Metrics Behind the Implementation of Photovoltaic Solar Energy In Urban Area: A Preliminary Literature Review

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Abstract

The massive implementation of solar energy in urban environment is part of the strategic efforts that aim to diversify the energy matrix of a territory, achieving energy independence from fossil fuels in the medium to long term and mitigating carbon emission impacts. However, even if policies are defined regarding the massive implementation of solar energy in urban areas, there is still a lack of studies on the metrics underlying decision-making enabling such an implementation. The improvement of decision making in the process which is complex calls for an integrated assessment of several metrics. Therefore, this work subscribes to the creating a framework that integrates and classifies the most important metrics indicating drivers and barriers for the implementation of photovoltaic panels in urban areas. The framework is assumed to be built in a systemic way in order to support the climate policy and public authorities aiming to integrate solar energy in their urban planning.

Keywords: decision-making metrics, solar energy, photovoltaic panels, urban planning, solar districts

1. Introduction

Currently, more than 75% of global energy consumption occurs in urban territories (Martins et al., 2016). In relation to this matter, a pressing transition to renewables is requited due to the scarcity of fossil fuel based energy and also its consequent pollution (Paleri, 2022) that can be partially addressed by the implementation of photovoltaic (PV) panels in urban areas (Cergibozan, 2022).

This subject has gained even more notoriety given the necessity to be also energy independent from conflict zones (Ostrowski, 2022). As solar energy is a promising sustainable energy, urban areas may become high-potential electricity producers by deploying photovoltaic systems (Fakhraian et al., 2021).

The growing scarcity of energy resources drives the incorporation of renewable energy sources in urban electrical systems worldwide (Goel et al., 2022). The increased use of solar energy in place of fossil fuel-based electricity can help cities striving to become more independent of highly polluting fossil energy to reach the net zero emissions.

The solar energy will be one of the fastest growing renewable energy sources from now to 2050 worldwide, (Rigo et al., 2022), with a potential forecast of 8.5TW and as solar PVs are present the lowest-cost option for renewable electricity it is expected that investments will be propelled for its massive deployment the coming years, IEA (2021).

To enable the implementation of photovoltaic systems in urban environments, it is important to make use of metrics capable of supporting decision makers, showing them clearly what are the benefits and limitations found in this kind of application.

The decision-making process for the implementation of photovoltaic panels (PVs) in urban areas is multifaceted and it involves different disciplines varying between technical, economic, political, environmental and social ones. Therefore, these different metrics may influence local decision-makers whether to invest or not in the photovoltaic technologies.

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In addition, the authorities responsible for renewable energy projects, urban planners and the policy makers come from different backgrounds and need to make decisions accounting for the local conditions and maximizing the socio-economic benefits for their communities (Lobaccaro et al., 2019).

Technological progress and cost reduction have allowed to significantly expand the use of solar energy in urban areas in recent years (Kammen and Sunter, 2016). Nevertheless, there is still a lack of studies to support decision makers in how to conduct a PV project in urban scale taking into account the various criteria that are essential for the implementation of solar energy in urban areas (P. et al., 2019).

Hence, it is necessary to focus on enabling the application of large solar energy systems in cities in such a way that makes energy transition strategies feasible. To address the current need to expand the energy resources through photovoltaics, this article was developed to identify the most used metrics when implementing photovoltaic systems in urban context.

2. Methodology

An extended systematic literature review (SLR) with scientific content produced in between 2002 and 2022 was carried out in three phases as shown in Fig 1. The concepts were formulated in order to answer the central research question of: what quantitative metrics are used to assess PV systems deployment at large urban scales?

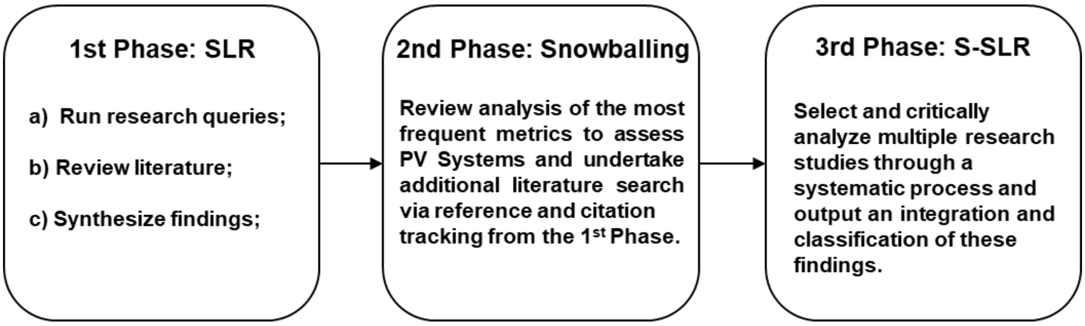


Fig. 1. Extended systematic literature review (SLR) phases inspired from (Rigo et al., 2022)

Firstly, the search criteria focused on identifying scientific literature review papers as these can assist in rapidly identifying the most common metrics present in this research field, as well as the research gaps and approaches in a given scientific field (Lagisz et al., 2022), which allow us to identify the key terms commonly used in this exploratory research.

Secondly, others broader scientific sources such as conference proceedings, grey literature reports, book chapters and thesis were also consulted later to integrate the scope of this research and help us to identify and classify the metrics related to the deployment of photovoltaic panels in urban areas. In total, more than 760 scientific contents were consulted, where 127 of them were selected to support the development of this research. In this paper, we chose to present an extraction of the most frequent metrics found in the literature, eliminate redundancies, define each of them and calculate their usage rate.

The usage rate was calculated for each metric type analyzed in this article by the Equation 1.

$$Usage\ rate\ (\%) = \frac{Number\ of\ Scientific\ Content\ Mentioning\ a\ given\ Metric}{Total\ Number\ of\ Scientific\ Content} \qquad \text{(eq. 1)}$$

Finally, the scientific findings were select and critically analyze through a systematic process made by integrating and classifying them in order to answer the central research question.

Tab. 1. Keywords used in this review

	1st Keywords	2nd Keywords	3rd Keywords	4th Keywords	5th Keywords
↑ OR ↓	Solar Energy	Planning Deployment Review Availability Feasibility	Metrics Indicators Requirements Enablers Assessment	Technical Economic Energy	Urban City District Neighborhood Building
			← AND →		

In the Tab. 2., we introduce the combined keywords used to identify the metrics searched on Google Scholar, Springer Link, ACM, Science Direct and IEEE and classified into technical, energy and economic metric types accordingly to the hierarchical approach firstly proposed by VanWijk and Coelingh (van Wijk and Coelingh, 1993) and later applied in different regions (Assouline et al., 2017). In this paper, we have chosen some representative metrics belonging to the technical, economic and energy metric types to discuss.

For the purpose of describing the overall view in research and use of the metrics identified through this article, we have Europe leading the production of content related to these metrics to deploy PV System in urban areas followed by Asia and North America in Fig. 2.

We also have identified the percentage of each type of scientific content selected in this SLR through the Fig. 3, where we can see the majority of chosen content comes from journals (84%) followed by Reviews and PhD Thesis totalizing together 9%.

While the frequency of contents related to the metrics selected for this SLR can be contemplated on Fig. 4 (a) as well as and the frequency of each type of quantitative metrics (Economic Technical or Energy related) approached in this SLR are plotted on the Fig. 4 (b).

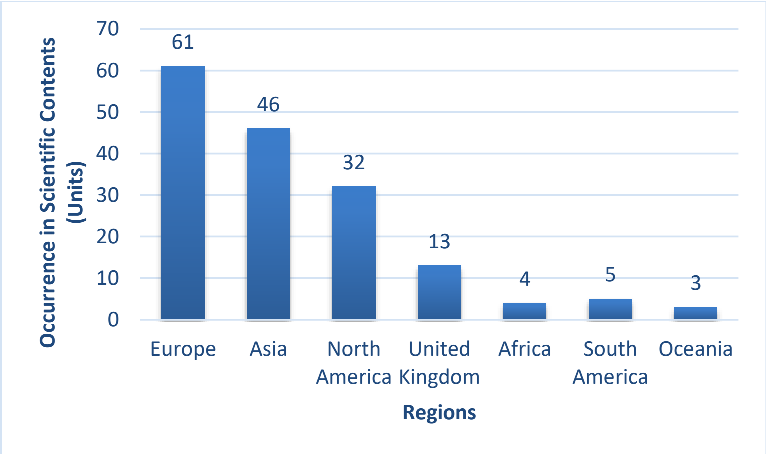


Fig. 2. Occurrence of Scientific Contents per Regions in the conducted SLR.

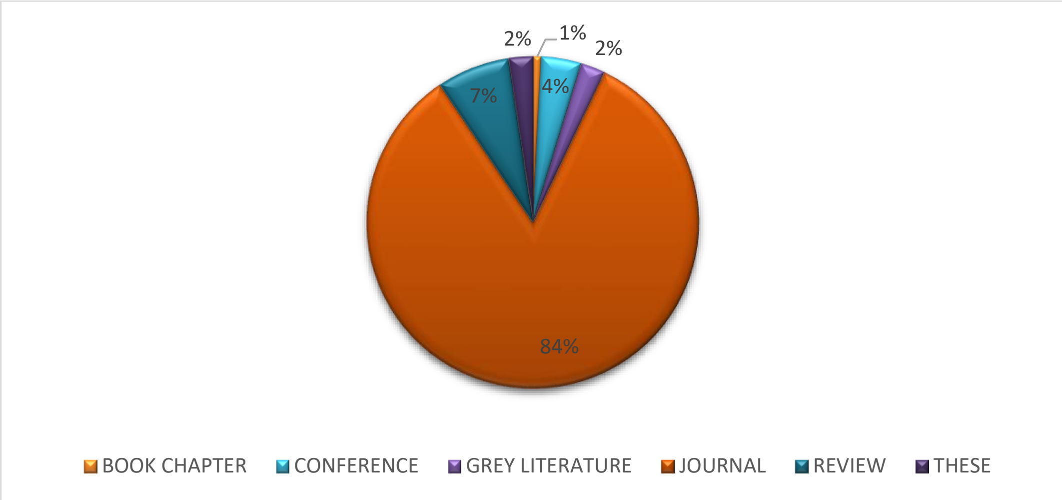
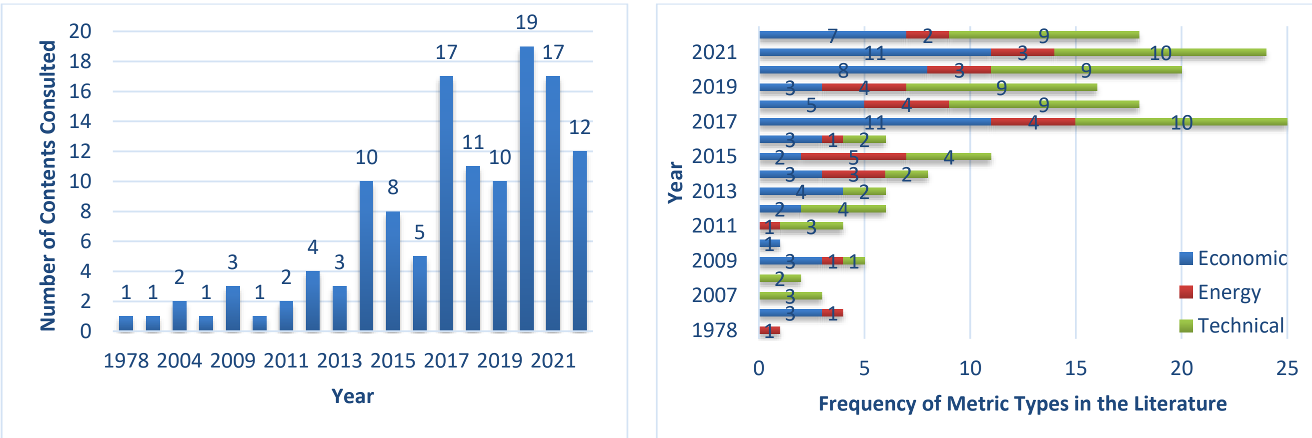


Fig. 3. Percentage of Content selected for this SLR



(a) (b)

Fig. 4. a) Frequency of scientific contents related to PV metrics per year. b) Cumulative frequency of scientific contents related to PV metrics per type yearly.

The occurrence of scientific content across regions may suggest where more studies are being developed in this regard. In the meanwhile, the percentage of selected content shows the scientific support to carry out the present SLR.

3. Results

At this stage, 20 technical metrics, 17 economic and 9 energy ones were identified as the most current in scientific contents related to PV Systems deployment.

The findings from this SLR were organized in an extracted version of the results through the tables **Tab. 2**, **Tab. 3** and **Tab. 4**. where the metrics related to the technical, economic and energy aspects were defined, analyzed according to their occurrence in scientific contents and associated to pertinent references.

The technical, economic and energy metrics related to the PV systems are able to betoken us the most used metrics approached for practical assessments and application in urban context.

In the technical overview of metrics, it has been found that the Rooftop Area (13%) suitable and available for PV Systems is the most used factor to determine whether or not is worth to proceed with a PV project as well as the Real efficiency delivered by this systems (13%) and followed by the grid capacity (11%) which is related to the power outputs enabled by the grid.

In this study, it was seen that the reasoning for the adoption or not of PV Systems in urban context is intrinsic related to the Grid-parity which is still a milestone for further PV diffusion (Breyer and Gerlach, 2013).

Tab. 2. Overview extraction of the main technical metrics behind the deployment of solar panels

Metrics	Definition	N. Articles	Usage rate (%)	Refs.
Rooftop Area (m^2)	The surface occupied by the photovoltaic modules and / or the suitable area available for implementation of solar panels on rooftop surfaces.	17	13%	(Hong et al., 2017), (Thebault et al., 2022)
Real efficiency (%)	Efficiency including pre-module losses, module losses, system losses and operation & maintenance downtime	16	13%	(Gupta et al., 2021)
Grid capacity (MWp)	The sum of the maximum power outputs of the generators attached to an electrical grid.	14	11%	(Assouline et al., 2017), (Yassuda Yamashita et al., 2021)
Unshaded ratio (Unitless Ratio)	The proportion of unshaded roof area	11	9%	(Walch et al., 2020)
Lifetime (years)	The duration for which a PV system works close to its nominal performances.	7	6%	(Zhu et al., 2020)

The most present economic metrics found in this scientific literature review are the Net Present Value (10%) and the Return on investment (9%), both responsible for the feasibility of a project in economic terms.

The economic potential analysis need arises because during the development of this SLR some economic models used for PV systems were identified and they make use of several metrics that together will show the economic feasibility of a given photovoltaic project.

Tab. 3. Overview extraction of the main economic metrics behind the deployment of solar panels

Metrics	Definition	N. Articles	Usage rate (%)	Refs.
Net Present Value (Currency)	The difference between the present value of cash inflows and the present	13	10%	(de Souza Dutra et al., 2019)

	value of cash outflows over a given period of time.			
Return on investment (%)	Evaluate the efficiency or profitability of an investment by comparing the amount of return on a particular investment related to the initial investment cost.	11	9%	(Müller and Trutnevyte, 2020)
Levelized Cost of Energy (Currency/ Energy)	A measure of the average net present cost of electricity generation by a certain technology over its lifetime.	10	8%	(Zou et al., 2017)
Simple Payback Time (Years)	The number of years to refund an investment.	8	6%	(Sommerfeldt and Madani, 2017)
Grid reinforcement cost (Currency)	Cost related to the electricity grid infrastructure to receive the photovoltaic panels.	5	4%	(Wang et al., 2022)

The most used energy metrics are Electricity generation (20%) and Insolation (9%) both correlated to the photovoltaic potential of a given region.

The energy analysis of photovoltaic systems is able to show us the capacity that a given case study has to produce electricity according to its characteristics as well as the return on investment in energy terms and it is a complementary evaluation that allow us to measure the viability of a PV project.

Tab. 4. Overview extraction of the main energy metrics behind the deployment of solar panels

Energy Metrics	Definition	N. Articles	Usage rate (%)	Refs.
Electricity generation (kWh/year)	The expected energy output per year (kWh/year)	25	20%	(Assouline et al., 2018)
Insolation (kWh/m²/(day)	The incoming solar radiation on a surface on earth in a given time-period.	12	9%	(Jones et al., 2004)
Energy Payback Time (years)	The required period in which the PV system can produce the same amount of electricity with the energy consumed over its life cycle.	6	5%	(Burg et al., 2017)
Energy Return on Investment (years)	A ratio of the amount of energy (the exergy) delivered from a certain energy resource to the amount of exergy used to obtain that energy resource.	4	3%	(Bhandari et al., 2015)

4. Discussion

After listing the various metrics, it is important to seek the complementary participation of stakeholders and urban experts in the construction of the context of the region that will adopt an energy transition strategy and which aims to focus efforts on the use of photovoltaic panels. Among the questions that may guide the following initiatives to enable decision making in the massive deployment of PV systems in urban scale are:

i) What are the stakeholders involved in the massive adoption of PV systems in urban scale?

ii) What are the level of influence of these stakeholders in the PV system massive deployment?

iii) What are the phases that will enable the massive deployment of panels in urban areas?

iv) What is the photovoltaic potential of the studied urban region?

v) What are the main enablers playing an important role in PV system's implementation in urban territories?

Some of these metrics are only informative or intermediary metrics, whereas others are key performance indicators that are directly related to the decision- making process for some solar asset stakeholders. Due to the complexity of decision making, there are metrics that can be seen as mere measures for some actors but have a high influence on decision making for others.

The discussion about metrics may become overly broad and unfocused because a metric that is considered a simple measure for a solar asset stakeholder may be deemed as an important indicator for an expert throughout a different perspective.

Thus, assessing the metrics behind the deployment of photovoltaic systems in urban areas is a preliminary step before creating a value proposition to aid the interested parties regarding the effective employment of these systems. The identified metrics demonstrate the significance of evaluating the urban photovoltaic potential while simultaneously taking into account technical, economic, and energy factors.

Even though these factors have each been well-covered by other studies, it is crucial to take them into account collectively in order to facilitate decision-making, particularly in the case of urban energy transition projects that aim for the fast pace deployment of photovoltaic energy systems in their territories.

Therefore, the metrics identified and described in this paper can provide answers to questions about technical and economic as well as energy feasibility, allowing investors, urban planners, and public authorities to make more informed decisions.

In practical terms, it has been demonstrated the importance of investigating the metrics underlying the implementation of photovoltaic energy as they serve as the basis for designing decision-making models that take into account the complementarity of various factors to make photovoltaic energy systems viable from a large-scale perspective.

The benefits of making decisions using the metrics identified in this paper include defining realistic spatial and time-based objectives for the urban area aiming to deploy photovoltaic systems, as well as ensuring a return on investment in both financial and energy terms.

By using these metrics, multi-criteria models can be proposed, created and integrated into the urban energy management system in order to respond to project demands in a meaningful, pertinent, and goal-aligned manner.

It is worth to highlight that the study of qualitative metrics may be complementary and also should be explored in order to understand how such factors influence the decision-making process of certain types of stakeholders.

5. Conclusion

This paper aimed to explore the main quantitative metrics behind the decision making process of PV Systems implementation in urban scale by developing an extensive review to lead us to fill the gap between the theoretical and practical application of the most used metrics.

Most of the metrics reviewed not cover in-detail the costs, technical constraints and energy generation production and benefits of PV systems at the same time, we have more often an overview using relatively simple analysis to evaluate the energy potential from a given region.

However, accordingly to the dimensions of the PV project and policies implemented, the simplicity in this assessment might not be enough to evaluate urban PV projects application in terms of techno-economic feasibility. Nonetheless, a simple assess may infer a point of departure to encourage greater initiatives towards a core techno-economic analysis in its viability to overcoming PV grid issues related to its deployment and energy production.

Other primary themes uncovered through this review are needed to complement the understanding of what are the global key-factors that can either enable or not the PV System adoption in urban scale (1) social (2) political commitment and also (3) regulatory aspects.

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