

Hybrid Renewable Energy Integration in Herat, Afghanistan: A Sector-Based Feasibility Study of Affordable Solar-Wind Systems

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ABSTRACT

This study investigates the technical feasibility and economic viability of implementing renewable energy systems, including solar photovoltaic (PV), small-scale wind, and hybrid solar-wind configurations, in Herat City, Afghanistan. Because Herat has high solar irradiance and strong seasonal wind resources, particularly the well-known “120 Days Wind,” the study evaluates practical energy alternatives for four representative end users: households, schools, hospitals, and small and medium-sized enterprises (SMEs). The methodology combines sector-based load estimation, PV and wind energy sizing, seasonal resource assessment, and financial evaluation using benefit-cost ratio (BCR), payback period (PBP), and levelized cost of energy (LCOE). The results show that solar PV systems are the most practical and reliable option for households and schools because their energy demand is relatively moderate and mostly aligned with daylight operation. Hybrid solar-wind systems are more suitable for hospitals and SMEs, where continuous and higher electricity demand requires complementary energy supply. For the SME case, the hybrid system provides approximately 67.8% of the annual electricity requirement, while the remaining 32.2% is supplied by public grid electricity. Overall, the study provides a practical roadmap for decentralized renewable energy development in semi-urban Afghan districts and demonstrates the potential of affordable solar-wind systems to improve energy security, reduce long-term costs, and support environmental sustainability in post-conflict regions.

Keywords- Affordable energy, benefit-cost ratio, global horizontal irradiance, Herat City, hybrid energy systems, payback period, renewable energy, solar photovoltaic, wind turbines.

I. INTRODUCTION

Access to reliable, affordable, and sustainable energy remains a major challenge in Afghanistan, particularly in semi-urban and rural regions where grid infrastructure is limited, unstable, or not fully available [1]. At the same time, rising global energy demand and the accelerating impacts of climate change have increased the importance of renewable energy transition as a practical and strategic necessity [2]. Herat Province, located in western Afghanistan, has strong potential for renewable energy development because of its high solar irradiance and seasonal wind patterns, especially the “120 Days Wind” phenomenon [3]. However, despite this potential, local implementation remains limited due to insufficient context-specific feasibility studies, lack of tailored technical models, and economic uncertainty at the end-user level [4].

This paper evaluates the technical and economic viability of solar and wind energy systems, both as stand-alone solutions and as integrated hybrid models, for Herat City. A case-based approach is used to assess four distinct energy

consumers: a residential household, a public school, a healthcare facility, and a small to medium-sized enterprise (SME) [5]. Each case is designed to reflect realistic demand patterns, system configurations, and environmental conditions, allowing the study to examine how renewable technologies perform across different use sectors.

The analysis uses meteorological and resource data, including global horizontal irradiance (GHI), ambient temperature, sun elevation, sunny-day patterns, and wind speed. Solar PV performance is estimated using panel tilt, temperature-adjusted efficiency, and performance-ratio corrections, while wind output is estimated using turbine parameters and monthly wind availability. A financial assessment is then carried out using benefit-cost ratio, payback period, and levelized cost of energy to evaluate long-term affordability and investment value [7].

Rather than proposing a single universal solution, this study demonstrates how renewable energy systems can be tailored to match specific energy needs, economic constraints, and resource availability. The findings can help engineers, development planners, policy-makers, and local communities design scalable and context-sensitive energy systems for Afghanistan and other regions with similar renewable resource potential.

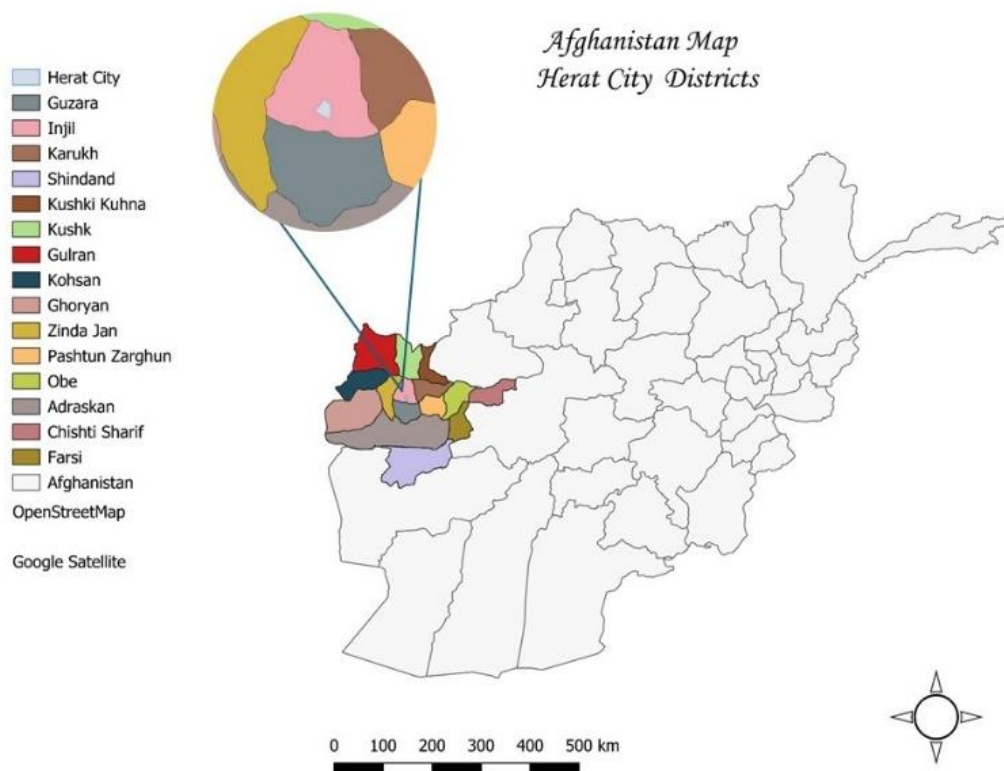


Figure 1: Location of Herat City in Afghanistan.

II. METHODOLOGY

A. Solar Energy Production Estimation

Solar energy production was estimated using a step-by-step model that considers irradiance level, panel orientation, temperature correction, and system losses. The global horizontal irradiance was adjusted for a fixed panel tilt angle of 30° , which is appropriate for the latitude of Herat. A simplified angle-of-incidence (AOI) approximation was used to represent how directly sunlight strikes the PV surface [6].

$$AOI = |\beta - \alpha|$$

where β is the panel tilt angle and α is the sun elevation angle for each hour. This simplified approximation does not explicitly include solar azimuth. A cosine correction is then applied to account for angular losses.

Because PV panels lose efficiency under high temperature, a temperature-adjusted efficiency equation was used:

$$\eta(T) = \eta_{ref} \times [1 + \gamma(T - 25)]$$

where η_{ref} is the reference efficiency at 25°C , γ is the temperature coefficient, and T is the ambient temperature in $^\circ\text{C}$. The final PV power output was calculated as:

$$P_{solar} = A \times \eta(T) \times GHI \times \cos(AOI) \times PR$$

where A is the panel area, $\eta(T)$ is the adjusted efficiency, GHI is global horizontal irradiance, and PR is the performance ratio. Hourly values were summed to estimate daily, monthly, and annual energy production.

B. Wind Energy Production Estimation

Wind energy modeling was based on Herat's seasonal wind regime, especially the strong summer wind period. The available power in the wind was estimated using the standard kinetic power equation [8]:

$$P_{\text{wind}} = 0.5 \times \rho \times A \times v^3$$

where ρ is air density, A is rotor swept area, and v is wind speed. The usable electrical energy was then obtained by applying the turbine power coefficient and electrical efficiency:

$$E_{\text{wind}} = P_{\text{wind}} \times t \times C_p \times \eta_e$$

where t is time, C_p is the turbine power coefficient, and η_e is the electrical conversion efficiency. This approach estimates usable energy output for small wind turbines under local wind conditions.

C. Economic Evaluation

The economic feasibility of each renewable energy option was evaluated using benefit-cost ratio, payback period, and levelized cost of energy. The benefit-cost ratio compares the total lifetime benefit obtained from electricity savings with the initial investment cost:

$$\text{BCR} = \text{Total lifetime benefit} / \text{Initial investment cost}$$

The payback period shows how many years are required for the investment to recover its initial cost:

$$\text{PBP} = \text{Initial investment cost} / \text{Annual savings}$$

These indicators were used to compare the evaluated systems across different end users in terms of affordability, reliability, and long-term benefit.

D. Seasonal and Hourly Modeling

Solar and wind calculations were performed across the year using hourly and seasonal climate data for Herat City. Solar output was modeled during daylight hours, while wind output was estimated using average monthly wind speeds and operational availability. This approach allows the study to compare solar and wind performance across different months and identify seasonal resource complementarities.

III. RENEWABLE RESOURCE ASSESSMENT IN HERAT**A. Solar Irradiance, Temperature, and Sun Conditions**

Global horizontal irradiance is one of the most important parameters for estimating photovoltaic output. The hourly irradiance profile indicates that Herat receives strong solar energy during the middle of the day, with the highest values generally occurring between 11:00 and 14:00. Peak irradiance is observed during the summer months, particularly from May to August, when values may approach 1000 W/m² [10].

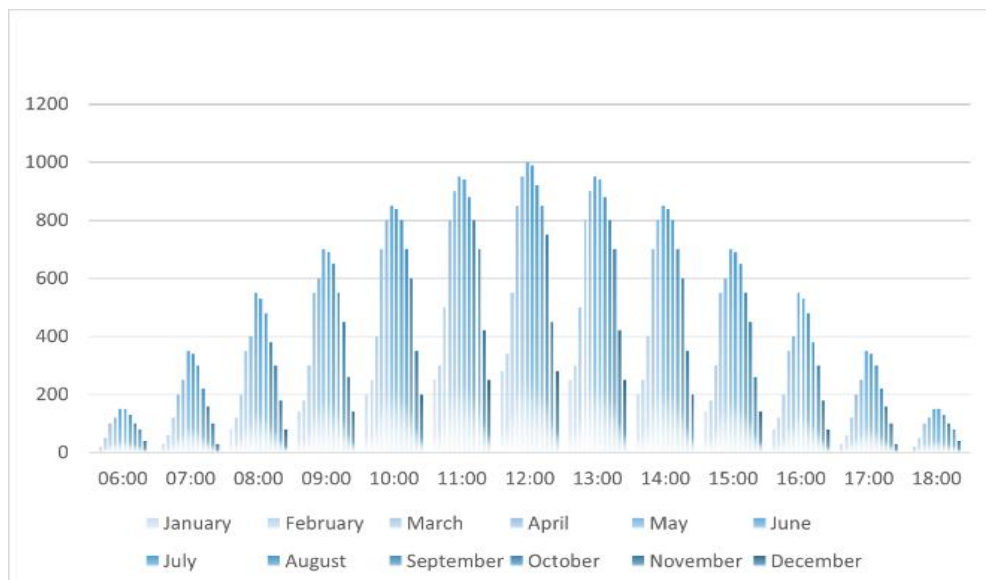


Figure 2: Hourly variation of global horizontal irradiance (GHI).

Ambient temperature affects PV performance because higher temperatures reduce module efficiency. The temperature profile shows a seasonal increase from winter to summer, with the highest values occurring in July and August. This confirms the importance of including temperature correction in the PV energy estimation model [11].

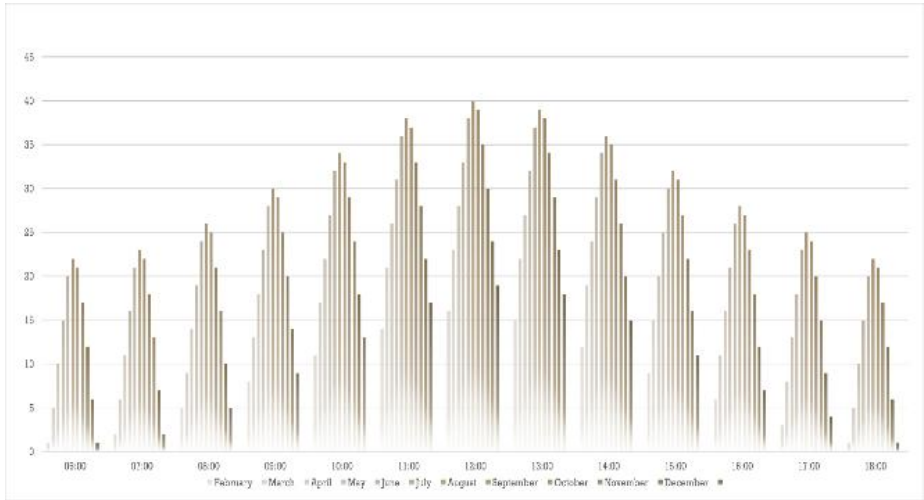


Figure 3: Hourly variation of ambient temperature.

The sun elevation angle determines the effectiveness of the selected panel tilt. The data show that the maximum elevation occurs around midday in summer, supporting the use of a fixed tilt angle around 30° for practical PV installation in Herat [11]. The monthly number of sunny days further confirms that Herat has strong solar resource availability, especially during summer months [12].

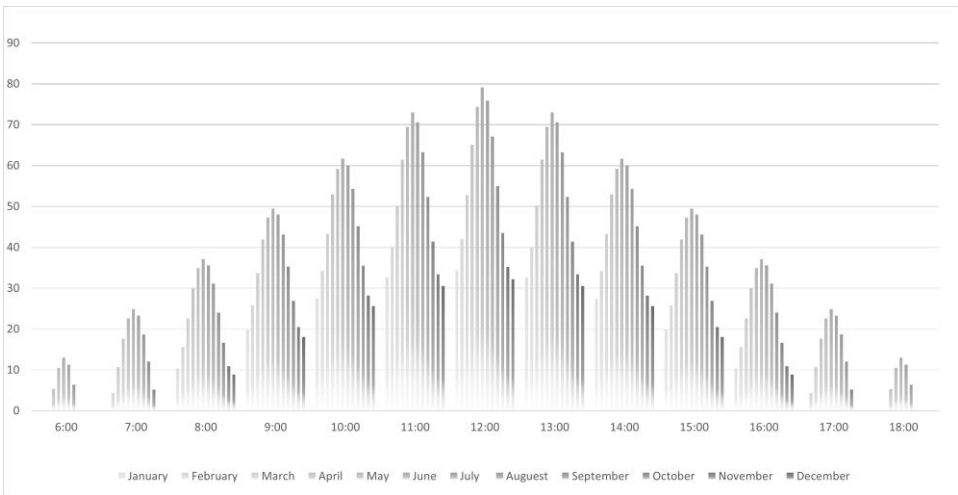


Figure 4: Hourly sun elevation angle across different months.

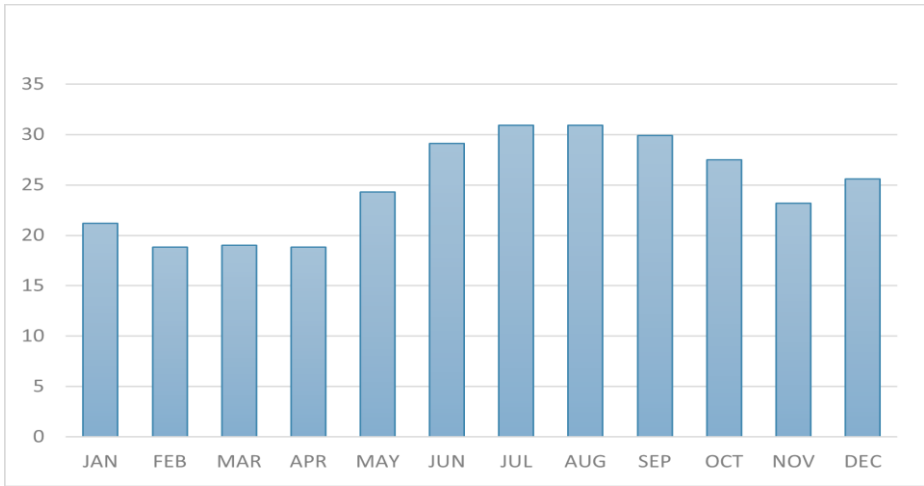


Figure 5: Monthly average number of sunny days.

B. Wind Resource and Operational Availability

Wind speed data show that Herat has significant seasonal wind potential. The average monthly wind speed reaches its highest level in July and August, approximately 8.9 m/s and 8.4 m/s, respectively. This period corresponds to the well-known “120 Days Wind” in western Afghanistan [13].

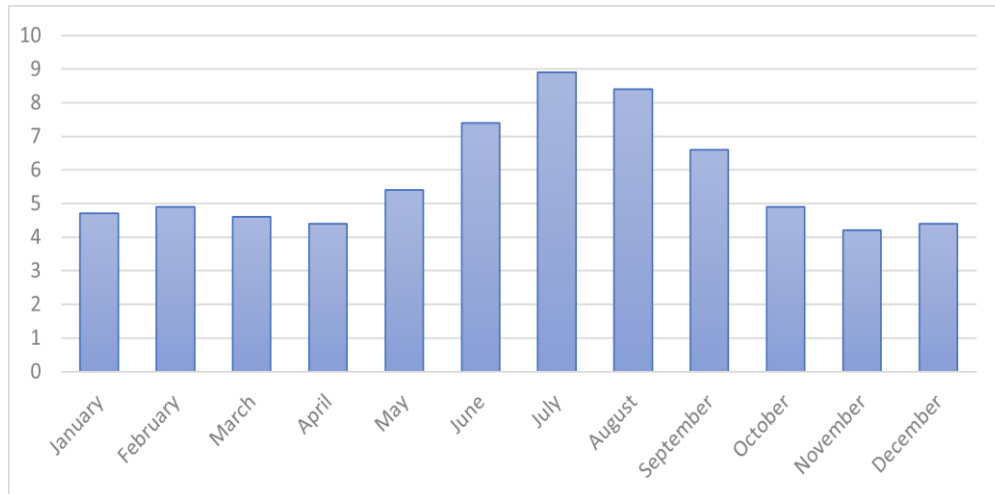


Figure 6: Average monthly wind speed in Herat.

The operational availability of wind turbines was estimated based on the proportion of hours when wind speed exceeds the cut-in threshold of 3 m/s. The results show that wind energy potential is strongest from June to September, while availability is lowest during winter months. This seasonal variation supports the use of hybrid systems, where wind complements solar energy during specific periods.

Table 1: Estimated monthly wind turbine operational availability and effective wind hours.

Month	Wind hours	Operational availability (%)	Effective wind hours
Jan	744	30	223
Feb	672	40	269
Mar	744	50	372
Apr	720	45	324
May	744	60	446
Jun	720	80	576
Jul	744	90	670
Aug	744	85	632
Sep	720	70	504
Oct	744	40	298
Nov	720	30	216
Dec	744	25	186

IV. CASE STUDY RESULTS AND DISCUSSION

A. Solar PV System for a Household

A typical household in Herat was assumed to consume approximately 2600 kWh of electricity per year for lighting, fans, a refrigerator, phone charging, and basic domestic appliances. A solar PV system with six 450 W monocrystalline panels was designed, providing a total installed capacity of approximately 2.70 kW and requiring about 12 m² of area. With an assumed efficiency of 22% and Herat's strong solar resource, the system can generate about 2870 kWh per year, which is higher than the household's annual demand.

The estimated installation cost is about USD 1400, including the panels, inverter, mounting frame, wiring, and labor. Over a 20-year lifetime, the system can produce approximately 57,400 kWh. The levelized cost of electricity is about USD 0.024/kWh, which is lower than the approximate grid electricity price of USD 0.07/kWh. Based on the stated household demand of 2600 kWh/year and the grid electricity price of USD 0.07/kWh, the annual electricity-saving benefit

is estimated at USD 182.00. The simple payback period is therefore approximately 7.7 years, while the total 20-year electricity-saving benefit is approximately USD 3640, giving a benefit-cost ratio of 2.60.

B. Wind Turbine System for a Household

A small household wind turbine was also evaluated using a rotor diameter of 4 m and a hub height of 10 m. Based on Herat's local wind conditions, especially the strong summer wind season, the system is estimated to produce approximately 3518.64 kWh/year, exceeding the annual household demand. The total installation cost is estimated at USD 1100, including the turbine, tower, controller, and labor.

The 20-year electricity-saving benefit is estimated at USD 3640, based on the household annual demand of 2600 kWh and a grid electricity price of USD 0.07/kWh. This results in a benefit-cost ratio of 3.31 and a payback period of about 6.0 years. The calculation assumes that electricity generated beyond the household's annual demand is not credited or sold to the grid.

Table 2: Comparative analysis of solar and wind energy systems for household application.

Factor	Solar PV system	Wind turbine system
Annual output (kWh)	2,870	3,518.64
System cost (US\$)	1,400	1,100
Payback period (years)	7.7	6.0
Total benefit (US\$)	3,640	3,640
Benefit-cost ratio	2.60	3.31
Practical reliability	High and stable year-round	Seasonal and maintenance-sensitive

C. Household Option Comparison

For household-scale application, the solar PV and wind systems show different technical and operational characteristics. Solar provides more stable year-round generation and generally requires less maintenance, while wind has a more seasonal output profile and requires additional maintenance. Under the stated assumptions, the solar system has a 7.7-year payback period, while the wind system has a 6.0-year payback period. The choice between the two depends on the household's resource conditions, maintenance capacity, and electricity-use pattern.

D. Solar PV System for a School

A solar PV system was evaluated for a typical school in Herat. Schools generally operate during daylight hours and use electricity mainly for lighting, fans, office equipment, and computer labs. Therefore, solar generation aligns well with school energy demand.

The proposed school system consists of 13 monocrystalline solar panels rated at 450 W each, covering approximately 26 m². The system is expected to generate about 5654.66 kWh/year. With an estimated installation cost of USD 2850 and a 20-year lifetime output of around 113,093 kWh, the LCOE is approximately USD 0.025/kWh. Annual savings are estimated at USD 395.83, while the total 20-year benefit is around USD 7916.53. The payback period is approximately 7.2 years, with a benefit-cost ratio of 2.78.

Wind energy was not selected for the school case because school demand occurs mainly during the day, when solar energy is most available. The evaluated solar PV system is therefore aligned with the school's daytime operating pattern and the stated energy demand.

E. Hybrid Solar-Wind System for a Hospital

Hospitals require continuous and reliable electricity for medical equipment, lighting, refrigeration, ventilation, laboratories, and information systems. For this reason, a hybrid solar-wind system was proposed to improve reliability and reduce dependence on diesel generators or unstable grid supply.

The solar component consists of 50 monocrystalline PV panels rated at 450 W each, providing 22.5 kW of installed capacity. The annual solar output is estimated at 21,748.71 kWh, with an installation cost of USD 9400. Over a 20-year lifespan, the solar subsystem provides a total benefit of about USD 30,448.20 and a benefit-cost ratio of 3.24.

The wind component consists of six small-scale turbines that collectively produce about 21,108 kWh/year. The wind system costs approximately USD 6600 and offers annual savings of USD 1477.56, a 20-year benefit of USD 29,551.20, and a benefit-cost ratio of 4.48. Together, the solar and wind systems generate approximately 42,857 kWh/year, exceeding the hospital's estimated annual demand of 36,500 kWh. This surplus can support storage, backup needs, or future expansion.

The hospital case demonstrates the advantage of hybrid design. Solar energy provides stable daytime production, while wind contributes during windy periods and may support nighttime or cloudy-day needs. This complementarity is important for healthcare facilities that require continuous operation.

F. Hybrid Solar-Wind System for SMEs

Small and medium-sized enterprises in Herat often require electricity for lighting, IT equipment, refrigeration, production equipment, and business operations. Because their energy demand is higher and more continuous than residential or school loads, a hybrid system supported by public grid electricity was evaluated.

The proposed system integrates 75 monocrystalline solar panels rated at 450 W and 10 small-scale wind turbines. The hybrid system produces approximately 67,803 kWh/year. Solar contributes 32,623 kWh/year, equal to 48.11% of the hybrid output, while wind contributes 35,180 kWh/year, equal to 51.89%. The total installation cost is estimated at USD 22,250.

Because the estimated SME demand is about 100,000 kWh/year, the hybrid system covers approximately 67.8% of the annual requirement. The remaining 32.2% is supplied by public electricity. This approach reduces operating costs while maintaining practical reliability for business operations.

Table 3: Technical and economic performance indicators of the hybrid solar-wind energy system for SMEs.

Description	Value
Total annual energy output (kWh/year)	67,803.07
Solar share (%)	48.11
Wind share (%)	51.89
Total installation cost (US\$)	22,250
Annual savings (US\$)	4,746.21
Total benefit (US\$)	94,924.29
Benefit-cost ratio (BCR)	4.27
Payback period (years)	4.69

V. CONCLUSION

This study examined the technical and economic feasibility of using solar PV, wind, and hybrid solar-wind systems in Herat City, Afghanistan, through four representative case studies: a household, a school, a hospital, and SMEs. The results show that system configuration should be selected according to the user's demand profile, reliability requirement, and available renewable resources.

For households and schools, the evaluated stand-alone solar PV systems are well matched to the stated demand profiles. The household solar system covers the estimated annual demand of 2600 kWh and has a simple payback period of approximately 7.7 years. The school solar system produces about 5654.66 kWh/year, with a payback period of approximately 7.2 years and a benefit-cost ratio of 2.78.

For hospitals, hybrid solar-wind systems are more suitable because healthcare facilities need continuous and reliable electricity. The proposed hospital system generates about 42,857 kWh/year, exceeding the estimated annual demand of 36,500 kWh. The combination of solar and wind improves reliability, reduces dependence on diesel generators, and supports critical operations.

For SMEs, the hybrid system supported by public electricity provides a practical and scalable solution. The proposed system supplies about 67.8% of annual energy demand, while the remaining 32.2% is supplied by the public grid. This configuration reduces energy costs while maintaining operational reliability.

Overall, the findings confirm that renewable energy can play an important role in improving energy security, affordability, and sustainability in Herat and similar Afghan regions. Solar energy is especially suitable for small-scale and daytime applications, while hybrid solar-wind systems are more effective for higher and continuous loads. Future work should include field validation, battery storage optimization, life-cycle environmental assessment, and policy-level analysis for wider implementation.

REFERENCES

- [1] World Bank. (2018). *Afghanistan energy sector: Background and key issues*. World Bank.
- [2] Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis*. Cambridge University Press.
- [3] GIZ. (2018). *Renewable energy potential in Herat Province, Afghanistan*. GIZ.
- [4] Asian Development Bank. (2017). *Afghanistan renewable energy development: Issues and options*. Asian Development Bank.
- [5] Campana, P. E., et al. (2019). Scalable off-grid energy planning using a case-based renewable energy model. *Renewable and Sustainable Energy Reviews*, 101, 214–232.
- [6] Duffie, J. A., & Beckman, W. A. (2013). *Solar engineering of thermal processes* (4th ed.). Wiley.
- [7] Short, W., Packey, D. J., & Holt, T. (1995). *A manual for the economic evaluation of energy efficiency and renewable energy technologies*. National Renewable Energy Laboratory.
- [8] Manwell, J. F., McGowan, J. G., & Rogers, A. L. (2010). *Wind energy explained: Theory, design and application*. John Wiley & Sons.

- [9] International Renewable Energy Agency. (2021). *Renewable power generation costs in 2020*. International Renewable Energy Agency.
- [10] NASA POWER Project. (2024). NASA Langley Research Center POWER Data Access Viewer (global horizontal irradiance data). <https://power.larc.nasa.gov/data-access-viewer/>
- [11] NASA POWER Project. (2021). POWER Data Access Viewer (temperature and solar-position data). NASA Langley Research Center. <https://power.larc.nasa.gov/data-access-viewer/>
- [12] Climate-Data.org. (2024). *Climate: Herat*. <https://en.climate-data.org/asia/afghanistan/herat/herat-4237/>
- [13] NASA POWER Project. (2024). *Surface wind speed at 10 m for Herat, Afghanistan*. NASA Langley Research Center. <https://power.larc.nasa.gov/data-access-viewer/>