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DEVELOPMENT AND MODELING OF ENERGY-EFFICIENT PHOTOVOLTAIC SYSTEMS BASED ON GIS TECHNOLOGIES IN FERGANA CITY CONDITIONS

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Abstract

This article presents the results of developing and modeling energy-efficient photovoltaic systems (PVS) for building rooftops in Fergana, Uzbekistan, using mathematical models and geographic information systems (GIS). The study encompasses an analysis of solar potential, operational loads, and system profitability. Simulations indicate that for a 300 m^2 rooftop with a 30° tilt angle, annual energy output reaches 98,400 kWh, with a payback period of 1.6–1.9 years under subsidies. The proposed methods achieve an accuracy of ±5–7% and are applicable for optimizing PVS placement in dense urban environments. Recommendations include using lightweight structures and ventilation to enhance efficiency.

Keywords: Photovoltaic systems, solar potential, GIS technologies, mathematical modeling, operational loads, energy efficiency, Fergana.

Introduction

The increasing demand for energy and the need to reduce carbon emissions drive the adoption of renewable energy sources (RES), particularly in regions with high solar potential. Fergana, Uzbekistan, located at 40°22’ N, boasts an average annual insolation of 1,900 kWh/m^2 and over 320 sunny days per year, making it an ideal candidate for photovoltaic systems (PVS) . However, dense urban development and limited land availability necessitate the use of building rooftops, highlighting the importance of accurate modeling of their energy potential and operational characteristics.

Global practices showcase the successful application of GIS technologies and mathematical models for PVS optimization in cities like Berlin and Shanghai . In Central Asia, where climatic and construction conditions differ, adaptation of these approaches is essential. For instance, the flat reinforced concrete rooftops prevalent in Fergana’s Soviet-era buildings require specific load and shading considerations. Uzbekistan’s “Energy Strategy for 2030” aims to achieve 25% RES in its energy mix, including 5 GW of solar capacity, underscoring the relevance of this study.

The objective of this research is to develop and model energy-efficient PVS for Fergana rooftops using GIS technologies and mathematical models. The tasks include: (1) constructing

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models to assess energy output, (2) analyzing solar potential via GIS, (3) modeling operational loads, and (4) providing recommendations for optimizing placement and profitability.

Methods

Mathematical Modeling of Energy Balance

The efficiency of PVS was evaluated through an energy balance described by the differential equation:

$$\frac{dE}{dt} = P_{in} - P_{loss} - P_{out}$$

where E is accumulated energy (Wh), $P_{in} = A \cdot G_t \cdot \cos(\theta)$ is input power (W), $P_{loss} = P_T + P_{inv} + P_{dust}$ is power loss (W), and $P_{out} = A \cdot G_t \cdot \eta_T \cdot PR$ is output power (W). Here, A is panel area (m^2), G_t is insolation (W/m^2), θ is the angle of incidence, η_T is temperature-adjusted efficiency, and $PR = 0.80$ is the performance ratio.
Daily insolation was modeled as:

$$G_t = G_{max} \cdot \sin\left(\frac{\pi t}{T_{day}}\right)$$

where $G_{max} = 1000\,\mathrm{W/m^2}$, $T_{day} = 14\,\mathrm{h}$ (summer). Cell temperature was calculated as $T_c = T_a + \frac{G_t}{800} \cdot 30$, and efficiency as:

$$\eta_T = \eta_{STC} \cdot [1 - \beta(T_c - 25)]$$

where $\eta_{STC} = 0.20$, $\beta = 0.0045\,°\mathrm{C}^{-1}$.

GIS Analysis of Solar Potential

Data collection included Sentinel-2 satellite imagery (10 m resolution), cadastral plans, and NASA POWER climate archives . Digital Surface Models (DSM) were constructed in QGIS using Rasterize, and insolation was calculated via ArcGIS Solar Radiation:

$$G_{tilt} = G_h \cdot \cos(\theta) + G_d \cdot F_d + G_r \cdot \rho$$

where $G_h = 1{,}900\,\mathrm{kWh/m^2/year}$, $G_d = 0.2G_h$, $F_d = 0.5$, $\rho = 0.2$ (concrete albedo). Areas with shading ($S_f > 0.20$) were excluded.

Load Modeling

Wind load was determined per SNiP 2.01.07-85*:

$$W_{wind} = \frac{q \cdot C_p \cdot k}{9.81}$$

where $q = 0.5\rho V^2$, $\rho = 1.225\,\mathrm{kg/m^3}$, $V = 20\,\mathrm{m/s}$, $C_p = 1.3$, $k = 1.1$. Snow load was $S = S_n \cdot \mu$, with $S_n = 100\,\mathrm{kg/m^2}$, $\mu = 0.8$ (30° tilt). Static load was $W_{static} = W_{panel} + W_{frame} = 12 + 4 = 16\,\mathrm{kg/m^2}$. Total load:

$$W_{total} = W_{static} + W_{wind} + S$$

Tools

- **MATLAB/Simulink**: Solved equations using the Runge-Kutta method. - **Python (NumPy, SciPy)**: Numerical integration and visualization. - **QGIS/ArcGIS**: Insolation and shading

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analysis. - **ANSYS Fluent**: CFD wind flow simulation. - **SolidWorks**: FEA deformation analysis.

Results

Energy Potential

For a 100 m^2 rooftop in July ($G_{max} = 1000\,\mathrm{W/m^2}$, $T_a = 35\,°\mathrm{C}$), daily output was 650 kWh, and annual output was 30,400 kWh with $\eta_T = 0.16$, $PR = 0.80$. For a 300 m^2 rooftop at 30°, $G_{tilt} = 2{,}050\,\mathrm{kWh/m^2/year}$, $E_{pot} = 98{,}400\,\mathrm{kWh/year}$, reduced to 83,640 kWh/year with shading ($S_f = 0.15$, $A_{usable} = 255\,\mathrm{m^2}$).

Energy Output in Different Conditions

Condition	T_a, °C	G_t, W/m^2	η_T, %	P_{out}, kW	E_{pot}, kWh
Morning (8:00)	25	300	18.2	4.37	—
Noon (12:00)	35	1000	15.7	12.56	—
July (avg)	35	650	16.0	8.32	650 (day)
December (avg)	5	250	19.0	3.80	250 (day)

Solar Potential

GIS analysis revealed that 70% of Fergana's rooftops are suitable for PVS. For a 300 m^2 rooftop, $E_{pot} = 98{,}400\,\mathrm{kWh/year}$ at $\beta = 30°$, 94,560 kWh/year at 15°, and 96,480 kWh/year at 45°.

Operational Loads

With $V = 20\,\mathrm{m/s}$, $S = 80\,\mathrm{kg/m^2}$, $W_{static} = 16\,\mathrm{kg/m^2}$, total load was $W_{total} = 131.6\,\mathrm{kg/m^2}$. Concrete (400 kg/m^2) has a 67% safety margin, while metal (200 kg/m^2) has 34%.

Loads in Different Conditions

V, m/s	S, kg/m^2	W_{static}, kg/m^2	W_{total}, kg/m^2	Safety Margin (Concrete), %
10	80	16	95.9	76
20	80	16	131.6	67
25	100	16	171.5	57

Profitability

A 50 kW system ($C_{install} = \$12{,}500$, subsidy \$6,250) with $E_{pot} = 85{,}000\,\mathrm{kWh/year}$ yields \$3,400/year, with a payback of 1.9 years.

Discussion

Mathematical models confirmed that temperature reduces PVS efficiency to 15.7% at noon in summer, consistent with. Ventilation could increase η_T by 2–3%, boosting E_{pot} by 5%. GIS analysis showed shading losses of 10–20%, lower than in megacities like New York (30%), due to Fergana's moderate building heights.

The 30° tilt angle optimizes insolation and load balance, aligning with PVGIS data. Loads of 131.6 kg/m^2 are safe for concrete but require reinforcement for metal rooftops. A 1.9-year payback with subsidies outperforms Europe (5–7 years), driven by low costs and government support.

Limitations include simplified G_t modeling and lack of LiDAR data, reducing DSM accuracy to ±5 m. Future work could incorporate cloud cover and test Building-Integrated Photovoltaics (BIPV) for enhanced E_{pot}.

Conclusion

The developed models and GIS tools accurately assess PVS efficiency in Fergana, yielding $E_{pot} = 98{,}400\ \text{kWh/year}$ for a 300 m^2 rooftop at 30°. Concrete rooftops withstand loads with a 67% margin, and a 1.6–1.9-year payback confirms economic viability. Recommendations include a 30° tilt, lightweight structures, and ventilation. These findings are scalable across Central Asia, pending experimental validation.

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