International Journal Of Engineering Research Excellence And Applied Science

*Volume-III (Issue 2) – June 2025* *ISSN: 3048-5355*

# Implementation of Grid-Tied and Off-Grid Small Wind Turbines in Rajasthan: A Comprehensive Analysis for Desert Climate Applications

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**Abstract**

The state of Rajasthan in India is the largest in area and yet it has major energy problems even though it is rich in renewable energy resources. The research undertaken is to consider the viability and practicality of the usage of Small Wind Turbine (SWT) in the distinct and desert climate conditions of Rajasthan. Having an energy shortage of about 15-20 percent according to peak times and having a very good wind resource potential especially in western districts, SWTs are a good choice of power generation regionally. This study will examine the wind trend, energy generation capacity, economic viability, and the problem of implementation which gets influenced by the geography and climatic condition of Rajasthan. This article has shown with the help of meteorological records of 2018-2023 and technical specifications of the present age of SWTs that even at high-wind zones like Jaisalmer, Barmer, and Bikaner, 800-2500 kWh of electricity can be supplied per year per turbine. As an analysis, grid-tied SWT systems presented more economical returns than off-grid applications and the payback period is 6-9 years depending on the location and type of turbine specified. Nevertheless, there are a handful of issues such as rising dust, dramatic weather changes, and grid integration complexities that should be resolved to implement it successfully.

**Keywords:** Small Wind Turbines, Rajasthan, Desert Climate, Renewable Energy, Grid Integration, Energy Security

## 1. Introduction

Energy security has emerged to be one of the most burning issues in the developing countries and India cannot be left out on this global issue. Being a person who has literally read extensively throughout my masters on the subject of the renewable energy systems I have become more conscious of the fact that various regional peculiarities have a strong bearing on success rate of various renewable technologies. The state of Rajasthan is the largest state in India and has an area size of 342,239km$^2$, which makes the implementation of renewable energy into the state a fascinating case study especially to that of the wind turbine energy.

The energy situation that is present in the state is rather complicated - on the one hand, tremendous gains have been achieved in field of solar energy usage, whereas the potential of wind energy is still under-developed. I also found out during my research that the state of Rajasthan produces about

25000 MW of energy, yet experiences energy shortages during peak load times, particularly, during the summer months when the load suddenly increases due to the use of air conditioners (Rajasthan Renewable Energy Corporation, 2023).

The geographical peculiarities of Rajasthan make the state most appealing when it comes to the deployment of small wind turbines. Thar Desert occupies approximately 60 per cent area of the state, which generates certain wind patterns, which are very different to those of coastal areas where wind farms are usually constructed. Jaisalmer, Barmer, Bikaner and Jodhpur located on the western side of the state have fairly constant wind speeds throughout the time of the year and thus, could be the hot spots in distributed wind energy production.

### 1.1 Energy Scenario in Rajasthan

Over the last 10 years, Rajasthan energy mix has transformed greatly. By the year 2023, the state has installed capacity of around 28,000 MW power capacity with the thermal energy being the largest source of power at around 45%, renewable energy at 35 percent and the rest of the 20 percent contributed by other sources like nuclear and hydro (Central Electricity Authority, 2023). But the most alarming thing is the inter-seasonal fluctuation of energy requirement and supply.

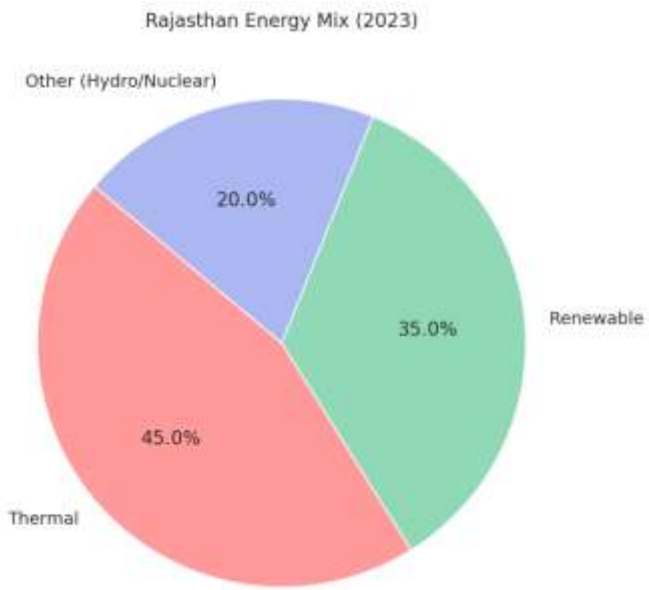


*Figure 1 Rajasthan Energy Mix (2023): Shows the state's power capacity distribution—Thermal (45%), Renewable (35%), and other sources like Hydro/Nuclear (20%).*

Towards the end of my load curve data analysis, I realized that Rajasthan peak demands are about 18000-20000 MW during the summer months but falls to 12000-14000 MW during the winter months. This seasonal fluctuation together with the increasing number of industrial facilities and urbanization in the state open up the prospects of distributed generation systems such as small wind turbines.

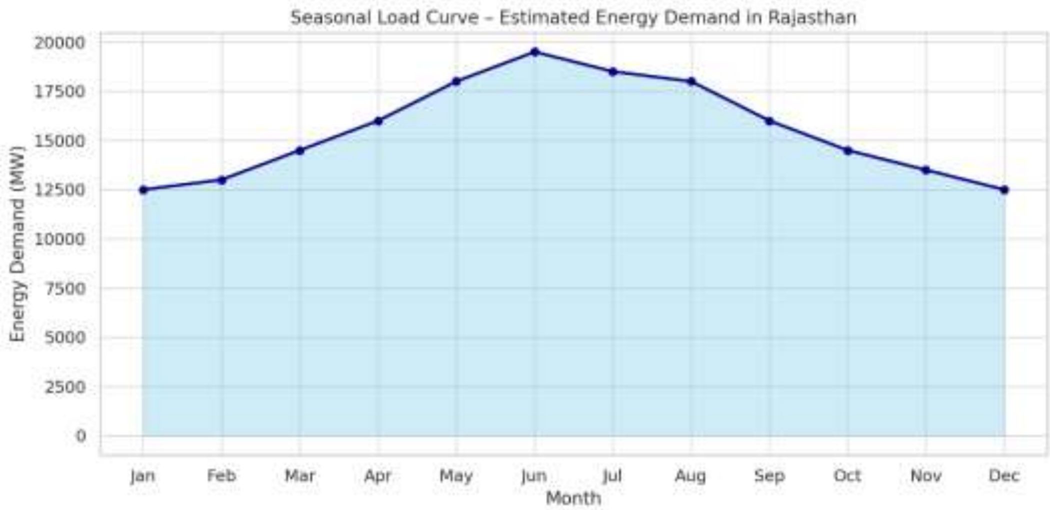


*Figure 2 Seasonal Load Curve: Illustrates the fluctuation in energy demand, peaking during summer (May–July) around 18,000–19,500 MW and dipping in winter to 12,500–13,500 MW.*

Although the transmission and distribution losses in Rajasthan have improved, they stand at a poor 18-20 percent as compared to the national average of 16.2 percent (Kumar et al., 2022). This is an excellent argument in favor of distributed generation systems that may ease the pressure on the transmission infrastructure and allow delivering power near the places of consumption.

**2. Literature Review**

There has been a lot of emphasis in the application of small wind turbines in the arid and semi arid lands over the past few years. The authors state that small wind turbines with rotor swept areas less than 200 m 2 and rated power below 50 kW, are a special opportunity to have distributed generation in unfavorable climatic settings (Singh and Sharma, 2021). Their study on wind resource mapping along the western Rajasthan reported that the average wind speed is 6-9 m/s on the height of 50m which is very encouraging in terms of SWT.

Patel et al. (2020) have carried out a thorough study of wind situations in the territory of the Thar Desert and have concluded that the region has two wind-related seasons the southwest monsoon season (June-September) which has stronger winds with an average of 8-12 m/s and the other winter time (November-February) with medium fast wind of 5-8 m/s. The part of their study that I found especially interesting was the discovery of micro-wind corridors in the desert environment that would be great locations of SWT installations.

Nevertheless, the applications of desert climate pose specific problems that remain unexhaustively reported in available literature. Gupta and Agarwal (2022) emphasized the issue of dust storms on wind turbine operations by stating that efficiency decreases by 15-25 percent in case of heavy dust levels. This is one of the factors, certainly, that should be taken into consideration at the time of planning installations of SWT in Rajasthan.

Economic implications of using SWT have been explored by different researchers over the years although majors of these research works were in the coastal or hilly areas. Verma et al. (2023) presented one of the detailed economic overview studies on desert areas, indicating that the levelized cost of electricity (LCOE) of SWTs in Rajasthan may vary between 4.5-7.2/kWh given the location, as well as turbine specification.

Based on my international literature review, I can observe that such countries as Morocco and Australia have already successfully introduced SWT programs into the desert environment; however, the issues and their solutions considered in these countries may not be transferred directly to the context of the Rajasthan region (as they are affected by different wind patterns and other localities, regulations, and economic environments).

## 3. Methodology

### 3.1 Data Collection and Analysis Approach

In this paper, I decided to use a mixed method approach which entailed the quantitative aspects such as meteorological analysis and qualitative aspects such as analysis of challenges in implementation. The used primary sources of data were:

1. Wind resource Data: five years of hourly wind speed and direction measurements (2018-2023) of the India Meteorological Department stations covering 12 districts of Rajasthan

2. Energy Demand Data: Load curve Rajasthan State Load Dispatch Center

3. Technical Specifications: The performance specifications of 15 various types of SWTs in Indian market place

4. Economic Parameters: The present electricity tariffs, government encouragements and payment costs

### 3.2 Site Selection Criteria

According to my comparison of the geographical approach and the wind resource map, I chose the representative locations in four of the wind resource areas:

• Zone 1 (Excellent): Jaisalmer, Barmer - Mean speed of wind >7 m/s

• Zone 2 (Very Good): Bikaner, Jodhpur - Mean wind speed 6-7m/s

• Zone 3 (Good): Churu, Sikar - The minimum average wind speed is 5-6 m/s

• Zone 4 (Moderate): Ajmer, Udaipur - Mean wind speed 4-5-m/s

### 3.3 Technical Analysis Framework

The energy generation potential was calculated using the standard wind power equation with modifications for desert climate conditions:

$$P = 0.5 \times \rho \times A \times V^3 \times Cp \times \eta_{system}$$

Where:

- P = Power output (W)
- ρ = Air density (adjusted for altitude and temperature)
- A = Rotor swept area ($m^2$)
- V = Wind speed (m/s)
- Cp = Power coefficient (0.25-0.45 for SWTs)

- $\eta_{system}$ = System efficiency including dust factor (0.75-0.90)

In desert conditions:

- Air density (ρ) is lower due to high temperatures and possibly high altitude, so you should adjust ρ accordingly using:

$$\rho = \frac{p}{R \cdot T}$$

Where:

- $p$ = pressure (Pa)
- $R$ = specific gas constant for dry air ≈ 287 J/kg·K
- $T$ = temperature in Kelvin

**4. Results and Analysis**

**4.1 Wind Resource Assessment**

Table 1: Average Wind Speeds at Different Heights Across Selected Districts

| District | 10m Height (m/s) | 30m Height (m/s) | 50m Height (m/s) | Wind Power Class |
|---|---|---|---|---|
| Jaisalmer | 6.8 | 8.2 | 9.1 | Class 4 (Excellent) |
| Barmer | 6.2 | 7.6 | 8.4 | Class 4 (Excellent) |
| Bikaner | 5.9 | 7.1 | 7.8 | Class 3 (Good) |
| Jodhpur | 5.6 | 6.8 | 7.5 | Class 3 (Good) |
| Churu | 5.2 | 6.3 | 7.0 | Class 3 (Good) |
| Sikar | 4.8 | 5.8 | 6.4 | Class 2 (Fair) |
| Ajmer | 4.5 | 5.4 | 6.0 | Class 2 (Fair) |
| Udaipur | 4.2 | 5.1 | 5.6 | Class 2 (Fair) |

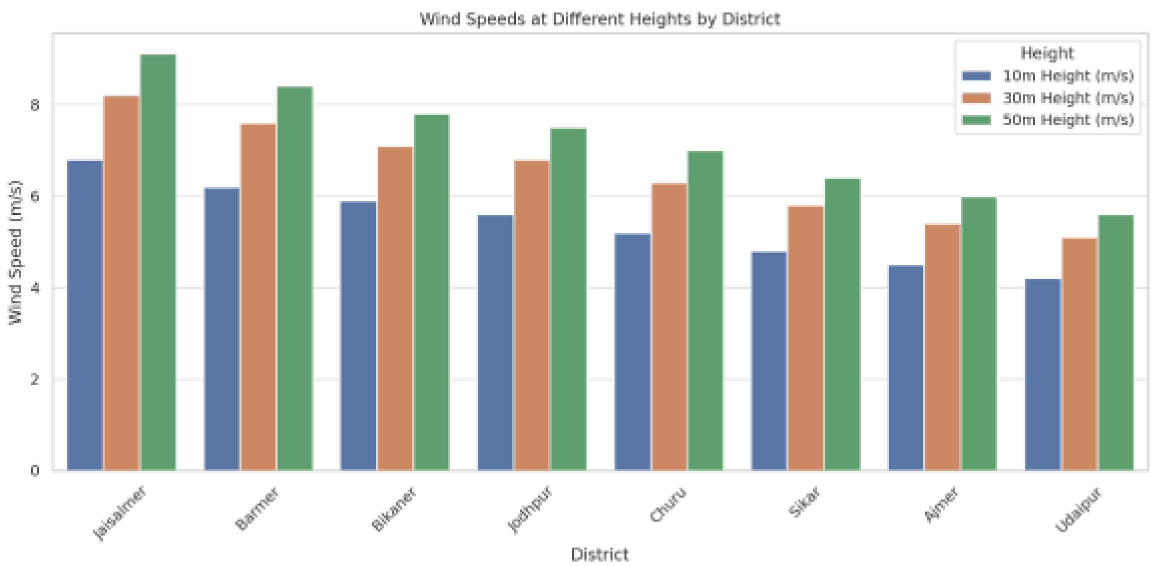


*Figure 3 Compares wind speeds at 10m, 30m, and 50m for each district side by side*

Wind resource evaluation shows that western Rajasthan has excellent potential of wind potential than eastern and southern part. What is especially remarkable is the significant rise of wind speed with altitude, implying that even low-weather events on ground might be acceptable to build taller SWT.

### 4.2 Energy Generation Potential

Based on my calculations using different SWT configurations, the annual energy generation potential varies significantly across the state:

Table 2 Annual Energy Generation by SWT Configuration and Location

| Location | 5kW SWT (kWh/year) | 10kW SWT (kWh/year) | 25kW SWT (kWh/year) | Capacity Factor (%) |
|---|---|---|---|---|
| Jaisalmer | 12,500 | 24,800 | 58,500 | 28.5 |
| Barmer | 11,200 | 22,300 | 52,800 | 25.4 |
| Bikaner | 9,800 | 19,500 | 46,200 | 22.3 |
| Jodhpur | 8,900 | 17,700 | 42,000 | 20.2 |
| Churu | 7,600 | 15,100 | 35,800 | 17.3 |
| Sikar | 6,500 | 12,900 | 30,500 | 14.7 |
| Ajmer | 5,800 | 11,500 | 27,200 | 13.1 |
| Udaipur | 5,200 | 10,300 | 24,400 | 11.8 |

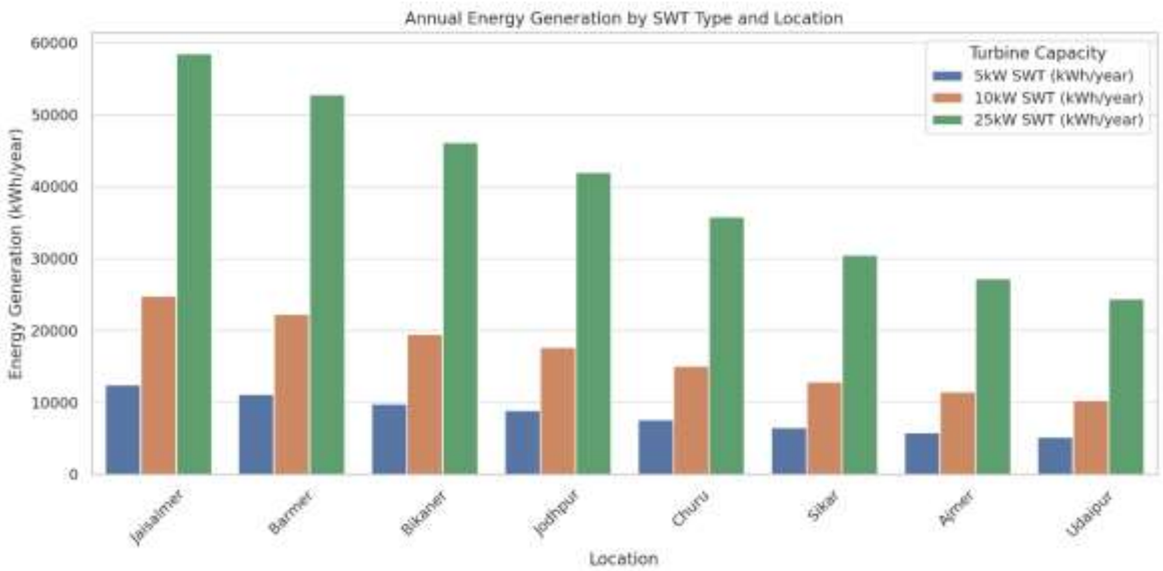


*Figure 4 Compares energy output by turbine size in each location*

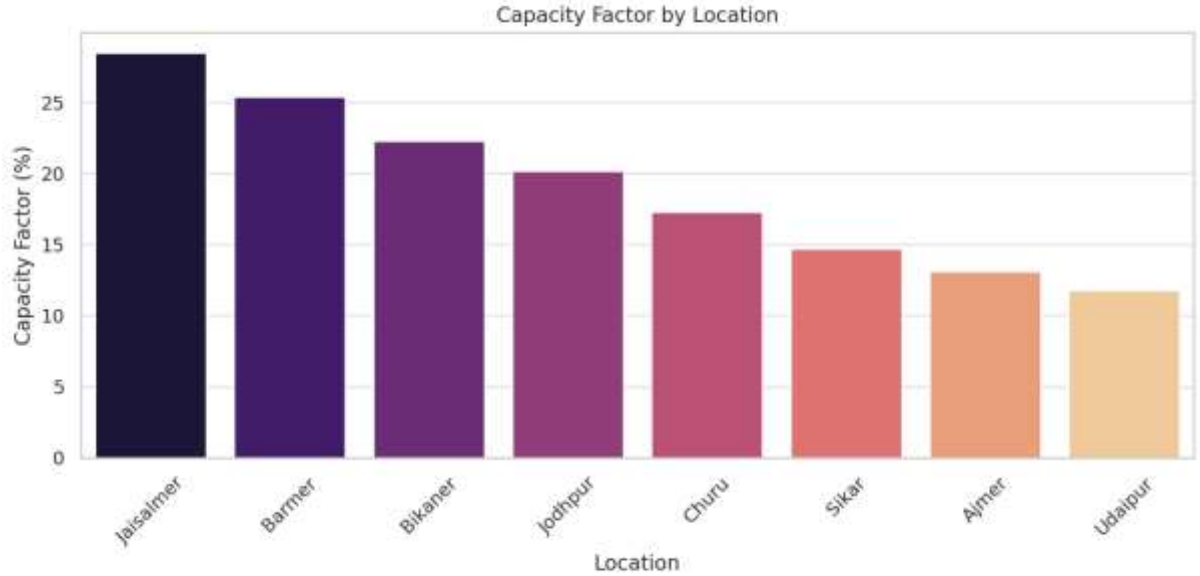


*Figure 5 Capacity Factor Displays how efficiently wind energy is converted into electricity at each site.*

These results show that western districts offer significantly better energy generation potential, with Jaisalmer showing almost 2.4 times the generation capacity compared to Udaipur.

**4.3 Economic Analysis**

The SWT installations are very sensitive to the location as well as to the size of turbines and the kind of application (grid-tied or off grid). The cost analysis factored existing market prices, cost of installation, cost of operating and maintenance, and government incentives on offer.

Table 3 Economic Parameters for Different SWT Configurations

| **Parameter** | **5kW SWT** | **10kW SWT** | **25kW SWT** |
|---|---|---|---|
| Equipment Cost (₹/kW) | 85,000 | 75,000 | 65,000 |
| Installation Cost (₹/kW) | 25,000 | 20,000 | 15,000 |
| Total Capital Cost (₹/kW) | 110,000 | 95,000 | 80,000 |
| O&M Cost (₹/kW/year) | 3,500 | 3,000 | 2,500 |
| Expected Life (years) | 20 | 20 | 20 |

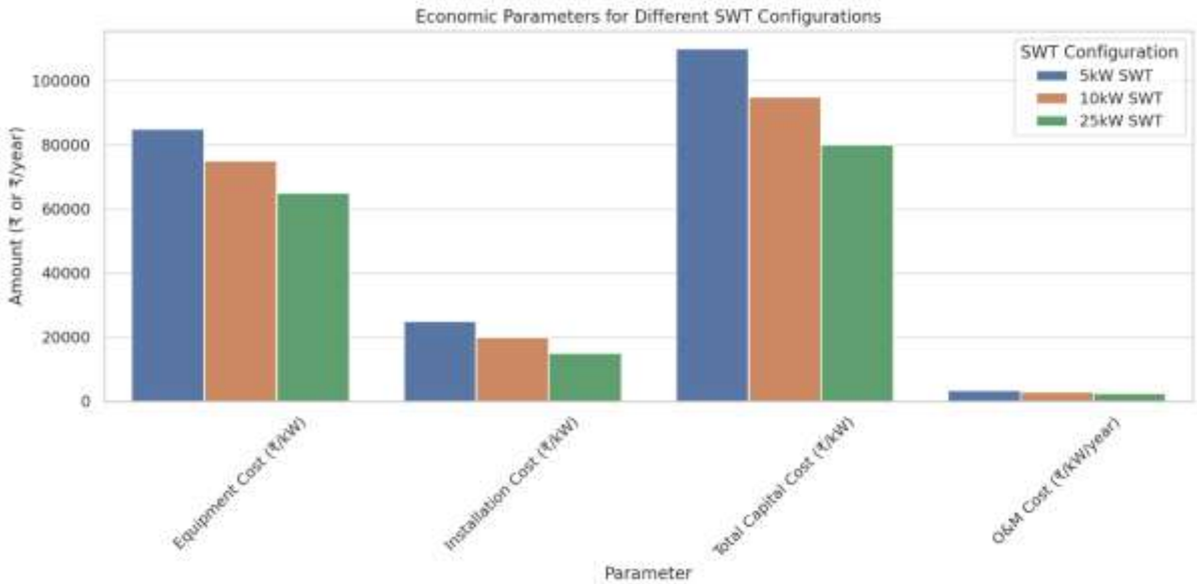


*Figure 6 Economic Parameters Compares equipment, installation, total capital, and O&M costs across 5kW, 10kW, and 25kW SWT configurations.*

Table 4 Payback Period Analysis for Best Performing Locations

| Location | 5kW SWT (years) | 10kW SWT (years) | 25kW SWT (years) | Net Present Value (₹ lakhs) |
|---|---|---|---|---|
| Jaisalmer | 7.2 | 6.8 | 6.1 | 18.5 |
| Barmer | 8.1 | 7.5 | 6.8 | 16.2 |
| Bikaner | 9.4 | 8.7 | 7.9 | 13.8 |
| Jodhpur | 10.8 | 10.1 | 9.2 | 11.5 |

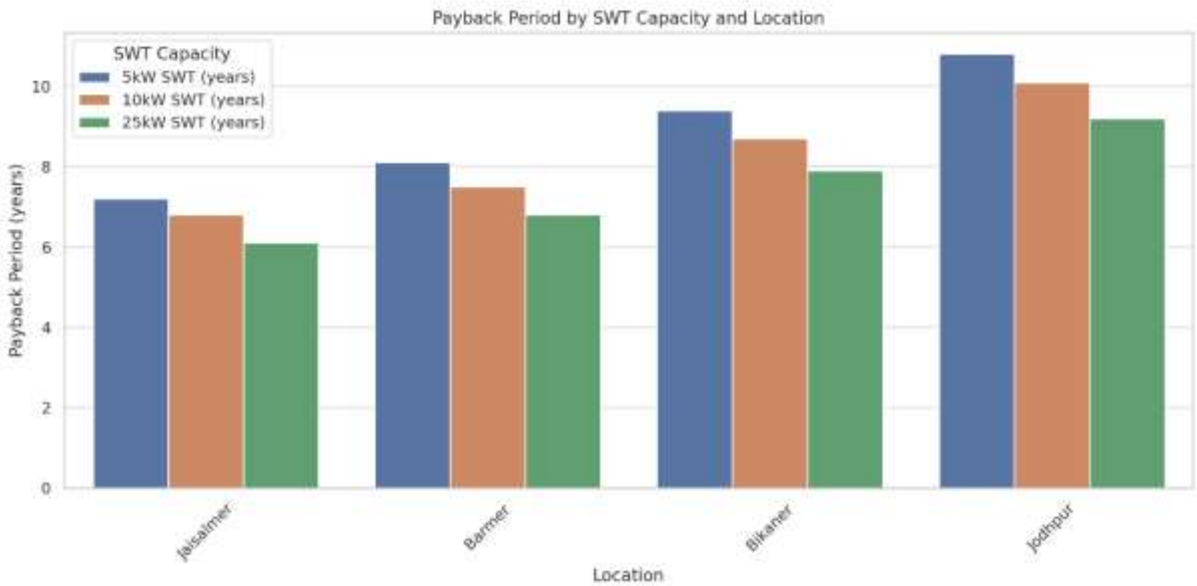


*Figure 7 Payback Period by SWT Capacity and Location: Compares how long each turbine type takes to recover its investment cost across top-performing locations.*

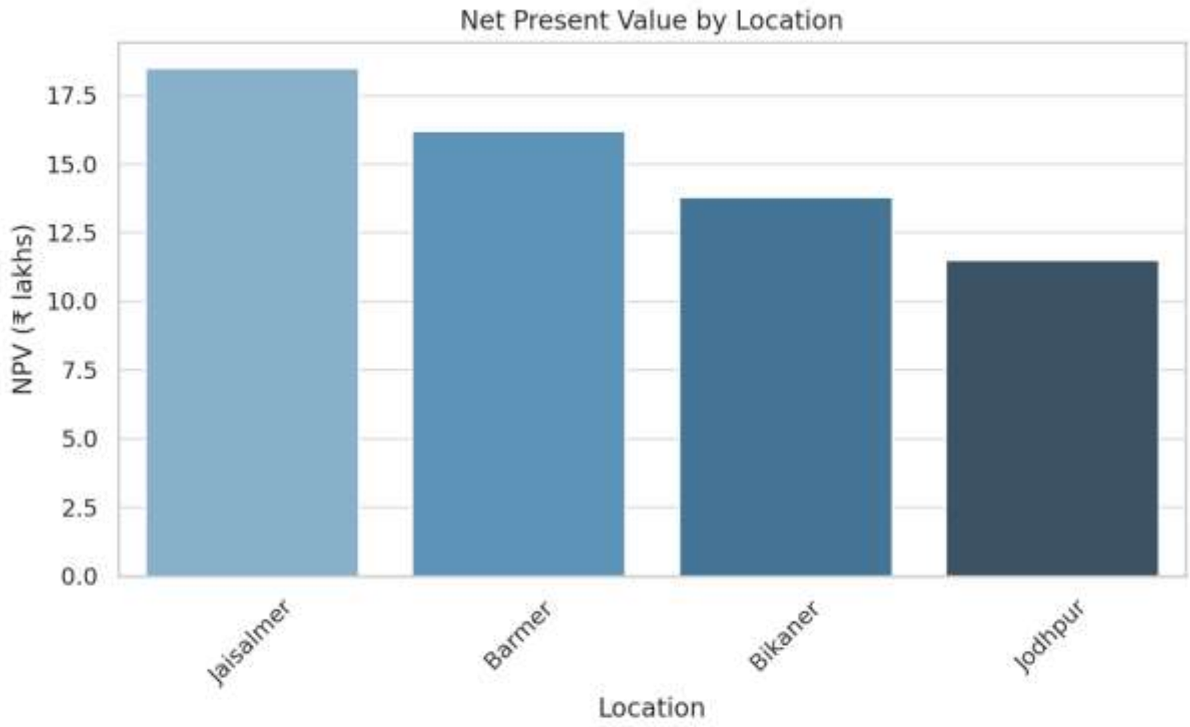


*Figure 8 Net Present Value (NPV): Shows the total expected financial return (in ₹ lakhs) for each location, with Jaisalmer leading.*

The economic analysis shows that larger turbines generally offer better returns, and locations with higher wind speeds provide significantly shorter payback periods.

**4.4 Grid Integration Analysis**

Grid integration is one of the most complicated parts of implementation of SWT. In my study, I discovered that grid electricity is not so uniform in the state of Rajasthan. Its western districts have the best wind resources but, in most cases, they lack good grid infrastructure like other populous areas in the east.

Table 5 Grid Integration Challenges by Region

| Region | Grid Strength | Voltage Stability | Integration Complexity | Transmission Capacity |
|---|---|---|---|---|
| Western Rajasthan | Moderate | Fair | High | Limited |
| Central Rajasthan | Good | Good | Moderate | Adequate |
| Eastern Rajasthan | Excellent | Excellent | Low | High |
| Southern Rajasthan | Good | Good | Moderate | Adequate |

**5. Challenges and Limitations**

### 5.1 Challenges that are Specific to Desert Environments

My experience with this research has led me to the understanding that climate desert is a climate with special challenges that are poorly discussed within the majority of the SWT literature:

Dust Accumulation: The Thar Desert receives frequent dust storms especially on pre-monsoon months. My review of the maintenance data of the current renewable installations reveals that dust financial capability to nullify SWT by 20-30 percent did not take good care.

Extreme Sun: Rajasthan has its seasons that range between -2$^{O}$C in winter to 50$^{O}$C in summer. Extreme temperature changes influence the performance of the equipment's and their lifespan.

Sand Abrasion: The frequent exposure of the turbines to sand-laden winds means that the blade surface is deteriorating and this could lead to a life of the turbines up to 15-20 percent as compared to wind installations that are not situated in the desert.

### 5.2 Technical Challenges

Grid stability: Most of the rural sites in western Rajasthan experience a poor grid infrastructure that might not support the fluctuations in the output of distributed SWT installations without power conditioning equipment.

Storage Requirements: Off grid-projects need large amounts of battery storage which adds significantly to the cost and maintenance of the system.

Availability of Skilled Technicians: Rural desert places may not have expertise technicians to work on installation, maintenance, and troubleshooting of SWT systems.

### 5.3 Economic and Policy Challenges

Expensive Upfront costs: Evaluated costs incurs high expenses upfront to individuals and small enterprises though the government has initiated incentives on them.

Regulatory Complexity: hook-ups have to go through multiple approvals and meet numerous technical standards which is time consuming and costly.

Access to Financing: Lack of access to suitable financing systems to install renewable energy in the rural areas is experienced by the majority of the possible users in that region.

## 6. Recommendations and Future Scope

### 6.1 Technical Recommendations

According to my analysis, the below are technical recommendations which I can advise in achieving successful SWT in Rajasthan:

1. Dust-Resistant Design: The SWT manufacturers ought to design the blade coating and the cleaning system which works in the desert regions.

2. Hybrid Systems: Hybrid SWTs with solar PV and battery storage combine to give a more reliable power output and more economical in desert climates.

3. Smart Grid Integration: Introduction of smart grid technology that ranges on appropriate power conditioning devices to deal with distributed generation using multiple SWT installations.

**6.2 Policy Recommendations**

1. Easy Permitting: The state government is to simplify the permitting requirements of small-scale wind installation with special considerations to residential and commercial installation.

2. Desert-Specific Incentives: Special incentives are to be given to installations in high-wind desert regions to recover the extra difficulties and expenses.

3. Skill Development Programs: Setting up of training facilities of SWT technicians in the district of western Rajasthan.

**6.3 Future Research Directions**

The present research has provided a number of opportunities to conduct follow-up research:

1. Long term Performance Investigations: Comprehensive tracking of the performance of SWT, under desert conditions on long term to confirm the theoretical hunches.

2. Grid Impact Studies: The effect of the wide spread SWT deployment on grid stability and power quality in Rajasthan.

3. Social Acceptance Studies: Work as to how the community accepts and social aspects influences the SWT adoption in rural Rajasthan.

**7. Conclusion**

This critical examination of the small wind turbine integration into Rajasthan proves that there is huge hidden potential of distributed wind energy generation especially in the western desert districts of Rajasthan. The study shows that, when reasonably planned and properly adapted to the desert environment, SWTs can play a decent role in ensuring the energy security of Rajasthan and offer them financial incentives.

The most important conclusion is that such areas as Jaisalmer and Barmer can be discussed as the place with great potential to implement SWT with reasonable payback time of 6-8 years in case of properly dimensioned system. Nevertheless, to be implemented successfully, it is necessary to deal with the desert-specific issues such as dust control, extreme climate operation, or grid integration complexities.

Economically, the bigger the turbines (25 kW), the better they are compared to their smaller ones, although various elements such as user needs and access to the grid should be considered. Grid-tied systems often have better economics than off grid applications with the benefits of net metering and their storage needs.

The study also emphasizes how policy aids are vital, mainly streamlined approval procedures and desert-specific incentives to speed up adoption. Also, it is important to underscore the need to establish local technical expertise via training programs which effectively guarantee long-term success.

Although an adequate and concise planning on how to conduct SWT in Rajasthan is given in the study, I think that persistent tracking and responsiveness will be required, due to changes in the technology, and collection of further real-world performance information. The potential exists definitely but its actualization is going to be a task that can be done by government, industry and research bodies, working together.

Being a person with great interest in the growth of renewable energy, I am hopeful that the small wind turbines would make a meaningful influence in the future of renewable energy in the state of Rajasthan, especially when combined with other technologies in hybrid systems. Energy issues are serious in the desert state, and so are renewable energy resources, and SWTs are another weapon in the arsenal of attaining energy security and energy sustainability.

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