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## **DESIGN FEATURES OF ROOFTOP SOLAR POWER PLANTS IN AN URBAN ENVIRONMENT**

**Summary.** *The article discusses the design features of rooftop solar power plants (SES - solar energy systems) in an urban setting. It covers the classification of rooftop SES, equipment requirements, power calculations, the impact of insolation, and architectural constraints. Economic and environmental efficiencies are analyzed, and key barriers to project implementation are identified. Special attention is given to the development potential of building-integrated photovoltaic (BIPV) technologies, digitalization, and integration with smart cities.*

**Key words:** *rooftop solar power plants, engineering, BIPV, urban energy, insolation, architecture, sustainable development, engineering loads, economic efficiency.*

The relevance of this study stems from the increasing interest in sustainable urban development and the need for a transition to renewable energy sources in light of rapid urbanization. As urban populations continue to grow and electricity consumption increases, there is a pressing need to integrate environmentally friendly energy solutions into urban infrastructure.

Rooftop solar power plants represent a promising area for efficient use of urban space. In dense urban areas, rooftops become a valuable resource for generating additional energy and reducing reliance on urban power networks.

The design of rooftop solar systems is challenging due to various factors such as structural features of buildings, microclimate, and shading from neighboring structures. Additionally, wind and snow loads must be considered, as well as regulatory and urban planning requirements.

Integration of photovoltaic systems with green architecture, such as operational and landscaped rooftops, is an important aspect that requires an integrated design and operational approach.

The economic efficiency of rooftop solar power plants is also essential and depends on various factors, such as architectural and planning solutions, climatic conditions in the region, and energy storage systems. Therefore, studying the design features of these installations in an urban environment has both scientific and practical significance.

To fully understand the structure and components of rooftop solar systems, it is important to refer to technical standards and operating procedures for photovoltaic installations. These standards provide information on the overall design and operation of these systems.

Solar power plants on rooftops can be classified based on various criteria that reflect their functional, technical, and architectural characteristics (Table 1).

*Table 1*

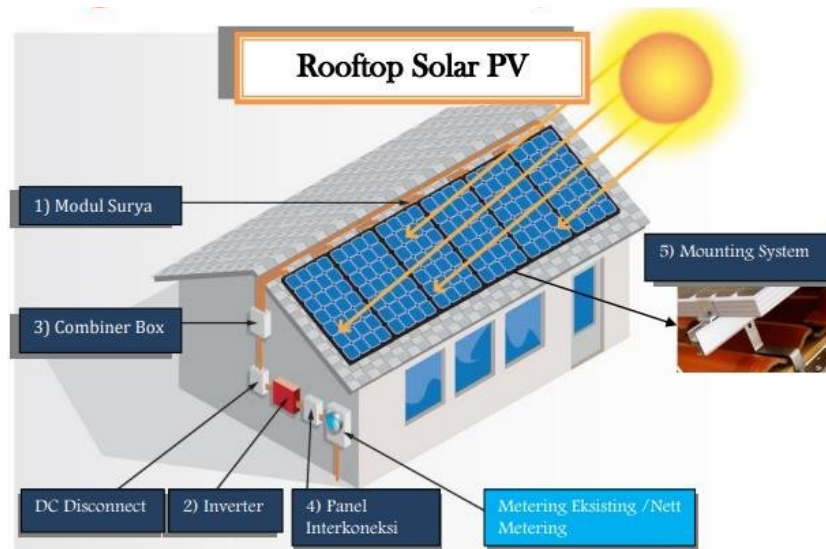
**Classification of roof SES**

<b>Classification criteria</b>	<b>Type name</b>	<b>Description</b>
By connection type	Network	Connected to a centralized power grid; surplus can be sold to the grid.
	Autonomous	It is not connected to an external network; it runs on batteries, and is used in homes and cottages.
	Hybrid	Combines both approaches: powered by mains and/or battery, switching as needed.

By appointment	Commercial	It is used on company buildings, shopping malls, and production facilities to reduce costs.
	Residential	It is installed on private houses or apartment buildings.
	Municipal / public	Schools, hospitals, government institutions; part of sustainable development programs.
On architectural integration	Added	The SES is installed on top of an existing roof with mounting structures.
	Integrated	Solar cells are embedded in the roofing material or replace it (for example, solar shingles).
On energy storage	With batteries	Batteries (such as Li-ion) are used to store energy.
	No accumulation (generation only)	The entire output is either consumed immediately or dumped into the network.
By roof geometry	On the pitched roof	Mounting takes place at an angle, often to the south, limited by the geometry of the ramps.
	On a flat roof	The panels are mounted on special supports with an optimal angle.

*Source:* author's development

The key components of the SES roof system are shown in the diagram: photovoltaic panels, mounting system, junction boxes, inverter, and connection points (see Figure 1).



**Fig. 1. Configuration of the rooftop solar power plant system [5]**

The design also includes inverters, often hybrid with MPPT function, DC and AC switches, protection devices for overload and isolation, monitoring systems, and, if necessary, battery packs.

Under conditions of dense urban development, the number of floors and type of buildings can significantly affect roof insolation. Research has shown that the urban morphology, including location, height, and density of buildings, directly determines the amount of solar radiation reaching the roofs and varies the energy flow throughout the year.

Requirements for the bearing capacity of roofs are strictly regulated. Guidelines for installing photovoltaic (PV) systems on residential building roofs specify that anchors should be spaced no more than 1.2 m apart and the distance between rows should be no more than 1.8 m, with a maximum roof height of 12 m. Additionally, structures must be able to support the weight of the panels (30-50 kg/m<sup>2</sup>) and account for wind, snow, and seismic loads.

Accounting for insolation and shadow zones is done through geometric or digital models. As much as 19% of annual insolation can be lost in the afternoon due to shadows from walls and neighboring objects [7]. Using solar trajectories, the location of modules can be optimized to minimize losses. Strategies for solar

access include the correct orientation of streets and buildings, such as the diagonal system in Barcelona.

In an architectural context, SES should harmoniously fit in with the appearance of buildings and neighborhoods. This is particularly important in protected areas, where the use of built-in photovoltaic modules can preserve the aesthetics of facades and roofs. Microclimate is also significant - panel surfaces with a low albedo compared to roofs can increase temperature by 1-1.5°C. This must be considered during design, especially in hot climates.

The engineering and technical aspects of designing rooftop solar power systems include capacity assessment, equipment selection, integration with the electrical grid, and load calculation.

Calculating the capacity for installing solar panels on urban rooftops typically begins with an analysis of available space and potential solar radiation. According to studies, the algorithm takes into account solar resource availability, roof size, and utilization rate (approximately 40%). PVWatts, a calculator, can quickly estimate the annual output of a system ranging from 5 to 20 kW for residential buildings and from 100 kW to 1 MW for commercial rooftops. In a well-known case in Nepal, for example, the average size of solar panels per household was 14 to 19 square meters, corresponding to a capacity of around 1.5 kW, providing up to 35% annual electricity generation [2].

The choice of equipment depends on the technical specifications and operating conditions. PV modules are selected based on their efficiency, cost, and weight. Typically, monocrystalline modules (17-22% efficiency) or polycrystalline modules (11-14% efficiency) are used. Inverters with MPPT functions are chosen, and if necessary, hybrid inverters that can work with batteries are considered.

Electrical integration involves choosing between network and hybrid modes, as well as DC/AC line protection and UV-resistant cables. Grounding systems and circuit breakers must also be installed according to international

standards such as IEC, NEC, and SolSmart [3]. Integration with the local grid requires the installation of a monitoring system to ensure compliance with energy quality and safety regulations.

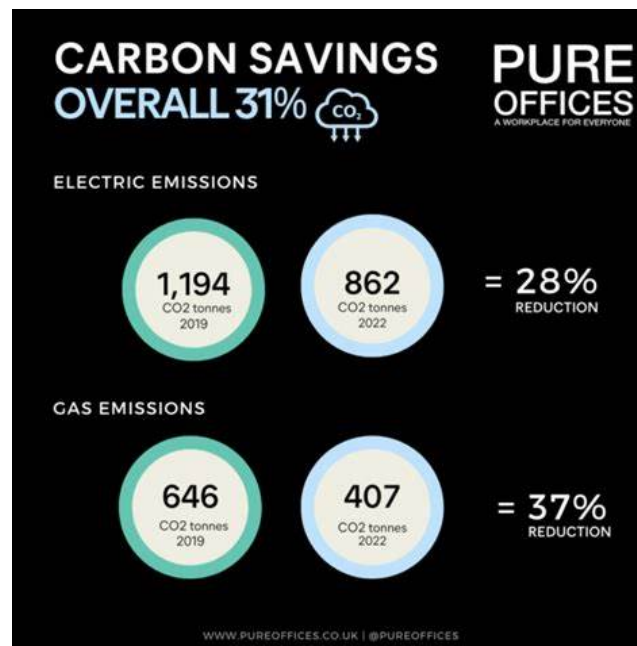
The design features that take into account wind and snow loads are determined by the ASCE 7 standard. Designers use online calculators, such as SkyCiv, to estimate wind pressure and snow weight based on roof parameters and regional conditions. These modules must be able to withstand lateral forces from the wind and vertical loads of up to approximately 5400 Pa from snow. [1].

The economic and environmental benefits of rooftop solar power plants are based on the evaluation of payback periods, energy costs, and carbon emission reductions. International studies indicate that the typical payback time for a 5-10 kW system ranges from 9 to 13 years, with benefits, and up to 17 years without them [4].

One of the major cost components is the modular panels, which account for approximately 18% of the total cost, followed by microinverters at 15%. Related costs such as installation, labor, and permits can account for up to 60% of the overall system cost.

Environmental performance is determined by the lifespan of the system. Carbon neutrality is achieved within 1-2.5 years in Europe due to high solar irradiance and the efficiency of PV modules. Over time, the system generates clean energy with emissions of less than 50 grams of CO<sub>2</sub> per kilowatt-hour (kWh), which is significantly lower than gas or coal power plants, with emissions ranging from 10 to 20 times higher.

Figure 2 shows an example of annual savings and environmental impact. In the case of the Pure Offices office building, the use of SES has reduced CO<sub>2</sub> emissions by 31% and saved several hundred tons of CO<sub>2</sub> per year in electricity supply.



**Fig. 2. Reduction of CO<sub>2</sub> emissions due to the introduction of a rooftop solar power plant in Pure Offices (UK) [6]**

It is also important to understand the dependence of payback on electricity tariffs and local energy policies. For low-income families, the economic benefit can exceed \$590 per year when installing a 3 kW solar system, which is equivalent to a 24% reduction in electricity bills. When incentive programs, such as subsidies and loans, are available, the payback period can be reduced to 9-10 years, if the tax credits are up to 30% of the cost of the system.

Before installing rooftop solar power plants in urban areas, it is essential to consider a number of factors that can significantly affect the efficiency, economic viability, and sustainability of the project. These factors include both physical and technical aspects of buildings, as well as regulatory, social, and economic considerations. Table 2 outlines the key challenges and limitations identified in international studies and reviews, along with their implications and sources of data.



Table 2

### Problems and limitations of the implementation of rooftop SES in the urban environment

Category of Limitation	Specific Problem	Consequence
Technical	Insufficient roof bearing capacity	Restrictions on the installation of modules, the need for structural reinforcement.
	Shading from neighboring buildings and infrastructure	Losses of up to 20-25% of generation, reduced system efficiency.
	Poor quality of the power grid (in the old housing stock)	Risks of overloads, the need to replace inputs, transformers and lines.
Economic	High proportion of "soft" costs: permits, insurance, engineering	Up to 60% of the project, cost is accounted for not by equipment, but by related services.
	No subsidies or tax benefits	Increase the payback period to 15-18 years.
Administrative	Complex and slow permit procedures	Delays in implementation are up to 6-12 months.
Legal	Prohibition or restrictions on installation in historical and protected areas	The inability to implement projects in the city center or in architecturally valuable areas.
Social	Disagreement of residents or management companies (in apartment buildings)	Blocking of collective projects, inability to share the roof.
Operational	Lack of trained service specialists	Reduced efficiency, increased failures due to lack of regular monitoring and cleaning.

Source: author's development

The modern development of rooftop solar power plant technologies is demonstrating a steady trend towards increased functionality, reduced cost, and integration with other smart city and sustainable architecture systems. This includes not only improvements to the technical characteristics of components



but also the digitalization of design processes and the emergence of new financing models. The development of integrated architectural and energy solutions is promising.

The development of international standards, government support programs, and urban planning strategies is opening up broad opportunities for large-scale implementation of rooftop solar panels as a component of decentralized energy systems.

Promising areas for the development of rooftop solar power plants include:

1. The development of BIPV technologies, which involve integrating solar modules into building materials such as tiles, facades, and glass. This allows for the installation of solar panels while preserving the architectural integrity of buildings.

2. Improvements in the energy efficiency and power output of modules with bifacial, perovskite, and thin-film technologies. These technologies aim to increase efficiency by up to 25-30% in the future, making solar power more competitive.

3. The integration of energy storage systems, such as batteries, to ensure autonomy and smooth peaks in energy supply. This also allows solar power to participate in local energy markets and contribute to grid stability.

4. The implementation of digitalization and intelligent management with IoT (Internet of Things) devices, cloud-based monitoring, and predictive analytics platforms. These tools enable real-time monitoring and management of solar energy systems.

5. Architectural and urban planning that incorporates solar-oriented design, with spaces provided for solar energy systems at the design stage. This ensures optimal placement of solar panels and maximizes their potential.

6. The development of models for collective ownership and consumption - allows residents of apartment buildings, rental premises and social housing to

participate in solar energy systems (SES) projects without the need for physical installation of modules.

7. Flexible financing and subscription plans - SES rental schemes, energy service contracts, cooperative investment opportunities and energy subscription options reduce the entry barrier for users.

8. Establishment of international standards for urban PV infrastructure - harmonization of safety, connectivity and fire protection requirements, BIPV design and sustainable construction practices.

9. Integration with green roofs and nature-oriented architecture - the creation of hybrid solutions combining PV technology with landscaping that improve urban microclimate conditions and thermal insulation in buildings.

10. Integrating smart cities and microgrid systems - the use of rooftop solar panels as part of distributed energy hubs integrated with the internet of things (IoT) and energy exchange networks between homes and buildings.

Thus, rooftop solar power plants have a high potential for sustainable urban energy development, but their successful implementation requires an integrated design approach that takes into account urban planning constraints and utilizes modern technological solutions.

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