope and intercept of the iteration-based regression line of a given solar metric would fall within a 95% confidence interval (CI) of the slope and intercept ranges of the case studies.

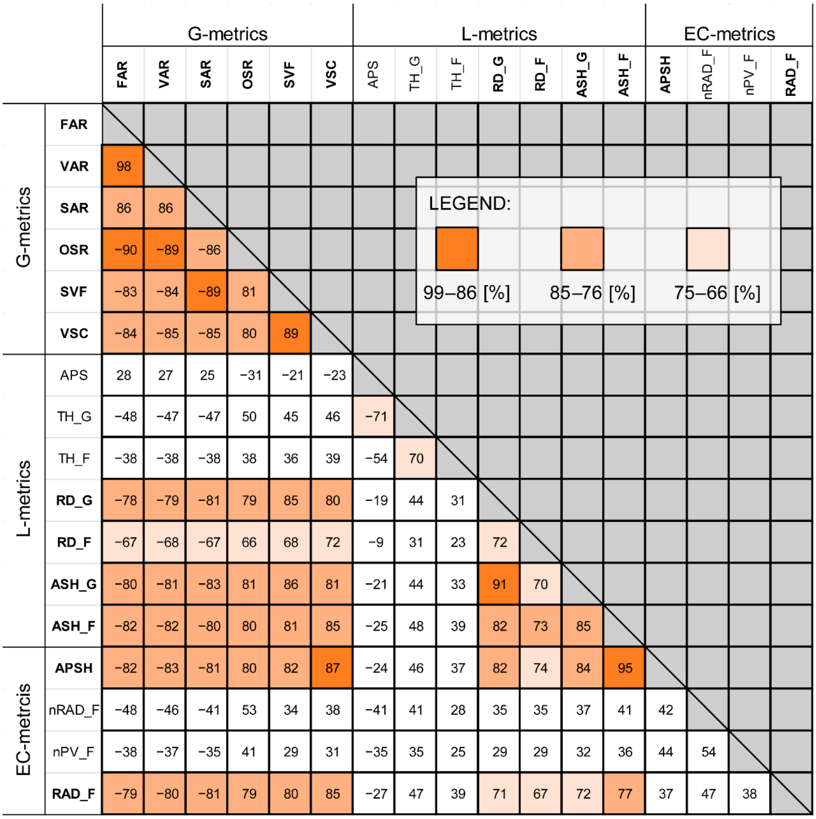
Pre-analysis of simulated datasets indicated that it is sufficient to focus on only one climate location and analyse metric relationships for that climate. Thus, for the ease of analysis, Frankfurt was selected as the base climate for analysis and results presentation in this paper. All datasets from this study were made available for further inspection and reuse and were uploaded to a scientific data sharing repository [see the Data Availability Statement].

3. Results

3.1. Metric Correlation

The results of the Kendall correlation analysis are presented in Figure 9. G-metrics show good correlation among themselves and with the comparative L- and EC-metrics. On the other hand, the correlation data hints that conforming metrics (metrics that are based on compliance to a threshold, e.g., pass/fail) do not correlate well with other metrics nor with each other. Furthermore, normalised radiation metrics did not prove high correlation to other metrics. The correlation study gave an initial indication of the strength of metrics' pairwise relations, which allowed for the identification of metrics with high correlation scores for further graphical analysis and interpretation. In Figure 9, the high scoring metrics were highlighted (in bold).

Additionally, a Pearson correlation was conducted to examine the linearity of metric relationships. It indicated that functions of metric pairs FAR–VAR and SVF–VSC might be linear because in addition to the high Kendall correlation, their Pearson correlation results were also close to 1.



		G-metrics						L-metrics							EC-metrics			
		FAR	**VAR**	**SAR**	**OSR**	**SVF**	**VSC**	APS	TH_G	TH_F	**RD_G**	**RD_F**	**ASH_G**	**ASH_F**	**APSH**	nRAD_F	nPV_F	**RAD_F**
G-metrics	**FAR**																	
	VAR	98																
	SAR	86	86															
	OSR	−90	−89	−86														
	SVF	−83	−84	−89	81													
	VSC	−84	−85	−85	80	89												
L-metrics	APS	28	27	25	−31	−21	−23											
	TH_G	−48	−47	−47	50	45	46	−71										
	TH_F	−38	−38	−38	38	36	39	−54	70									
	RD_G	−78	−79	−81	79	85	80	−19	44	31								
	RD_F	−67	−68	−67	66	68	72	−9	31	23	72							
	ASH_G	−80	−81	−83	81	86	81	−21	44	33	91	70						
	ASH_F	−82	−82	−80	80	81	85	−25	48	39	82	73	85					
EC-metrcis	**APSH**	−82	−83	−81	80	82	87	−24	46	37	82	74	84	95				
	nRAD_F	−48	−46	−41	53	34	38	−41	41	28	35	35	37	41	42			
	nPV_F	−38	−37	−35	41	29	31	−35	35	25	29	29	32	36	44	54		
	RAD_F	−79	−80	−81	79	80	85	−27	47	39	71	67	72	77	37	47	38	

LEGEND:

🟧	🟧	🟧
99–86 [%]	85–76 [%]	75–66 [%]

Figure 9. Correlation (Kendall) of metrics from iteration-based datasets simulated for Frankfurt and Stockholm presented in percentage format. τ_B values equal to 100% indicate perfect agreement. Metrics were described in Table 2.

3.2. Urban Density

Two metrics pertaining to urban density were studied: FAR and VAR. They demonstrated a high Kendall correlation (τ_B = 0.98) and a potentially linear relationship (r = 1.00).

Figure 10 presents VAR as a function of FAR. The design iterations (black dots) show a nearly perfect linear function, while the case studies (red dots) diverge from the linear regression line. It is observed that the case studies do not fit the function well; that is because the case study storey heights varied, while storey height in design iterations was a constant.

Equation (1) explains the linear relationship between FAR and VAR, assuming that the storey height (h_s) is constant.

$$\mathrm{VAR} = \mathrm{FAR} \cdot \mathrm{h_s}, \tag{1}$$

Figure 10 suggests that VAR is a better indicator of urban density for assessing real neighbourhood examples for solar access because it is free of the independent variable: storey height. Indeed, FAR has been used in studies where urban density is an indirect indication of population density, such as in land or property value, and in transportation studies [30,43,44]. VAR might be a better indicator of urban density for solar access considerations because it pertains to volumes of buildings rather than population. Therefore, throughout this study, for the purpose of relating metrics to the urban density of the designs, the VAR metric was used as a density indicator.

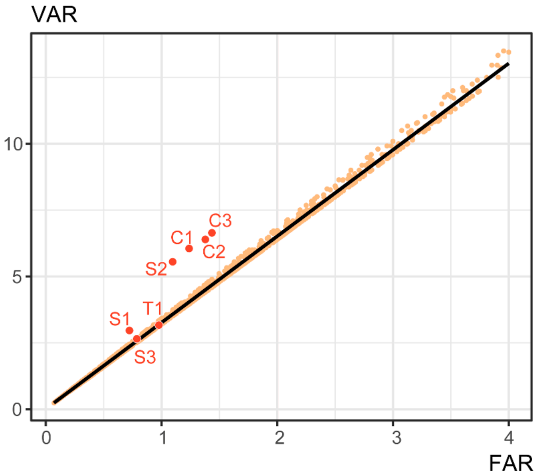


Figure 10. Iteration-based linear regression analysis of urban density metrics, FAR and VAR. Case studies are marked in red with labels (codes explained in Figures 5 and 6).

Figure 11 presents the VAR iteration-based dataset distribution and the density of the case studies (blue dots). The iteration-based distribution is positively skewed. Although the case studies were randomly selected, their densities distribute roughly symmetrically on the opposite sides of the mean line and form two clusters. An explanation for this could be found in the consistency of spatial or temporal aspects in the urban planning practices in Malmö city.

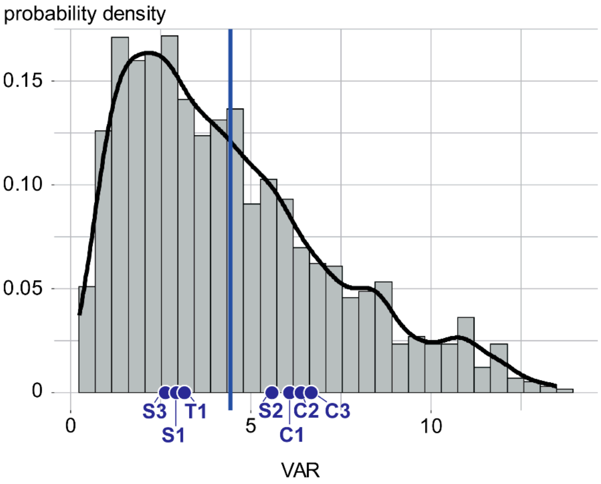


Figure 11. Probability distribution of VAR dataset. Blue line marks the dataset mean, and blue dots mark the case study values (codes explained in Figures 5 and 6).

3.3. G-Metrics

In this section, the results presented as metric datasets in graphs are identical for both simulated locations, Stockholm and Frankfurt, as G-metrics are only influenced by the geometry layout (see Table 3 in Section 2.3).

The G-metrics demonstrate a high Kendall correlation (Figure 9). The Pearson correlation analysis on these metrics resulted in equally high scores on the level of r $\approx$ 0.95, except for the OSR metric. Graphs in Figure 12, which display pairwise plots, show a nearly linear relationship for most of the G-metric pairs.

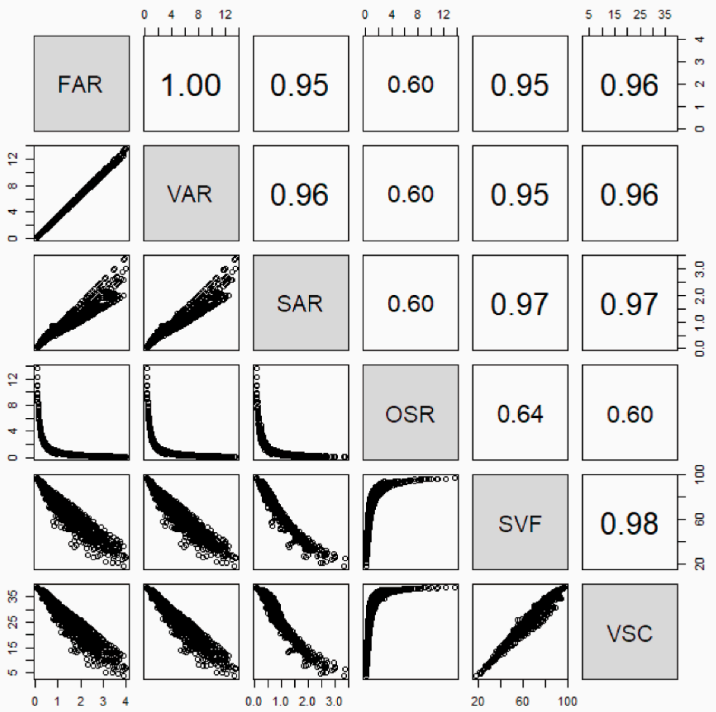


Figure 12. Summary of pairwise relationships between G-metrics with graphical plots (lower half) and Pearson correlation results (upper half).

Among the morphological G-metrics, FAR, VAR, and SAR have similar correlation scores and appearance of graphs, which may indicate that they play a similar role in assessment and could be used interchangeably. SAR as a function of either of the density metrics, FAR or VAR, forms a fan-shaped data graph, meaning that the variance becomes larger the higher the metric values. The OSR metric, albeit having similar correlation scores, has a reciprocal graph shape. Since OSR is a ratio that takes similar inputs as FAR, it is considered inferior to FAR because of the unfavourable graph appearance.

To further investigate the relationships between G-metrics, a linear regression analysis was conducted. Metrics SVF and VSC were tested against density VAR (Figures 13 and 14) and against each other (Figure 15). The case studies fit well within the iteration-based datasets, as they appear close to the regression lines and within the simulated iterative designs. The graphs in Figures 13 and 14 show fan-shaped relationships, which implies a heterogenous variance in the data. The SVF-VSC graph (Figure 15) shows a linear function with lower variance, though the function loses linearity at the data tails.

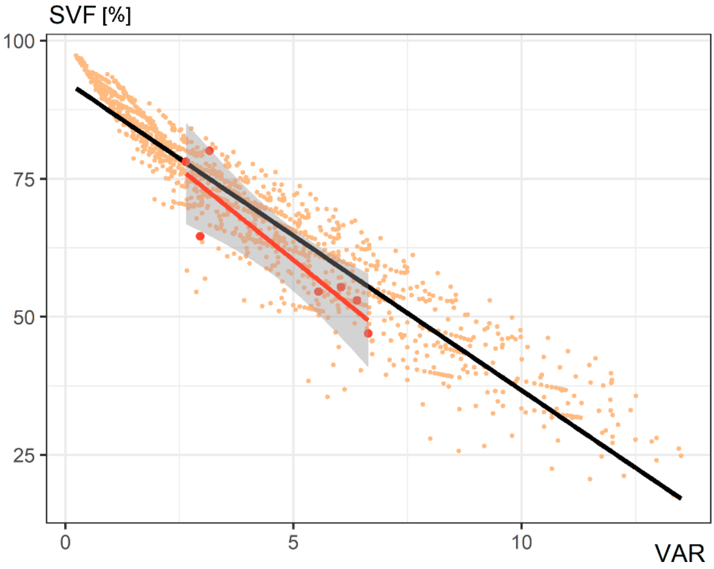


Figure 13. Linear regression function of metrics VAR and SVF based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

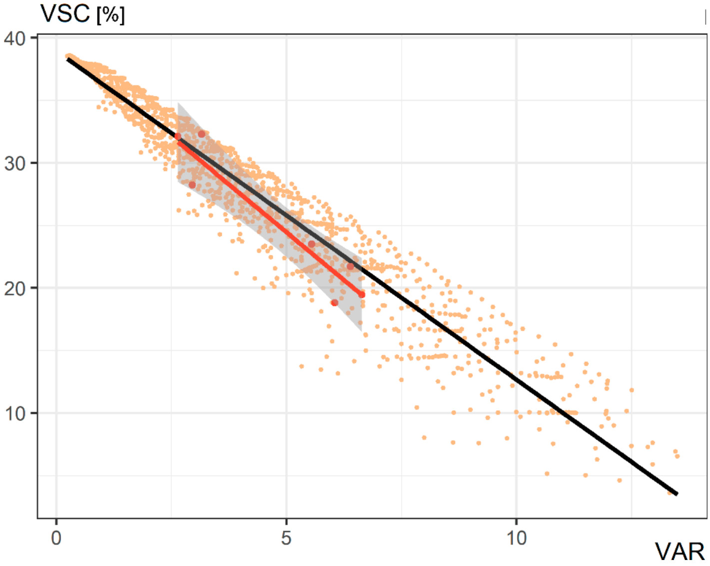


Figure 14. Linear regression function of metrics VAR and VSC based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

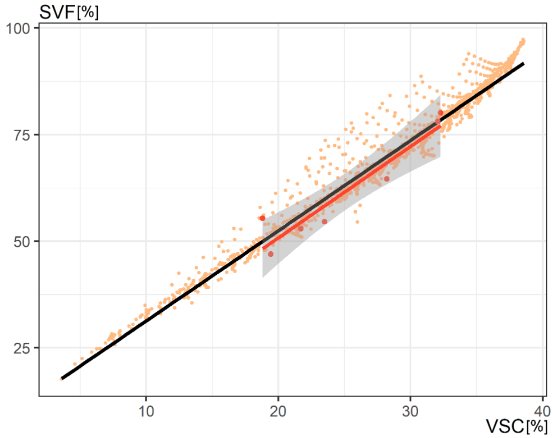


Figure 15. Linear regression function of metrics VSC and SVF based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

3.4. L-Metrics

L-metrics communicate solar access based on a set time period. The length of the reference time period affects the intensity of the computer simulation. To simplify the calculation, legislation normally recommends checking solar access for only a single reference day [45]. Looking at two L-metrics, RD_G and ASH_G, which were simulated at the ground surface but assume different time periods (reference day and a whole year), their graph shows linear characteristics (Figure 16). This relationship hints that the single-day-based RD_G metric may be used instead of the annually based ground ASH_G metric, which assumes a longer simulation period and thus takes more time to simulate. Additionally, the case studies regression line is nearly colinear with the iteration-based regression line, which validates the occurring relationship between RD_G and ASH_G.

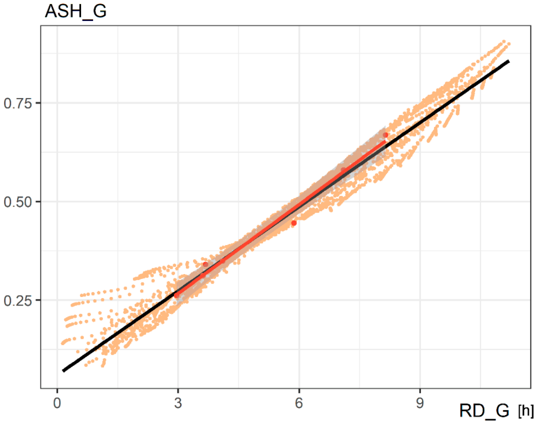


Figure 16. Linear regression function of ground-based L-metrics RD_G and ASH_G based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

The ground-based L-metrics (RD_G and ASH_G) show a non-linear relationship with density expressed by VAR (Figure 17). However, linear regression lines drawn for the case studies seem to approximate the respective parts of the iteration-based functions. In particular, the case studies regression line for the RD_G metric appears to be a close approximation of the original iteration-based trendline. Notably, graphs showing relation of density to ASH_G and RD_G have a similar shape (Figure 17), which is in line with their high mutual correlation and linear relationship in Figure 16.

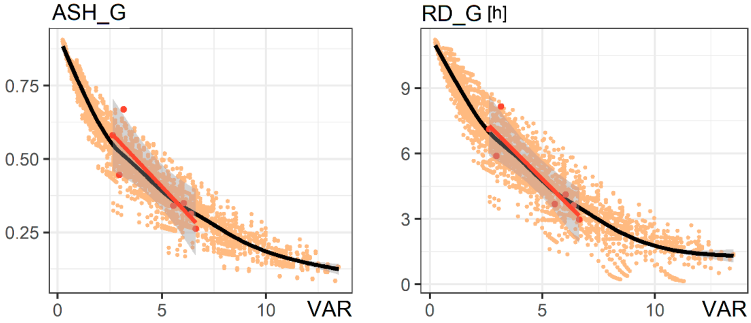


Figure 17. Non-linear regression functions of density metric VAR with L-metrics ASH_G (**left**) and RD_G (**right**) based on neighbourhood iterations (black line) and case-study-fitted linear regression line (red) with 95% CI in grey. The case study linear regression approximates the respective section of the non-linear regression from iterations.

Looking at the same metrics (RD and ASH) but calculated for the facades, the relationship does not show the same high-definition linearity, and a larger variance is present in the datasets (Figure 18). Similarly, the relation of RD_F to VAR is dispersed and non-linear (Figure 19). The dispersion and lack of continuity in the data could be attributed to the orientation of the analysis surfaces. Facades are vertical surfaces, which see only half of the sky dome for any given façade orientation, as opposed to the ground surface, which sees the whole sky dome. For the iteration-based neighbourhood cases, four facades facing four different directions (right-angled) were considered. Slab typology is more sensitive to rotation because it has two lines of symmetry (the square courtyard and tower have four), and this sensitivity can be seen in the graph (Figure 19). Furthermore, RD_F is a simpler version of the direct sunlight hours metric and is only based on a single reference day (21 March), as opposed to the whole year in the calculation of ASH_F; the simulation uses 12 hourly solar vectors for calculation of the sunlight hours. The sparse number of vectors means that the measurement may lack continuity, as time is divided into few discrete intervals. This can create a stepwise appearance of the datasets in the graph. The difference is apparent when comparing the relationships of the two façade L-metrics (RD and ASH) to VAR (Figures 19 and 20). The ASH_F metric not only shows higher correlation scores (Figure 9), but its relation graph also has a nearly linear data distribution (Figure 20), particularly for the lower densities.

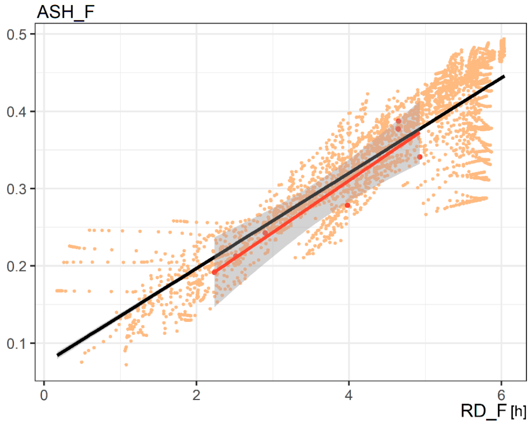


Figure 18. Linear regression function of façade-based L-metrics RD_F and ASH_F based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

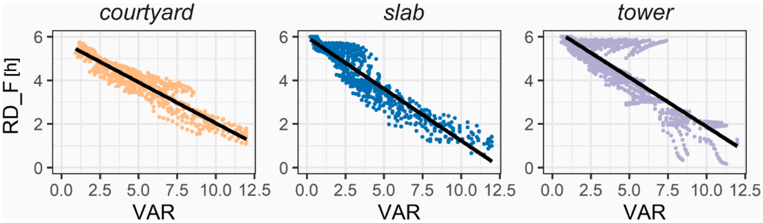


Figure 19. Linear regression functions of metrics VAR and RD_F based on neighbourhood iterations (black line), presenting results for each neighbourhood typology in a separate graph.

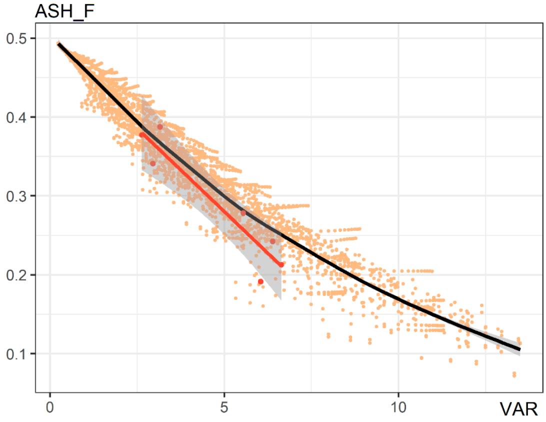


Figure 20. Non-linear regression function of density metric VAR with L-metric ASH_F based on neighbourhood iterations (black line) and case-study-fitted linear regression line (red) with 95% CI in grey.

3.5. EC-Metrics

APSH was the only metric in the EC-metric class that was not based on radiation; it was built on the hourly scores of the ASH_F metric with added information about cloud coverage, which was taken directly from the weather file. The correlation results for APSH (Figure 9) show almost identical scores as the simpler ASH_F metric. The correlation between ASH_F and APSH was at the level of 0.95, and their relationship was linear. This suggests that the simpler L-metric ASH_F may be used instead of the APSH, as there is no need to introduce an extra level of complexity with APSH.

Figure 21 shows an example of how a graph with a normalized (in this case per floor area) or conforming (threshold based) radiation metric tends to look. The data distribution is scattered and clustered in a stepwise manner due to the initial discrete parameter settings. The normalized metrics also show low correlation levels with other metrics (Figure 9).

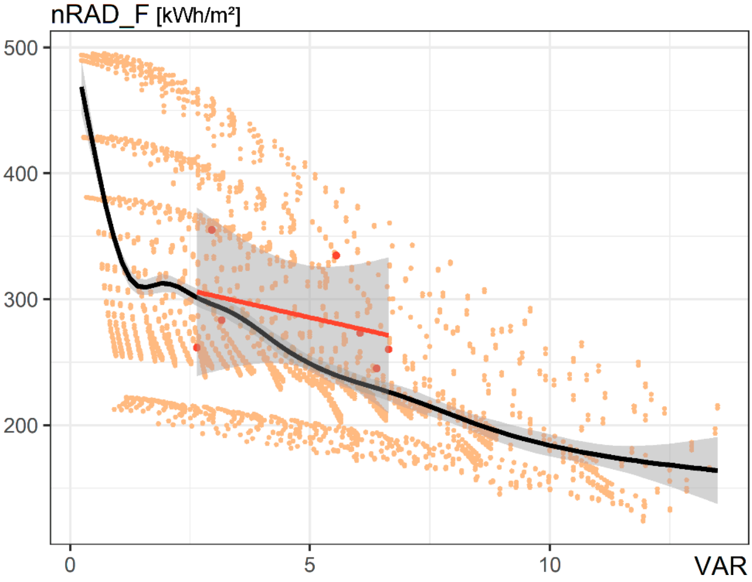


Figure 21. Non-linear regression function of density metric VAR and normalised EC-metric (black line) with case-study-fitted linear regression line (red) and 95% CI in grey. The graph indicates a low correlation with the scattering and clustering of data points.

Considering the comparative façade radiation metric, RAD_F, the example pairwise graph in Figure 22 relating RAD_F metric with density shows that the case studies' data points diverge from design iterations, as they scored significantly lower values of RAD_F. Façade irradiation was overestimated for the uniform, perfectly square, and evenly distributed neighbourhood typologies (iterations), while for the case studies, in which facades had non-right angles and more geometrical complexity, the scores were largely reduced. Compared with lower complexity metrics that were seen to have a good match between iterations and case studies, it seems that radiation metrics are more sensitive to changes in layout, surroundings, building forms and façade details. Furthermore, the lack of uniformity in building heights within case studies might have an additional impact on radiation estimates. The results suggest that, despite clearly defined curves of the iteration-based metric functions, these relationships do not hold for real neighbourhood cases.

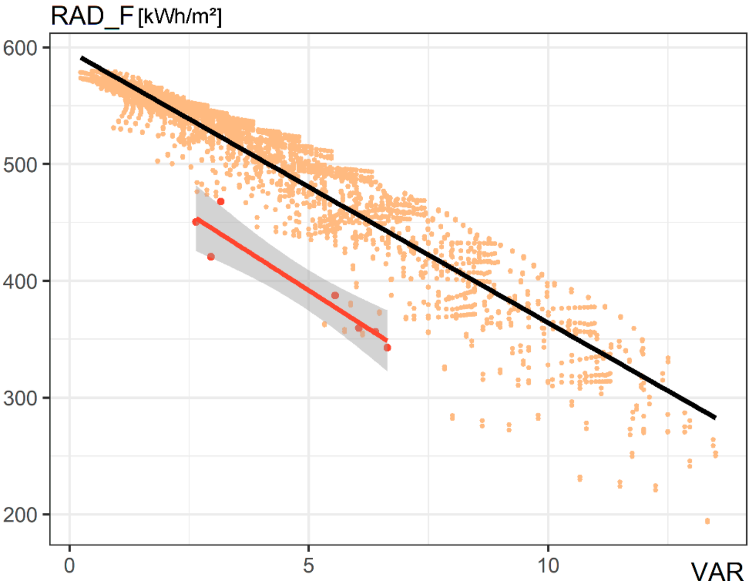


Figure 22. Linear regression function of metrics VAR and RAD_F based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

Comparing the linear regression lines of the iterations and the case studies, it can be noted that their functions appear parallel. This may suggest that the regression lines based on the two datasets have a similar slope, just a different intercept (Figure 22). If the rate of change is similar, it may be justified to use the simpler metrics, such as VSC or ASH, to inform the selection of better performing designs. Although they might not be able to provide a precise estimation of radiation on facades, they may point towards designs that will provide a better radiation score in comparison to other proposals.

Table 4 presents 95% CIs of linear regression coefficients in some pairs of metrics. It confirms the observation on the regression slopes of the pairs containing the EC radiation metric. For all metrics pairs but the EC ones, the iteration-based CIs are narrower than the case study intervals (due to the higher number of degrees of freedom) and fall within the CIs of the case study regression coefficients. For those metrics pairs that include an EC metric, the intercept of the iteration-based cases does not fall within the case study interval, but the slope does. This means that the rate of change is expected to be the same, but the values will be reduced for more realistic neighbourhood geometries. The homogeneity of iteration design cases inflates the radiation results, and the CIs indicate an average reduction of 12% due to higher geometrical complexity. Reduction factors are typically applied for radiation estimates with urban designs of low LoD [46].

Table 4. Confidence intervals (CIs) of 95% level for linear regression model coefficients of iteration- (I) and case study- (CS) based metric datasets. A metric pair is validated when CI for I data fits within the CI of CS data.

Metric Pair	Data	Intercept		Slope	
		Lower CI	Higher CI	Lower CI	Higher CI
SVF-VAR	I	92.4	92.9	−5.65	−5.56
	CS	76.3	110.8	−10.08	−3.24
VSC-VAR	I	38.8	39.0	−2.65	−2.61
	CS	33.8	45.8	−4.25	−1.87
SVF-VSC	I	9.84	10.4	2.10	2.12
	CS	−13.1	29.0	1.32	2.96
ASH_G-VAR	I	0.731	0.740	−0.061	−0.059
	CS	0.548	1.013	−0.121	−0.029
RD_G-VAR	I	9.36	9.49	−0.84	−0.81
	CS	7.41	12.6	−1.54	−0.52
ASH_F-VAR	I	0.472	0.476	−0.032	−0.032
	CS	0.402	0.580	−0.060	−0.025
RD_F-VAR	I	6.06	6.14	−0.44	−0.42
	CS	5.00	7.94	−0.87	−0.29
RAD_F-VAR	I	595.3	598.3	−23.6	−23.0
	CS	470.1	576.2	−36.8	−15.8
ASH_G-RD_G	I	0.058	0.063	0.071	0.071
	CS	−0.017	0.101	0.064	0.086
RAD_F-VSC	I	252.0	256.0	8.71	8.85
	CS	134.1	237.0	6.43	10.44

4. Discussion

This study showed that many simple metrics can potentially be suitable for solar evaluations at the urban planning stages due to good correlations. The solar access assessments may have varying objectives, and the two main paths of evaluation have been found to be the daylighting and sunlighting provision. For each of these assessment targets, the most suitable metrics were identified and listed in Table 5. Sections 4.1 and 4.2 discuss the aspects of indoor and outdoor solar access assessments in relation to sunlight and daylight.

Table 5. Suggested metrics that may be suitable for early assessments of solar access at the urban planning level.

	Indoors	Outdoors
Daylighting	VSC	SVF
Sunlighting	ASH_F	RD_G

4.1. Solar Access Indoors

4.1.1. Daylight

The daylight factor (DF) is a common indicator of indoor daylighting. It is a G-metric, which means it is independent of location and climate inputs. The Swedish Building Code (SS-EN 17037) specifies that daylight in buildings should be measured using the DF metric simulated for a single point in a room [45]. The point, which is located halfway into the room from the aperture, 1 m away from the darkest wall, and 0.8 m above the ground, should score a DF of at least 1%. Driven by this legal constraint, urban planners in Sweden prioritise the daylighting objective when planning for solar access [16].

VSC can be used as an early indicator of daylighting at the façade level when aperture location and internal layouts are not yet established. Like the DF, the VSC is a G-metric, which is simulated for the CIE overcast sky model. The present study showed that the VSC correlates well with metrics of different complexities (e.g., Figure 14), also those which relate to sunlight (Figure 23). The Building Research Establishment (BRE) recommends a VSC level of at least 27% when conventional window design is used and cautions that a room with a VSC lower than 15% would likely need large windows to ensure good daylighting [47]. BRE states that VSC levels between 15% and 27% may provide enough daylighting if proper layout and fenestration design strategies are applied. However, it is important to note that the recommended VSC levels were given for the UK context, where national daylighting requirements are not mandated (BS-EN 17037 was withdrawn). It is thus yet uncertain how these recommended VSC levels would translate to meet the Swedish daylighting requirements.

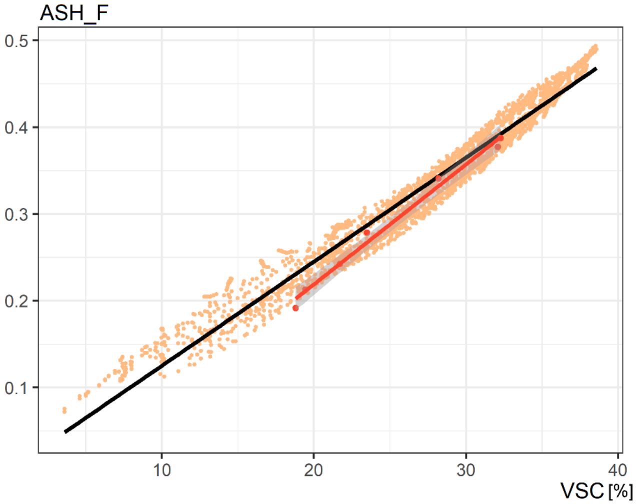
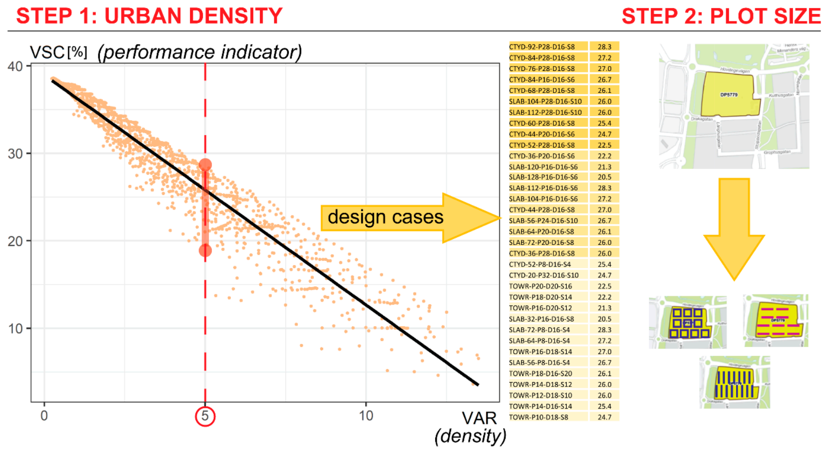


Figure 23. Linear regression function of façade-based metrics VSC and ASH_F based on neighbourhood iterations (black line) and case studies (red line), including the 95% CI for the case studies regression line indicated by the grey area.

The VSC metric dataset created in this study can be used to guide urban planners towards good daylight potential. We suggest two alternative methods to apply this dataset in practice, which are derived from a fixed variable: urban density as VAR. This means that, prior to the assessments, urban planning authorities must decide on the planned population density of a developed area. Assuming the amount of occupied floor area per inhabitant, the population density can be translated into urban density e.g., VAR. Knowing the target range of VAR, urban planners may use the simulated VSC dataset to retrieve a list of possible design cases from highest to lowest performing ones for the assigned density (Figure 24). Further on, introducing the area of the developed plot, the list can be reduced to include only those cases that fit a given plot (Figure 24). Alternatively, the method can provide urban planners with a range of expected VSC values to inform their design (Figure 25). In this case, the urban planners must perform VSC analysis themselves, and then use the VSC range as a guiding tool. It is important to mark that the method is intended for comparative design assessments, i.e., to determine which design proposals perform best, and not to accurately predict performance scores. This is future work which requires the identification of value benchmarks for performance levels backed by empirical evidence.



CTYD-92-P28-D16-S8	28.3
CTYD-84-P28-D16-S8	27.2
CTYD-76-P28-D16-S8	27.0
CTYD-84-P16-D16-S6	26.7
CTYD-68-P28-D16-S8	26.1
SLAB-104-P28-D16-S10	26.0
SLAB-112-P28-D16-S10	26.0
CTYD-60-P28-D16-S8	25.4
CTYD-44-P20-D16-S6	24.7
CTYD-52-P28-D16-S8	22.5
CTYD-36-P20-D16-S6	22.2
SLAB-120-P16-D16-S6	21.3
SLAB-128-P16-D16-S6	20.5
SLAB-112-P16-D16-S6	28.3
SLAB-104-P16-D16-S6	27.2
CTYD-44-P28-D16-S8	27.0
SLAB-56-P24-D16-S10	26.7
SLAB-64-P20-D16-S8	26.1
SLAB-72-P20-D16-S8	26.0
CTYD-36-P28-D16-S8	26.0
CTYD-52-P8-D16-S4	25.4
CTYD-20-P32-D16-S10	24.7
TOWR-P20-D20-S16	22.5
TOWR-P18-D20-S14	22.2
TOWR-P16-D20-S12	21.3
SLAB-32-P16-D16-S8	20.5
SLAB-72-P8-D16-S4	28.3
SLAB-64-P8-D16-S4	27.2
TOWR-P16-D18-S14	27.0
SLAB-56-P8-D16-S4	26.7
TOWR-P18-D16-S20	26.1
TOWR-P14-D18-S12	26.0
TOWR-P12-D18-S10	26.0
TOWR-P14-D16-S14	25.4
TOWR-P10-D18-S8	24.7

Figure 24. A suggestion for using the metric datasets in solar assessment of neighbourhood design in urban planning. In this example, the objective is daylighting of facades. Assuming target density and using the plot as an input, urban planners get suggestions for the best design options.

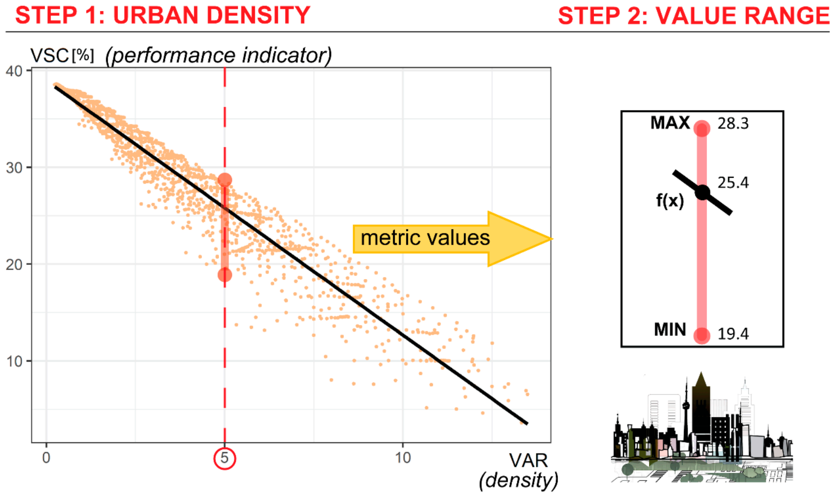


Figure 25. An alternative suggestion for using the metric datasets in solar assessment of neighbourhood design in urban planning. Assuming target density, the urban planners are presented with the expected ranges of metrics as a reference to compare range values with the results of their designs.

4.1.2. Sunlight

Access to direct sunlight in dwellings in Sweden is acknowledged in building legislation; however, it is not regulated as strictly as daylight. The Swedish Building Regulations [48] state that a minimum one room in a dwelling which people frequent more than occasionally should have access to sunlight, but how this should be enforced or measured is not specified. The European Daylighting Standard [45], on the other hand, provides a more concrete assessment method. It uses an L-metric, direct sunlight hours, calculated for a point on the façade and for a single reference day between 1 February and 21 March. The exposure-to-sunlight levels are given from minimum: 1.5 h, through medium: 3 h, to maximum: 4 h. The European Standard sunlight metric is thus of conforming function, using a time constraint of one day. The stated sunlight stipulation is thus far just a recommendation.

The results of this study showed that some metrics have lower correlation to other solar metrics, and their pairwise relationships may have a dispersed appearance. Thus, may be less suitable for early assessment purposes. In particular, the conforming metrics were poorly correlated with other metrics, presenting high variance and lack of order in the data. Furthermore, the comparison of façade-based sunlight metrics, ASH_F and RD_F (Figure 18) was favourable to the annual time constraint, as it provides higher correlations, more continuous relationships with other metrics, and better linearity (Figures 20 and 23). The present study showed that the single-day RD_F metric has a large variance in the data in relation to other metrics. Current sunlight recommendations are based on a single day metric, and the present study showed that this time constraint may be less suitable in assessments due to the directionality of façade surfaces and a low number of simulated solar vectors. As a result of that, for example, the recommendation disqualifies dwellings from having all habitable rooms directly facing the North. There is insufficient evidence regarding user preferences with regard to solar access. These considerations may call into question the current assessment method for sunlight exposure, which is based on a poorly correlated conforming and single-day-based metric.

Conforming metrics, albeit their poor correlation, play an important role in assessments and should not be discounted. However, to apply design criteria using fixed thresholds with confidence, datasets need to have assigned evidence-based benchmarks, and the evidence on the amount of sunlight needed is currently lacking. More technical- and observation-based evidence on solar access at the façade level is needed in support of sustainable design objectives.

4.2. Solar Access Outdoors

Solar access in urban settings is often assessed at the outdoor ground level for visualization purposes (e.g., shadowing on the ground), but it has not yet been legislated. Ensuring solar access outdoors may be important for wellbeing, energy applications, and greenery growth. The results of this study showed that there is a good correlation and linear relationship between façade-based and ground-based G-metrics, i.e., VSC and SVF (Figure 15). Similarly, there is a strong correlation between ASH on the ground (ASH_G) and ASH at the façade level (ASH_F) (Figure 26). An interpretation of this result is that the indication of performance quality obtained from analysing only one type of target surface, either ground or façade, may be applicable to both indoor and outdoor environments.

The provision of solar access outdoors is also important in the aspects of urban heat island and microclimate. This study suggests that SVF is a promising early design indicator of daylighting performance of outdoor solar access. Since SVF has been previously linked to urban heat island mitigation [49], it strengthens the argument for implementing this metric into early solar access evaluations. Future work should establish limiting values for outdoor solar access SVF recommendations relative to the mitigation of the unwanted heat retention in cities.

An example of how the ground- and façade-based solar access data may be used in urban design assessments is presented in Figure 27. There are differences between different typologies depending on the target analysis surface used. The comparative solar performance graphs may be used as a tool to inform urban planners about the differences in performance of certain typologies and the trade-offs when considering different objectives. Currently, due to the legislative emphasis on the indoor environment, the priority in design assessments might be given to those typologies that score better solar access metrics at the façade level, e.g., slab; however, if significance was given to solar access outdoors, the courtyard typology could be more preferable.

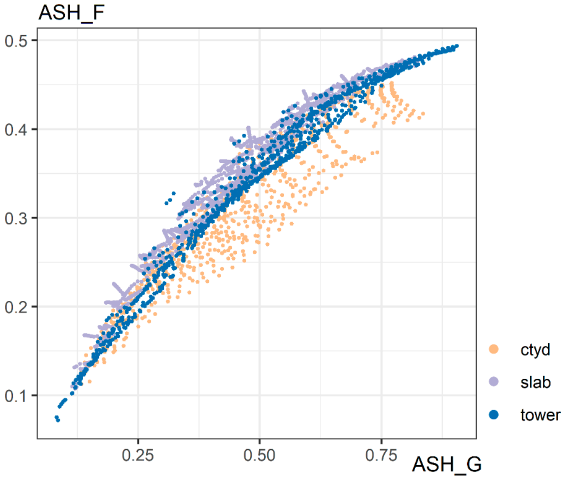


Figure 26. Relationship graph of metrics ASH_G and ASH_F, comparing the same metric calculated for ground and facades and presenting data points for the three analysed typologies.

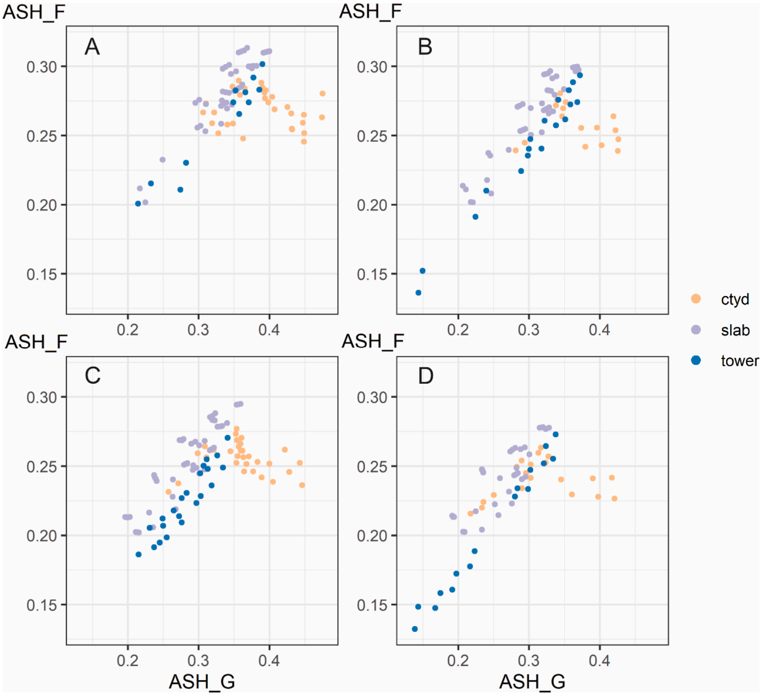


Figure 27. Selected neighbourhood cases presented as relation graphs based on the ASH on ground and façade. The graphs show cases with FAR in range of (**A**): (1.4–1.49), (**B**): (1.5–1.59), (**C**): (1.6–1.69), (**D**): (1.7–1.79).

4.3. Limitations and Future Work

This study was limited to particular neighbourhood typologies. The prerequisites for the selection of neighbourhood case studies, as well as the assumptions for modelling neighbourhood design iterations, gave constraints to the resulting metric datasets. In the future, these datasets could be expanded by adding neighbourhood cases of a wider variety, including diverse typologies and non-homogenous designs. A more complete database of solar metrics will support the decision-making process and improve solar-driven urban planning assessment methods, such as the two alternative approaches suggested in Section 4.1.1. An extended database could also open up possibilities for more advanced prediction models based on data statistics and machine learning.

The study focused on the European climates, and the solar performance metrics were selected assuming the northern latitude context for performance assessments. The solar access design objectives of northern locations may differ for other climates; for instance, in the hot climate regions, sunlight might be considered a liability, and access to it may have to be restricted in the design planning. The effect of different climates and latitudes should be studied further to also consider the impact of solar access on the microclimate.

Some metrics in this paper were calculated as an average value for the entire analysis area. This kind of assessment may be simplifying and reducing the design performance score. In some cases, in design assessments, it may be more valuable to have the metric displayed visually over the entire analysis area in order to be able to check for critical spots, especially in case of a non-homogenous neighbourhood.

Future work should establish relevant performance benchmarks for the suitable metrics that were presented in this study. Another point of perspective is also needed: occupants' perception of sunlight, both indoors and outdoors. There is scarce empirical evidence to support existing recommendations. This input will be instrumental in creating holistic methods of solar access evaluation, as it can help establish solar access targets assuming wellbeing as one of the urban design drivers alongside energy sustainability.

5. Conclusions

This study evaluated solar performance metrics, their graphical relations, and statistical correlations. The study was based on homogenous neighbourhood designs and focused on the context of northern Europe. The neighbourhood designs were validated via comparison with six case studies.

The outcomes of this study suggest that simple geometrical and latitudinal metric classes are valid candidates for potential solar performance indicators in the urban planning level of building design stages, whereas the external climatic metrics deem too complex. It was shown that, in some cases, the simpler metrics are even better suited for evaluating the performance of simple building blocks, i.e., the level of detail used in the early urban planning stage. More complex metrics were indeed more sensitive to geometrical details of the urban models and building facades.

In particular, it is concluded that VSC and SVF (for daylighting) and ASH_F and RD_G (for sunlighting) are good candidate metrics for describing solar access indoors and outdoors, respectively.

The urban design and metric database created in this study may be useful for establishing assessment paradigms and prediction models. The database of metric values can be used in solar assessments of urban designs, may be used in prediction models, and can be of interest for future studies involving design optimization using advanced machine learning techniques. More diverse design solutions may be added to the datasets for increased validity and reliability. Some examples of urban-level solar assessment methods applying appropriate metrics specific for a given solar design objective were presented in this study.

Selecting appropriate metric thresholds is a challenge for the next phases of research into solar performance indicators. Performance benchmarks should be supported by evidence-based research, balancing energy and wellbeing objectives of sustainable neighbourhoods.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

References

1. Littlefair, P. Passive Solar Urban Design: Ensuring the Penetration of Solar Energy into the City. *Renew. Sustain. Energy Rev.* **1998**, *2*, 303–326. [CrossRef]
2. Beckers, B. *Solar Energy at Urban Scale*; John Wiley and Sons: Hoboken, NJ, USA, 2013; ISBN 9781848213562.
3. Knowles, R.L. The Solar Envelope: Its Meaning for Energy and Buildings. *Energy Build.* **2003**, *35*, 15–25. [CrossRef]
4. IEA SHC. Task 51 Solar Energy in Urban Planning. In *Approaches, Methods and Tools for Solar Energy in Urban Planning*; IEA SHC: Cedar, MI, USA, 2018.
5. Peronato, G.; Rastogi, P.; Rey, E.; Andersen, M. A Toolkit for Multi-Scale Mapping of the Solar Energy-Generation Potential of Buildings in Urban Environments under Uncertainty. *Sol. Energy* **2018**, *173*, 861–874. [CrossRef]
6. Sarralde, J.J.; Quinn, D.J.; Wiesmann, D.; Steemers, K. Solar Energy and Urban Morphology: Scenarios for Increasing the Renewable Energy Potential of Neighbourhoods in London. *Renew. Energy* **2015**, *73*, 10–17. [CrossRef]
7. Bilu, C.; Einat, H.; Zimmet, P.; Vishnevskia-Dai, V.; Kronfeld-Schor, N. Beneficial Effects of Daytime High-Intensity Light Exposure on Daily Rhythms, Metabolic State and Affect. *Sci. Rep.* **2020**, *10*, 19782. [CrossRef] [PubMed]
8. Knoop, M.; Stefani, O.; Bueno, B.; Matusiak, B.; Hobday, R.; Wirz-Justice, A.; Martiny, K.; Kantermann, T.; Aarts, M.P.J.; Zemmouri, N.; et al. Daylight: What Makes the Difference? *Light. Res. Technol.* **2020**, *52*, 423–442. [CrossRef]
9. Holick, M.F. Sunlight and Vitamin D for Bone Health and Prevention of Autoimmune Diseases, Cancers, and Cardiovascular Disease. *Am. J. Clin. Nutr.* **2004**, *80*, 1678S–1688S. [CrossRef] [PubMed]
10. Fahimipour, A.K.; Hartmann, E.M.; Siemens, A.; Kline, J.; Levin, D.A.; Wilson, H.; Betancourt-Román, C.M.; Brown, G.; Fretz, M.; Northcutt, D.; et al. Daylight Exposure Modulates Bacterial Communities Associated with Household Dust. *Microbiome* **2018**, *6*, 175. [CrossRef]
11. United Nations-Department of Economic and Social Affairs-Population Division. *World Urbanization Prospects. The 2018 Revision*; United Nations: New York, NY, USA, 2019.
12. Angel, S.; Lamson-Hall, P.; Blei, A.; Shingade, S.; Kumar, S. Densify and Expand: A Global Analysis of Recent Urban Growth. *Sustainability* **2021**, *13*, 3835. [CrossRef]
13. Bournas, I.; Dubois, M.-C. Daylight Regulation Compliance of Existing Multi-Family Apartment Blocks in Sweden. *Build. Environ.* **2019**, *150*, 254–265. [CrossRef]
14. Kanters, J.; Wall, M. Experiences from the Urban Planning Process of a Solar Neighbourhood in Malmö, Sweden. *Urban Plan. Transp. Res.* **2018**, *6*, 54–80. [CrossRef]
15. Lobaccaro, G.; Croce, S.; Lindkvist, C.; Munari Probst, M.C.; Scognamiglio, A.; Dahlberg, J.; Lundgren, M.; Wall, M. A Cross-Country Perspective on Solar Energy in Urban Planning: Lessons Learned from International Case Studies. *Renew. Sustain. Energy Rev.* **2019**, *108*, 209–237. [CrossRef]
16. Kanters, J.; Gentile, N.; Bernardo, R. Planning for Solar Access in Sweden: Routines, Metrics, and Tools. *Urban Plan. Transp. Res.* **2021**, *9*, 348–368. [CrossRef]
17. Nault, E.; Peronato, G.; Rey, E.; Andersen, M. Review and Critical Analysis of Early-Design Phase Evaluation Metrics for the Solar Potential of Neighborhood Designs. *Build. Environ.* **2015**, *92*, 679–691. [CrossRef]
18. Czachura, A.; Kanters, J.; Gentile, N.; Wall, M. Solar Performance Metrics in Urban Planning: A Review and Taxonomy. *Buildings* **2022**, *12*, 393. [CrossRef]
19. Morganti, M.; Salvati, A.; Coch, H.; Cecere, C. Urban Morphology Indicators for Solar Energy Analysis. *Energy Procedia* **2017**, *134*, 807–814. [CrossRef]
20. Shi, Z.; Fonseca, J.A.; Schlueter, A. A Parametric Method Using Vernacular Urban Block Typologies for Investigating Interactions between Solar Energy Use and Urban Design. *Renew. Energy* **2021**, *165*, 823–841. [CrossRef]

21. Zhang, J.; Heng, C.K.; Malone-Lee, L.C.; Hii, D.J.C.; Janssen, P.; Leung, K.S.; Tan, B.K. Evaluating Environmental Implications of Density: A Comparative Case Study on the Relationship between Density, Urban Block Typology and Sky Exposure. *Autom. Constr.* **2012**, *22*, 90–101. [CrossRef]
22. Chen, K.W.; Norford, L. Evaluating Urban Forms for Comparison Studies in the Massing Design Stage. *Sustainability* **2017**, *9*, 987. [CrossRef]
23. Statistics Sweden (SCB) Nearly 5.1 Million Dwellings in Sweden. Available online: https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/housing-construction-and-conversion/dwelling-stock/pong/statistical-news/dwelling-stock-december-31-2021/ (accessed on 10 May 2022).
24. Rådberg, J.; Friberg, A. *Svenska Stadstyper: Historik, Exempel, Klassificering*; Kungliga tekniska högskolan, Institutionen för arkitektur och stadsbyggnad: Stockholm, Sweden, 1996; ISBN 9171706992.
25. Nouvel, R.; Schulte, C.; Eicker, U.; Pietruschka, D.; Coors, V. CityGML-Based 3D City Model for Energy Diagnostics and Urban Energy Policy Support. In Proceedings of the BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, 26–28 August 2013; pp. 218–225.
26. McNeel, R. Associates Rhinoceros 3D, Version 7. Available online: https://www.rhino3d.com/ (accessed on 6 December 2021).
27. McNeel, R. Associates Grasshopper—Algorithmic Modeling for Rhino. 2022. Available online: https://www.grasshopper3d.com/?overrideMobileRedirect=1 (accessed on 6 December 2021).
28. American Society of Planning Officials. *Information Report No. 111: Floor Area Ratio*; American Society of Planning Officials: Chicago, IL, USA, 1958.
29. Krehl, A.; Siedentop, S.; Taubenböck, H.; Wurm, M.; Behnisch, M.; Meinel, G.; Kainz, W. A Comprehensive View on Urban Spatial Structure: Urban Density Patterns of German City Regions. *ISPRS Int. J. Geo-Inf.* **2016**, *5*, 76. [CrossRef]
30. Moon, B. The Effect of FAR (Floor Area Ratio) Regulations on Land Values: The Case of New York. *Pap. Reg. Sci.* **2019**, *98*, 2343–2354. [CrossRef]
31. Perry, C. The Neighborhood Unit: A Scheme of Arrangement for the Family-Life Community. In *The Regional Plan of New York and Its Environs*; Russell Sage Foundation: New York, NY, USA, 1929; Volume VII, ISBN 9781136205668.
32. Mumford, L. The Neighborhood and the Neighborhood Unit. *Town Plan. Rev.* **1954**, *24*, 256–270. [CrossRef]
33. Mehaffy, M.W.; Porta, S.; Romice, O. The "Neighborhood Unit" on Trial: A Case Study in the Impacts of Urban Morphology. *J. Urban* **2015**, *8*, 199–217. [CrossRef]
34. Byun, N.; Choi, Y.; Choi, J. Neighborhood Unit: Effective or Obsolete? *J. Asian Archit. Build. Eng.* **2014**, *13*, 617–624. [CrossRef]
35. Olson, P. Urban Neighborhood Research: Its Development and Current Focus. *Urban Aff. Rev.* **1982**, *17*, 491–518. [CrossRef]
36. Gallion, A.B.; Eisner, S. *The Urban Pattern: City Planning and Design*, 5th ed.; Van Nostrand Reinhold: New York, NY, USA, 1985; ISBN 0442227310.
37. Dahlberg, G.-B.; Ödmann, E. *Stadsutveckling Och Planering i Sverige*; Läromedelsförl. i samverkan med Byggforskningen; T/Statens råd för byggnadsforskning: Stockholm, Sweden, 1969.
38. Lantmäteriet Geodataportalen. Available online: https://www.lantmateriet.se/sv/geodata/Geodataportalen/ (accessed on 30 August 2022).
39. Ladybug Tools Ladybug Tools | Home Page. Available online: https://www.ladybug.tools/ (accessed on 11 October 2021).
40. European Environment Agency (EEA). Main Climates of Europe. Available online: https://www.eea.europa.eu/data-and-maps/figures/climate (accessed on 30 August 2022).
41. ASHRAE. *International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM*; ASHRAE: Atlanta, GA, USA, 2001.
42. RStudio Team. *RStudio: Integrated Development Environment for R*; RStudio, PBC: Boston, MA, USA, 2021.
43. Joshi, K.K.; Kono, T. Optimization of Floor Area Ratio Regulation in a Growing City. *Reg. Sci. Urban Econ.* **2009**, *39*, 502–511. [CrossRef]
44. Kono, T.; Kusum Joshi, K. A New Interpretation on the Optimal Density Regulations: Closed and Open City. *J. Hous. Econ.* **2012**, *21*, 223–234. [CrossRef]
45. SSI. *CEN SS-EN 17037:2018+A1:2021*; Daylight in Buildings. Swedish Standards Institute: Stockholm, Sweden, 2021.
46. Lobaccaro, G.; Lisowska, M.M.; Saretta, E.; Bonomo, P.; Frontini, F. A Methodological Analysis Approach to Assess Solar Energy Potential at the Neighborhood Scale. *Energies* **2019**, *12*, 3554. [CrossRef]
47. Littlefair, P.J.; King, S.; Howlett, G.; Ticleanu, C.; Longfield, A. *Site Layout Planning for Daylight and Sunlight (BR 209)*, 3rd ed.; S&P Global: New York, NY, USA, 2022; ISBN 978-1-84806-483-6.
48. Boverket. *Boverkets Byggregler (BFS 2019:2)—Föreskrifter Och Allmänna Råd*; Boverket: Karlskrona, Sweden, 2011.
49. Oke, T.R. Canyon Geometry and the Nocturnal Urban Heat Island: Comparison of Scale Model and Field Observations. *J. Climatol.* **1981**, *1*, 237–254. [CrossRef]

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