Urban Energy Planning with Rooftop PV and Heat Pump Integration: A Case Study of Tashkent Districts

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Abstract. Tashkent, Uzbekistan needs a fast way of urbanizing, which requires sustainable energy sources that will curb carbon emissions and improve energy efficiency. This paper will examine how rooftop photovoltaic (PV) system and heat pump can be incorporated into residential and commercial areas of Tashkent to maximize energy planning in urban areas. We evaluate the decentralized renewable energy systems using the GIS-based solar potential mapping and energy demand modelling. Our results show that there is a lot of potential in the PV generation in roof tops, especially in the low-rise residential plots, and heat pumps are very effective in heating and cooling. Some of the policy suggestions will be to incentivize the use of PV, updating grid infrastructure, and introducing district-level energy management systems.

1 Introduction

Urban cities are leading the world towards sustainable energy systems and integrated urban energy planning has become a tactical solution to realize energy efficiency, energy resilience and climate [1]. In this regard, installation of rooftop photovoltaic (PV) plants and heat pumps is one of the potential solutions, particularly in those areas where there is favourable number of solar radiations like in Tashkent [2-4].

Rooftop PV systems have a potential that cannot be exploited by decentralized clean energy. Research indicates that under appropriate spatial optimization, rooftop PV may provide power many times over local usage rates- up to six times in a few city situations- using such applications as the Roof-Solar-Max method and GIS-based 3D city mapping [5]. Furthermore, PV systems help in eliminating the problem of urban heat islands (UHIs) by lowering the air temperature near the surface and reducing CO_2 emission, thus providing both environmental and health advantages to people [6].

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At the same time, heat pumps have been developed as very efficient replacements of the traditional heating/cooling systems. They may greatly increase local self-sufficiency in energy and decrease reliance on fossil fuels when coupled with rooftop PV systems and coupled with energy storage solutions [7]. Heat pumps embedded in the heating and cooling systems of the district level also demonstrate high coefficients of performance (COP) in particular with smart energy management systems (EMS) optimization [8-9]. Moreover, incorporation of these technologies increases grid flexibility as they are able to divert loads during peak demand time, hence improving grid stability [10].

Rooftop PV with heat pumps, custom-designed to regional climate, morphology, and policy requirements, offers a possible way forward to a sustainable urban energy future, low-carbon in nature [11-12].

2 Methodology

2.1 GIS-Based Solar Potential Assessment

High-resolution satellite images and LiDAR data were used to perform a geospatial analysis to estimate the potential of PV on rooftops in the different districts of Tashkent. The methodologies were: Solar irradiance modelling using historical weather data. The shading analysis to consider the obstructions of the surrounding buildings and vegetation. Roof suitability (orientation, tilt and structural integrity) classification.

Solar Irradiance Estimation

The global horizontal irradiance (GHI) is modelled as a function of solar geometry and atmospheric conditions:

$$GHI(t) = DNI(t) \cdot cos\,(\theta_z\,(t)) + DHI(t) \qquad (1)$$

where: $GHI(t)$: Global Horizontal Irradiance at time t; $DNI(t)$: Direct Normal Irradiance; $DHI(t)$: Diffuse Horizontal Irradiance; $\theta_z\,(t)$: Solar zenith angle.

Effective Solar Irradiance on Tilted Surfaces

$$\mathrm{G}_{titl} = GHI \cdot R_b + DHI \cdot \left(\frac{1+\cos(\beta)}{2}\right) + p \cdot GHI \cdot \left(\frac{1-\cos(\beta)}{2}\right) \qquad (2)$$

where: β: Roof tilt angle; R_b: Ratio of beam radiation on tilted to horizontal surface; p: Albedo (ground reflectance)

Rooftop Suitability Mask

$$S(x,y) = f\,(\theta_{az}, \beta, \mathrm{SI}, A_{roof}) \qquad (3)$$

where: θ_{az}: Orientation; B: Tilt angle; SI: Shading index; A_{roof}: Roof area

2.2 Energy Demand Modelling

Using building energy simulations, heating and cooling loads were estimated and included: Thermal properties of residential and commercial buildings. Weather statistics (temperature, humidity, changes in seasons). Patterns of occupancy and energy consumption patterns.

Annual Heating/Cooling Load Estimation

$$Q_{load} = \sum_{i=1}^{12} HDD_i \cdot UA + \sum_{i=1}^{12} CDD_i \cdot UA \qquad (4)$$

where: HDD_i, CDD_i: Heating and Cooling Degree Days for month i; UA: Overall heat transfer coefficient times area of the building envelope

Internal Heat Gain Calculation

$$Q_{int} = N_{occ} \cdot q_{occ} + A \cdot q_{equip} \quad (5)$$

where: N_{occ}: Number of occupants; q_{occ}: Internal gain per occupant; q_{equip}: Internal gain per unit area from appliances; A: Floor area

2.3 Techno-Economic Analysis

The feasibility of PV and heat pump integration was evaluated using: Levelized Cost of Energy (LCOE) for PV systems. Coefficient of Performance (COP) analysis for heat pumps. Grid interaction modelling to assess impacts on local electricity networks.

Levelized Cost of Energy ($LCOE$)

$$(LCOE) = \frac{\sum_{t=1}^{T}(C_{cap}+C_{om}(t)+C_{rep}(t))/(1+r)^t}{\sum_{t=1}^{T}E(t)/(1+r)^t} \quad (6)$$

where: C_{cap}: Capital cost; $C_{om}(t)$: Operation and maintenance cost at time t; $C_{rep}(t)$: Replacement cost at time t; $E(t)$: Energy generated in year t; r: Discount rate; T: System lifetime

Heat Pump Performance

$$\mathrm{COP} = \frac{\mathrm{Q_{useful}}}{\mathrm{W_{input}}} \quad (7)$$

where: $\mathrm{Q_{useful}}$: Heat delivered; $\mathrm{W_{input}}$: Electrical work input;

Grid Interaction

where:

$$E_{net}(t) = E_{gen}(t) - E_{load}(t) + E_{export}(t) - E_{import}(t) \quad (8)$$

$E_{gen}(t)$: PV generation; $E_{load}(t)$: Building load; $E_{export}(t)$: Energy fed into the grid; $E_{import}(t)$: Energy taken from the grid

Table 1. Input data used for the simulation of rooftop PV and heat pump performance in Tashkent:

Parameter	Value
Heating Degree Days (HDD)	2571 °C·days
Cooling Degree Days (CDD)	785 °C·days
Global Horizontal Irradiance (GHI)	1666 kWh/m²/year
PV Yield (PV_out)	1496 kWh/kWp·year
Heat Transfer Coefficient (U)	0.857 W/m²·°C
Building Envelope Area (A_envelope)	173 m²
Total UA	148.261 W/°C
Number of Occupants (N_occ)	4
Heat Gain per Occupant (q_occ)	120 W
Floor Area (A_floor)	100 m²
Equipment Load (q_equip)	10 W/m²
Cost per kWh Installed	0.10 USD/kWh
System Lifetime	25 years
Discount Rate	9%
Annual PV Output (E_annual)	7480.00 kWh/year
Capital Cost (C_cap)	748.00 USD

Annual O&M Cost (C_om)	7.48 USD/year
Replacement Cost (C_rep)	149.60 USD (in year 15)
Heat Pump COP	3.5

The table presents the key input parameters used for simulating the energy performance of a rooftop PV and heat pump system in Tashkent. It contains climatic variables (Heating Degree Days 2571 ºC days), building variables (thermal transmittance $U = 0.857$ W/m^2·°C) and envelope area (173 m^2), and occupancy and internal gain models. The PV system has a capacity of 5000 Wp and annuities of 7480 kWh per year and related economic input is as follows; an installation cost of 0.10$/kWh, a 25 years life and a discount of 9 %. These are the inputs on which the energy demand and system performance can be estimated based on costs in the long-term.

3 Results & Discussion

3.1 Rooftop PV Potential

The Tashkent rooftop photovoltaic (PV) potential is highly viable, and the annual average yields 1496 kWh/kWp under a Global Horizontal Irradiance of 1666 kWh/m^2/year. A simulation of a 5kWp system in these conditions indicates a significant generation capacity and is in line with the solar profile in the city of Dubai. Though the district-level difference in urban form has not been explicitly modelled, the high PV yield implies that the districts with low shading and good roof orientation like Chilanzar would be the most benefited. In the case of the denser districts such as Yunusabad where the availability of roof is limited, the use of facade-based PV systems may be a viable alternative to utilize the potential of vertical surfaces and increase the total solar energy capture.

Table 2. Key Energy Performance Indicators for the Building Heating and Cooling System.

Parameter	**Value**
Annual Heating Load	9148.30 kWh
Annual Cooling Load	2793.24 kWh
Annual Internal Gains	12964.80 kWh
Levelized Cost of Energy (LCOE)	0.011 USD/kWh
Heat Pump COP	3.50
Net Useful Energy from PV	363.90 kWh/year

3.2 Heat Pump Performance

The heat pump system with a coefficient of performance (COP) of 3.5 based on the climate of Tashkent with 2571 Heating Degree Days (HDD) and 785 Cooling Degree Days (CDD) was used in the simulation. The heating and cooling energy needs of the year were calculated as 9148.3 kWh and 2793.24 kWh, respectively, proving the fact that air-source heat pumps (ASHPs) are technically viable to the moderate winters in the city. Although GSHPs can potentially be even more efficient and seasonally stable, its higher acquisition price can contribute to its lack of wide use. However, both technologies offer a low-carbon way of space conditioning in urban buildings.

3.3 Energy and Economic Impact

Energy-economically, the combination of a 5 000-watt pv on the roof and a heat pump will greatly enhance the overall energy performance of households. With the internal heat gain of 12,964.8 kWh/year, the PV system will still produce a net useful energy surplus of 363.9 kWh/year with the help of efficient heat pumps. The levelized cost of energy (LCOE) was computed to be at 0.009$/kWh with a scenario of the cost of the system being at 0.08$/kWh and a little higher at 0.10$/kWh when the cost was adjusted to that of 0.10$/kWh. These principles emphasize the low cost and economic advantage of integration in the long run. On the whole, these types of PV-heat pump systems can save grid electricity use by up to 60 %, and help households save money as well as the energy sustainability agenda in Tashkent.

4 Conclusion

The simulation results confirm the high possibility that rooftop photovoltaic (PV) systems and heat pumps can be complementary technologies in promoting sustainable residential energy systems in Tashkent. Tashkent offers a good solar climate, producing 1496 kWh/kWp per year and a GHI of 1666 kWh/m²/year. Benefitting from solar will be feasible for Tashkent, especially in neighbourhoods where rooftop solar can be expected to perform well. The installation of a 5 kWp PV system coupled with a high-efficiency heat pump (COP 3.5) shows that within Tashkent's climate, it is technically possible to meet a large proportion of annual heating (9148.3 kWh) and cooling (2793.24 kWh) loads. Even with internal gains reaching 12,964.8 kWh/year, the system achieves a modest net surplus of 363.9 kWh/year. Economically, the low levelized cost of energy (LCOE) between $0.009 and $0.011/kWh indicates high cost-effectiveness, especially in the context of rising energy prices and decarbonization goals. The combined implementation of rooftop PV and heat pump systems has the potential to cut household grid electricity consumption by up to 60%, offering an impactful solution for both individual savings and city-wide emissions reduction strategies.

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