Comparative Analysis for a Solar Tracking Mechanism of Solar PV in Five Different Climatic Locations in South Indian States: A Techno-Economic Feasibility

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Abstract: As the second most populous country in the world, India’s needs related to electricity production are still growing; thus, the country is seeking renewable energy resources as an alternative to conventional resources. Currently, India’s use of renewable energies ranks as fifth worldwide, with approximately 13.22% of the total amount of energy used in the form of solar energy, which is very nominal. Therefore, in the present study, a large-scale 20 MW solar PV power plant was modelled to access the technological and economic performances using the System Advisor Model (SAM) for the selected locations: Vishakhapatnam (VSKP), Hyderabad (HYD), Madurai (MDU), Thiruvananthapuram (TVC), and Bangalore (SBC), where solar radiation is high for South Indian states. In order to carry this out, three solar tracking mechanisms, i.e., fixed tracking (FT), single-axis tracking (SAT), and double-axis tracking (DAT), are taken into consideration at the selected locations. The results from the assessment of the FT mechanism’s yearly energy production show that 31 GWh were produced at TVC and 33 GWh were produced at VSKP, HYD, MDU, and SBC in the first year of the project, with a capacity factor (CF) from 18.5% to 19.5%. Conversely, the SAT mechanism generated an annual amount of energy, ranging from 38 GWh to 42 GWh, with an increase in the CF ranging from 22% to 23%. Furthermore, the DAT mechanism’s annual energy generated 44 GWh to 46 GWh, with the CF ranging between 25% and 26.5%. However, the recorded levelized cost of energy (LCOE) ranges were between 3.25 ¢/kWh to 4.25 ¢/kWh at the selected locations for all three mechanisms. The sensitivity analysis results also suggest that the FT and SAT mechanisms are not economically feasible because of their negative net present values (NPV) in all five locations, whereas the DAT mechanism generated positive results for all of the locations after 20 years. Furthermore, according to the study, we concluded that HYD was identified as the most feasible location in the South Indian region for installing a large-scale solar PV power project.

Keywords: renewable energy; techno-economic analysis; solar tracking system; LCOE; NPV

1. Introduction

Early in the 19th century, the production of electrical energy utilizing fossil fuel technology was adopted, and it was also recognized as the main source of power generation worldwide [1–3]. However, more than 33% of greenhouse gas emissions in the environment
result from these fossil fuel technologies [4]. Consequently, researchers worldwide concluded that generating power using renewable energy (RE) sources was more eco-friendly and more cost-effective [5]. As a result, the production of power by solar PV has acquired prominence and interest on a global scale [6,7]. As observed in other nations, India has begun to utilize its economic potential to supply the nation with the electricity it needs. The world reported the use of 758.3 GW in total, with India coming in fifth place behind China, the EU, the USA, and Japan. India generates 47.3 GW of electricity using solar energy, as described in Figure 1 [8].

Numerous studies on India’s potential for renewable energy have sought to change the energy regulations, its potential obstacles [9], and prospects. Major difficulties highlighted are a lack of financial resources and technical expertise. According to the literature review, there are not enough studies specifically addressing India’s economic potential regarding RE sources. In addition to discussing the solar energy markets in India, the current study is focused on solar energy for the Republic of India.

Several researchers have conducted studies concerned with evaluating solar PV assessments. Kymakis et al. [10] evaluated a large-scale PV operation in Crete. The average power output, average performance ratio, and average CF were 1.33 MWh, 67.4%, and 15.3%, respectively. Sundaram et al. [11] also monitored the annual performance of a 5 MWp solar park at Sivaganga Oblast in India. Similarly, D’Adamo et al. [12] monitored the PV systems for residential buildings in Italy, and reported that the estimation of the NPV varies from 44 to 1007 EUR/kW in 25kW and 105kW plants, respectively.

Additionally, Bouacha et al. [13] monitored a 9.5 kWp PV grid connected for three years in Algeria as part of an experimental analysis. According to the findings of their investigation, the inverter and PV module efficiencies are 96% and 8.3%, respectively, and the low-performance ratio is tolerable due to the shading losses and the inverter type. However, according to a techno-economic assessment conducted in Baghdad by Aziz et al. [14], the NPV of the PV grid system decreased by 12% when diesel generators were added, whereas the carbon dioxide emissions rose by 33%. A techno assessment was carried out by Pillai et al. [15] for a 1 MW solar PV grid system on Bahrain Island. According to the assessment, Bahrain’s current cost of a kWh generation is less than 43% of the LCOE. Zou et al. [16] conducted the PV viability tests for five large sun radiation areas in China. According to the assessment, the Xigaze site’s performance is suitable for
installing a PV park due to the good provision of yearly energy and high solar radiation compared with all other sites. Kazem et al. [17] performed a techno-economic assessment for a 1 MW PV grid in Oman. The study revealed that the LCOE and the CF of the proposed system of 0.228 USD/kWh, and 21.7 USD/kWh, respectively, demonstrated great promise. Furthermore, XU et al. [18] performed a techno-economic assessment for PV power generation in rural regions in Sindh Oblast, Pakistan. The preliminary results from the study revealed that the PV power generation cost 6.87 PKR/kWh, which is relatively more economical than conventional energy sources. The annual performance of a 5 MW PV grid system at the Jordan University of Science and Technology in Jordan was studied by Alshare et al. [19], and they compared their results with the SAM program. Agyekum [20] performed a techno-economic assessment for Ghana in three climatic regions. His study’s reports reveal that the northern region is a large-scale PV system because of high solar irradiance, a higher annual energy generation, and a lower LCOE. Camilo et al. [21] performed an economic assessment for a residential complex in Portugal. The study revealed the vital finding that energy storage is not profitable for residential complexes because of the high investment in batteries. Adaramola [22] calculated the cost for a rooftop 2.07 kW PV power grid system, and his study reported that the LCOE was minimized to 0.246 USD/kWh.

As per the author’s best knowledge, no study has been presented to date where a comparison between the FT, SAT, and DAT mechanisms has been demonstrated where specific potential sites in Southern India have been considered to perform a techno-economic assessment of a solar power plant (SPP). In order to understand the impact of the FT, SAT, and DAT mechanisms on the various performance parameters such as electricity to the grid, the LCOE, and NPV, a 20 MW solar power plant was chosen and separated into five South Indian regions, namely, Andhra Pradesh, Tamil Nadu, Kerala, Telangana, and Karnataka. Each region’s specific location was chosen, which had different climatic characteristics. This study will be useful for decision makers in India and other developing regions or countries that lie in the country’s equatorial line for future cleaner energy production and developing solar PV power plants.

1.1. India’s Solar Energy Potential and Solar Radiation

Solar energy is the sector of renewable energy sources in India that is growing the fastest. By the end of March 2021, the installed solar capacity in the nation was estimated to be around 154.08 GW [23], accounting for 13.2% of all the country’s RE sources. It is planned to grow electricity generation through solar PV to 450 GW by 2030 [24]. The total installed solar PV capacity in various years is shown in Figure 2. Due to solar power’s efficiency, dependability, and affordability for both business and residential complexes, India presently generates roughly 9.8% of its total electricity, a figure which is rising rapidly on a daily basis. As a result, Figure 3 depicts the geographic distribution of India’s long-term average solar energy power output from 1999 to 2018. Selected eminent places, i.e., Vishakhapatnam (VSKP), Hyderabad (HYD), Madurai (MDU), Thiruvananthapuram (TVC), and Bangalore (SBC), have an annual solar energy potential that ranges from 4.5 to 5.0 kWh/m²/day.

1.2. Mechanism of Solar Tracking System

Solar energy technology is less popular than other RE sources because solar PV panels are set at the proper angle to capture solar energy. The main disadvantage is that fixed angels cannot adjust their orientation to follow the sun’s path, which would reduce the power and effectiveness of solar PV panels [25,26]. Therefore, several studies have been conducted by different scholars worldwide to increase efficiency, either theoretically or empirically. A study found that the solar tracking mechanism is a diverse way that harnesses the sun’s energy most effectively [27]. As a result, the solar tracking mechanism is divided into single-axis tracking (SAT) and dual-axis tracking (DAT) mechanisms, respectively. The SAT mechanism is efficient, but can only move in one direction, either horizontally or verti-
cally [28]. To obtain the maximum energy and efficiency from the sun, however, another form of the DAT mechanism can change its movement in all directions (North, South, East, and West), and the DAT movement continues until the sun’s rays are perpendicular to the solar PV panels [29]. The DAT technology includes two rotational axes and two popular ways to execute it: azimuth altitude DAT and tip-tilt DAT [20].

1.3. Geographical Features and Solar Resource of the Present Study

In this segment, South India is divided into five regions. One location from each region was selected for the techno-economic analysis, where the annual solar radiation is high. The potential geographical locations of the sites are presented with the help of SolarGIS in Figure 3. Simultaneously, their latitude, longitude, and annual solar energy are in Table 1. The Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) are measures of the quantity of solar energy that a surface receives per unit area when it is held perpendicular (or normal) to the rays that originate from the direction of the sun at its current location in the sky, and the total amount of shortwave terrestrial irradiance received by a surface horizontal to the ground, respectively.

Table 1. Selected locations in southern regions in India [30].

<table>
<thead>
<tr>
<th>Region</th>
<th>Location</th>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>DNI (kWh/m²/Day)</th>
<th>GHI (kWh/m²/Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhra Pradesh</td>
<td>VSKP</td>
<td>17.68</td>
<td>83.21</td>
<td>4.6</td>
<td>5.4</td>
</tr>
<tr>
<td>Telangana</td>
<td>HYD</td>
<td>17.38</td>
<td>78.48</td>
<td>4.8</td>
<td>5.7</td>
</tr>
<tr>
<td>Tamil Nadu</td>
<td>MDU</td>
<td>9.92</td>
<td>78.11</td>
<td>5.0</td>
<td>5.9</td>
</tr>
<tr>
<td>Kerala</td>
<td>TVC</td>
<td>8.48</td>
<td>76.95</td>
<td>4.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Karnataka</td>
<td>SBC</td>
<td>12.97</td>
<td>77.54</td>
<td>5.5</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Figure 2. The total capacity of solar energy in India between 2010 and 2021 [23,24].
Figure 3. Solar energy potential in India (downloaded from solargis) [31].

2. Materials and Methods

The approach utilized for the study is covered in this section. This study uses the SAM program (2021.12.2 version) to design solar power plants for all sub-regional sites. The SAM program is utilized for business, academic, or personal purposes [32]. The application assists in calculating the financial parameters and performance measures for building RE sources globally. It is a model for producing electricity that operates on the premise that a renewable energy system will provide its energy to a facility that will meet an electric load or to a building connected to the grid [20]. SAM incorporates financial models for projects with Power Purchase Agreements (PPA) and analyses some renewable energy sources’ financial and performance parameters. Based on the project’s input parameters, it forecasts the system costs and energy performance. Several academics have utilized the program to conduct techno-economic assessments of various SPPs worldwide [20]. The financial parameters used to design the solar power plant are therefore shown in Table 2, and the technical characteristics utilized for the simulation are listed in Appendix A.

Table 2. Financial parameters used for the study.

<table>
<thead>
<tr>
<th>Description</th>
<th>Financial Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analysis parameter</td>
<td>Analysis period</td>
<td>25 Years</td>
<td>[33]</td>
</tr>
<tr>
<td></td>
<td>Inflation rate</td>
<td>2.9% /Year</td>
<td>[34]</td>
</tr>
<tr>
<td></td>
<td>Real discount rate</td>
<td>10% /Year</td>
<td>[35]</td>
</tr>
<tr>
<td></td>
<td>Nominal discount rate</td>
<td>13.19% /Year</td>
<td>Calculated</td>
</tr>
<tr>
<td>Project tax</td>
<td>Federal income tax rate</td>
<td>25% /Year</td>
<td>[36]</td>
</tr>
<tr>
<td></td>
<td>State income tax rate</td>
<td>6.5% /Year</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td>Sales tax</td>
<td>5% of total direct</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td>Internal rate of return</td>
<td>11%</td>
<td>[20]</td>
</tr>
</tbody>
</table>
2.1. Financial Factors

The LCOE and NPV indicators were used to assess the power facilities’ economic potential to execute the analysis. The electricity cost generated by a plant is referred to as the LCOE. It is the standard statistic for examining the energy cost generated by various generation systems. The project’s total cost is represented in dollars per kilowatt-hour of electricity generated by the plant throughout its full life. The model computes both the nominal and real LCOEs. However, the real LCOE was utilized in this research since it takes extended years of inflation into consideration during the project, i.e., it incorporates the long-term analysis, whereas the nominal LCOE is excellent for short-term evaluations.

Equation (1) [32]:

\[ LCOE_{(real)} = \frac{-A_0 - \sum_{n=1}^{N} A_n}{\sum_{n=1}^{N} E_n \left(1 + d_{real} \right)} \]  

where: \( A_0 \) signifies the portion for the plant’s equity fund (USD), \( A_n \) signifies the project’s cost in \( n \) years (USD), \( d_{real} \) signifies the real discount rate (%), \( d_{nominal} \) indicates the nominal discount rate (i.e., the discount rate with inflation) (%), \( N \) denotes the analysis’s time frame (years), and \( E_n \) denotes the amount of electricity the plant generated in \( n \) year (kWh).

When calculating the LCOE, the SAM model takes the following factors into account:

- The charges for local and state taxes;
- Operational costs, such as insurance premiums, maintenance and repair (O&M), and real estate taxes;
- Capital for disbursal of assets or reserves, such as working capital, debt servicing, and equipment replacement;
- The project’s equity investment covers sales tax, project development fees, labour and equipment expenditures, and finance fees.

The PPA financial model was chosen since it is an adequate method for determining the financial sustainability of large-scale solar power projects. The SAM replicates several financial structures using this model. In a solar power PPA, a developer arranges for the design, financing, permitting, and installation of a power plant—in this example, an SPP system—on a customer’s land for little to no cost. The customer is then charged a fixed fee by the developer, which is typically less expensive than the rate charged by the local utility. While the developer receives revenues from the sale of the electricity or energy and any tax credits that the system may create, the reduced electricity rate is intended to offset the customer’s procurement of electricity from the grid. Typically, PPA agreements last between 10 and 25 years, during which the facility’s operation and maintenance are the developers’ responsibility. The facility may be removed, the agreement may be extended, or the client may decide to purchase the facility after the term. The 25-year analysis period (lifetime) was considered in this study when calculating the LCOE. The financial criteria considered for the analysis are displayed in Table 1. Using Equation (2), the nominal discount rate can be calculated [20].

\[ discount \ rate_{nominal} = \left[ \left(1 + \frac{D_R}{100}\right) \times \left(1 + \frac{I_R}{100}\right) - 1\right] \times 100 \]  

where: \( D_R \) is real discount rate and \( I_R \) is inflation rate.

The net present value (NPV) is a different statistic frequently employed in assessing a project’s cost efficiency. A project’s whole cost-effectiveness, including costs and revenues, is measured by its net present value (NPV). Equation (3) can be used to determine the NPV [20]. When the NPV has a favorable assessment, the project is economically viable; the opposite is true when it has a negative scope.

\[ NPV = \sum_{n=0}^{N} \frac{A_n}{\left(1 + d_{nominal}\right)^n} \]
2.2. Performance of Weather Characteristics Obtained from the Study

For a few locations in south India, the weather-characteristic performance of an SPP is depicted in Figures 4 and 5. Figure 4 displays the average wind speed for all the chosen locations: VSKP, HYD, MDU, TVC, and SBC, with average values of 4.71 m/s, 3.20 m/s, 2.81 m/s, 3.53 m/s, and 3.44 m/s, respectively. The VSKP location’s average wind speed is the highest because it is close to the Andhra Pradesh region’s sea shore, whereas the MDU location’s average wind speed is the lowest in Tamil Nadu’s central region. Figure 5 shows the GHI for the chosen areas, and it was found that from March to May, GHI was high across all the locations due to strong solar radiation. Furthermore, the GHI slightly decreases for most locations from June to November because of the monsoon and winter seasons that affect solar radiation, whereas from December to February, GHI gradually increases as solar radiation increases.

![Figure 4. Hourly wind speed data for selected locations (data obtained from the SAM program).](image)

![Figure 5. Hourly GHI data for selected location (data obtained from the SAM program).](image)
3. Results

The technical and financial outcomes for a 20 MW solar power plant that is suited for the chosen locations are provided in this section. The three components of this study address technical, economic, and, lastly, the impact of financial and economic factors on the solar PV power plant under discussion. The SAM program calculates a few parameters, and the findings are based on the chosen technical and financial parameters collected from other studies.

3.1. Technical Results for PV System for Three Mechanisms

In this paper, a 20 MW solar power plant is designed using the SAM program for all the potential locations. This section is dedicated to the technical results from the simulation for the three mechanisms, i.e., FT, SAT, and DAT, at selected locations that are presented. The characteristics of the behavior of solar PV panels that actively respond to the sun’s daylight and shut down during the sunset and monsoon seasons, remaining so until sunrise. Due to the major drawback of solar PV, these factors will affect the CF of solar PV compared with other RE sources. For a better understanding of the results, the daytime chosen in this study ranges from 7 am to 5 pm for all three configurations. Electricity exported to the grid from the system for the three mechanisms is presented in Figure 6 (annual profile) and Figures 7–9, for all the locations. Figure 6 depicts the annual variation of electricity export to the grid from the system, and it can be observed that the area under the curve for FT is less than SAT and DAT. It is also worth noting that the electricity exported to the grid from the system average profile differs for different tracking systems. For FT, the peak can be seen for Hyderabad; for SAT, the peak is available for Madurai and DAT; Hyderabad and Madurai are nearly overlapping.

![Figure 6. Yearly electricity export to grid (kW) for all the selected locations and tracking systems.](image URL)

![Figure 7. Cont.](image URL)
Figure 7. Monthly (January to April) electricity export to grid (kW) for all the selected locations and tracking systems.
Figure 8. Monthly (May to August) electricity export to grid (kW) SAT for all the selected locations and tracking systems.
Figure 9. Monthly (Sept to Dec) electricity export to grid (kW) DAT for all the selected locations and tracking systems.

Moreover, the peak value for almost all the sites is greater for DAT followed by SAT and then FT, which is desirable as the concept of a dual tracing system is meant for such performances. The detailed monthly variation of the electricity exported to the grid from the system can be found in Figures 7–9. From the monthly variation of electricity export to the grid from the system, the curve’s width is greater for SAT and DAT compared with FT.
This implies that PV panels with SAT and DAT configurations could extract more heat flux than FT. The peak value varies depending on the seasons. Furthermore, the annual energy output is highest for the DAT tracking mechanism and lowest for the FT mechanism, and it is because the FT mechanism cannot alter the PV panel’s position according to the sun direction and is mounted to a fixed position [39]. In contrast, the DAT mechanism can alter the PV panel’s position according to the sun’s position.

Furthermore, technical results from the simulation presented for the FT, SAT, and DAT mechanisms are presented in Table 3. The annual energy generated from the FT mechanism to the grid during the first year of the project is 33.07 GWh, 33.57 GWh, 33.78 GWh, 31.87 GWh, and 33.54 GWh, with a CF of 18.9%, 19.2%, 19.5%, 18.2%, and 19.1% for VSKP, HYD, MDU, TVC, and SBC locations, respectively.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>VSKP</th>
<th>HYD</th>
<th>MDU</th>
<th>TVC</th>
<th>SBC</th>
<th>VSKP</th>
<th>HYD</th>
<th>MDU</th>
<th>TVC</th>
<th>SBC</th>
<th>VSKP</th>
<th>HYD</th>
<th>MDU</th>
<th>TVC</th>
<th>SBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual energy, MWh</td>
<td>33,075</td>
<td>33,577</td>
<td>33,786</td>
<td>31,879</td>
<td>33,549</td>
<td>38,969</td>
<td>41,372</td>
<td>41,919</td>
<td>40,176</td>
<td>41,334</td>
<td>44,287</td>
<td>45,573</td>
<td>46,195</td>
<td>44,385</td>
<td>45,160</td>
</tr>
<tr>
<td>Capacity factor, %</td>
<td>18.9</td>
<td>19.2</td>
<td>19.5</td>
<td>18.2</td>
<td>19.1</td>
<td>22.2</td>
<td>23.2</td>
<td>23.9</td>
<td>23.6</td>
<td>25.3</td>
<td>25.8</td>
<td>26.4</td>
<td>25.3</td>
<td>25.3</td>
<td></td>
</tr>
<tr>
<td>Energy yield, kWh/kW</td>
<td>1666</td>
<td>1692</td>
<td>1652</td>
<td>1607</td>
<td>1692</td>
<td>1961</td>
<td>2032</td>
<td>2110</td>
<td>2080</td>
<td>2214</td>
<td>2279</td>
<td>2310</td>
<td>2219</td>
<td>2209</td>
<td></td>
</tr>
</tbody>
</table>

On the other hand, for the SAT mechanism, the maximum annual energy generated from the grid to the system for the selected locations is 38.96 GWh, 40.37, 41.91 GWh, 40.17 GWh, and 41.33 GWh at a capacity factor of 22.2%, 23.0%, 23.9%, 22.9%, and 23.6%, respectively. On the other hand, for the DAT mechanism, the solar PV power plant generated a total electricity amount of 44.28 GWh for VSKP, 45.57 GWh for HYD, and 46.19 GWh for MDU, 44.38 GWh for TVC, and 44.16 GWh for SBC, respectively, in the first year of the project. The CF for the DAT mechanism was 25.3% for VSKP and TVC, 25.8% for HYD, 26.4% for MDU, and 25.1 for SBC, respectively.

Furthermore, Table 3 in the above results indicates that HYD and SBC have a marginal difference in electricity generation, which will be considered almost equal, and also, the CF ratio is almost the same during the project’s first year compared with other locations. Although the generation of electricity through the grid has a marginal difference, the HYD location is more feasible for the project’s construction because of better infrastructure, grid stations, and transportation system facilities (i.e., road, rail, and air) to import goods from the international markets as compared with the SBC location. The findings demonstrate that the tracking system significantly affects the systems’ performance across all sites.

CF is defined as the total amount of energy that a power plant produces to the maximum output energy over that period of the installed capacity of a power plant [40]. According to other researchers, the recorded CFs for the present study are acceptable according to Sundaram et al. [11], Martin et al. [41], and Kumar et al. [42]. In India, the CF ranges from 16% to 26% for the three solar tracking mechanisms for the selected locations.
Meanwhile, these CFs will put the project on the right platform related to the performance of the solar PV panels.

3.2. Economic Analysis for PV System for Three Mechanisms

This section presents a detailed economic analysis of the selected locations of a PV power plant for the three solar tracking mechanisms. From the simulation results, locations such as HYD and SBC almost had the same LCOE (real), i.e., 4.17 ¢/kWh & 4.19 ¢/kWh for FT mechanism; 3.56 ¢/kWh, & 3.53 ¢/kWh for SAT mechanism, and 3.42 ¢/kWh for DAT mechanism compared to other VSKP, MDU, and SBC locations respectively presented in Table 3.

3.3. Sensitivity Analysis for PV System for Three Mechanisms

In this section, the sensitivity analysis results of a solar PV system for the five selected locations in South Indian states have been examined. Sensitivity analysis provides additional information to the decision makers (i.e., investors or government) about the project’s benefits. However, the sensitivity analysis shows that the predictions of the project may be far more reliable. Meanwhile, it allows the decision makers to implement additional improvements for projects in the future.

This segment applies sensitivity analysis studies to the 20 MW solar PV plant at the selected locations. Therefore, the present study’s three sensitivity analyses are conducted by varying analysis periods, sales tax rates, and annual interest rates. The first sensitivity analysis investigated the effect of varying the analysis period on the LCOE and NPV. The second sensitivity analysis has been conducted by varying imposed sales tax rates on the economic LCOE. Furthermore, the third sensitivity analysis investigated the effect of the annual interest on the economic feasibility, i.e., the LCOE for a PV project.

Figures 10–13 illustrate the impact of LCOE and NPV values by varying the lifetime of a solar PV project. Results from the simulation indicate that LCOE values at the selected sites for the three solar mechanisms decrease with an increase in the analysis period. In addition, it was recorded that the TVC location recorded the highest LCOE, and HYD and SBC recorded the lowest LCOE for the first year of a solar project of all three solar tracking mechanisms. At the same time, the NPV value has negatively impacted the FT and SAT mechanisms during the project lifetime. However, in the case of the DAT mechanism, the impact on the NPV value starts with negative values and changes to positive values slowly only after the end of the project’s lifetime, i.e., after 20 years. The findings indicate that the PV system will not generate enough revenue to cover the project’s costs in the expected 25-year analysis period for the fixed and single-tracker technologies. However, the installation of a dual tracking system may enable the system to produce more electricity throughout the project, thereby recouping the initial expenditure.

Figure 10. Sensitivity analysis showing LCOE corresponding to project life-time period.
Figure 10. Sensitivity analysis showing LCOE corresponding to project life-time period.

Figure 11. Effect of NPV corresponding to project life-time period for fixed tracking system.

Figure 12. Effect of NPV corresponding to project life-time period for single tracking system.

Figure 13. Effect of NPV corresponding to project life-time period for dual tracking system.

Figure 14. Behavior of LCOE corresponding to sales tax rate.

Figure 15. Impact of LCOE corresponding to annual interest rate.
Figure 14 illustrates that varying the imposed sales tax rate for the project has a minor impact on the LCOEs in selected locations. While Figure 15 shows a significant impact on the LCOEs by varying the annual interest rate of the project, LCOEs increase as the sales tax rate and annual interest rate increase. Furthermore, the DAT mechanism recorded the lowest LCOEs for the selected locations.

3.4. Comparison with Other Studies

A detailed survey has been conducted to compare the results of the present study and is listed in Table 4. The list will provide a review of the location, software/program used, and key findings from the study.

Table 4. Key findings with other published works.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Reference</th>
<th>Location, Country</th>
<th>Developed System</th>
<th>Software</th>
<th>Key Findings</th>
</tr>
</thead>
</table>
| 1     | [20]      | Wa, Sunyani, Nsawam, Ghana | A 20 MW power plant with and without DC battery for the SAT and DAT mechanisms | SAM      | 1. Annual energy generated is 36 GWh for SAT, and 43 GWh for the DAT Mechanism  
2. CF range is between 16%–18% for both mechanisms.  
3. LCOE is minimized from 5–6¢/kWh for both mechanisms. |
| 3     | [44]      | Quetta, Pakistan  | A 2.5 MW for the SAT and DAT mechanisms | PV_Syst Software | 1. 4.44 GWh annual generation of electricity  
2. CF is 20.3%  
3. LCOE of 0.026 $/kWh  
4. DAT generated 34.3% higher annual electricity |
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Reference</th>
<th>Location, Country</th>
<th>Developed System</th>
<th>Software</th>
<th>Key Findings</th>
</tr>
</thead>
</table>
| 2     | [43]      | NUST lake Islamabad, Pakistan | A 100kW FPV designed | SAM      | 1. A total of 4.5 MW of power generated.  
2. LCOE of the system 5.6 ¢/kWh. |
2. CF is 26.7%.  
3. LCOE is minimized 5.44 ¢/kWh. |
| 5     | [46]      | Bangladesh | 1.4 MW mini grid system | MATLAB/Simulink, Homer | 1. Overall, 228 tons of carbon dioxide can be saved per year for 2500 households.  
2. The cost of energy is 18.3 US cents |
| 6     | [47]      | Sweden | Sizing and rule-based operation of grid-connected PV battery system | SAM      | 1. Three different operations proposed.  
2. NPV increases with battery capacity. |
| 7     | [48]      | Doha, Qatar | Long-term solar PV | SAM      | 1. In total, 200 MW has already been in operation since 2020.  
3. Solar PV and CSP coupled with DC system |
| 8     | [49]      | Sweden | Design of a grid-connected PV system | MATLAB      | 1. Reduction in battery life cost more than 9% of the time.  
2. The overestimate of the battery capacity is 243 kWh. |
| 9     | [50]      | Dubai, UAE | Comparison study off/on PV grid system for 4.08 kW | RETscreen | 1. CF ranges between 3%–5%.  
2. NPV increases by more than 41%.  
3. Less initial investment. |
| 10    | [51]      | Northwest, China | 5kWP with and Without battery system | SAM      | 1. A total of 0.49 MWh, the highest annual amount of electricity for Urumqi.  
2. A total of 0.56 MWh, the lowest annual amount of electricity for Yinchaun. |
| 11    | Present Study | VSKP, HYD, MDU, TVC, HYD, South India | 20 MW solar PV system is selected for techno-economic assessment analysis for three mechanisms | SAM      | 1. The DAT mechanism produced better results for the selected locations.  
2. The HYD location is feasible for installation of the PV system. |

### 3.5. Comparative Analysis of the Present Study

Figure 16a,b depicts the electricity tariff for high-voltage industries and India’s residential sector. Figure 16a shows the cost of electricity in the industrial sector, which is recorded as an average of 388 USD/MWh power purchase parity for the FY 2009–2019. The electricity tariff rates in India are higher than in other countries, including Japan, the Russian Federation, the USA, Brazil, Canada, and China—related to the cost of energy [52] for the industrial sector. The highest cost of electricity in industrial sectors is one factor that hinders the development of the renewable energy sectors in India. On the other hand, Figure 16b shows that the average cost of electricity for the residential sector is 4.86 INR/kWh (0.06 $/kWh) from 2009 to 2019, which is nominal.
he industrial sector, which is predominantly energy-intensive, is 4.86% of the total GDP of India [42, 52, 53]. In the context of South Indian climatic conditions, the obtained LCOE in the present study ranges between 3.85 to 5¢/kWh, almost two times lower than that of the three selected mechanisms at all the locations. The obtained LCOE for a 20 MW solar PV project shows a promising result compared with other countries, such as Pakistan, Saudi Arabia, and Ghana, as shown in Table 4.

4. Conclusions, limitations and Policy Recommendations from the Study

In the present study, a techno-economic assessment of a 20 MW solar PV system has been studied in five (i.e., VSKP, HYD, MDU, TVC, and SBC) different climatic conditions in a South Indian State. The study includes the three selected mechanisms (i.e., FT, SAT, and DAT). As shown in Table 3, the annual energy output from the system ranges from 31 GWh to 33 GWh for the FT mechanism, 38 GWh to 42 GWh for the SAT mechanism, and 44 GWh to 46 GWH for the DAT mechanism, respectively, during the first year of the project at the selected locations. The solar PV system also recorded a CF ratio of 18% to 25%, which is feasible for the South Indian climatic conditions from other available studies [42], and the energy yield from the system ranges from 1.6 to 2.2 kWh/kW for all the tracking mechanisms. The performance ratio from the obtained study is between 0.74 and 0.79 for all the locations.

Furthermore, the LCOE financial results presented in Table 3 are recorded for the FT mechanism, ranging from 4.5¢/kWh to 5¢/kWh, for SAT mechanism, the obtained LCOE ranges from 4.25 ¢/kWh to 4.5¢/kWh, and the obtained LCOE for the DAT mechanism is ranged 4.0¢/kWh to 4.25 ¢/kWh, respectively. In addition, the present study conducted a sensitivity analysis on all the mechanisms at the selected locations; the effect of NPV on the FT and SAT mechanisms showed negative NPV values. The study results conclude that the DAT mechanism is promising in all aspects. The findings indicate that the PV system will not generate enough revenue to cover the project’s costs in the expected 25-year analysis period for the fixed and single-tracker technologies. However, installing a dual tracking system may enable the system to produce more electricity throughout the project, thereby recouping the initial expenditure.

In addition, the results from the SAM simulation at HYD and SBC locations generated similar annual energy output, LCOE, and CF ratio. However, we conclude that HYD is the best feasible site to install the solar system because the location is well equipped with infrastructure, transportation systems (i.e., air, rail, and road), and grid connection. Meanwhile, the Telangana region was carved out of the Andhra Pradesh region and formed a new state government in 2014, according to the state recognition act 1956 (under Article 4).
of the Constitution of India [54,55]. For the development of infrastructure in any region of the state that lies within the Indian boundaries, the central government of India will provide tax relaxations to attract investors and entrepreneurs for ten years from the actual formation date.

4.1. Limitations of the Current Study

India is the seventh largest country in the world by area. The territory of India is divided into four regions: North, South, East, and West. The present study has considered only five regions of South India. However, the obtained results from the present study may not be feasible for other locations in India. Therefore, a similar techno-economic assessment analysis should be conducted for other locations to obtain solar PV potential.

Furthermore, a similar techno-economic assessment can be made for the hybrid RE sources generated for the potential regions in India, which have all unique weather conditions. Moreover, limitations such as the availability and cost of land have not been considered because the cost of land in India varies from location to location and region-to-region, which can significantly impact LCOE and NPV values. In the future, factors affecting soiling losses, annual degradation, and probability figures should be considered; thus, adding additional information will act as reference material for the other studies.

4.2. Policy Implications Development of RE Sources in South India

The following section highlights the policy implications for deploying solar RE sources in the southern region of India.

- To install a proper RE source in India, proper strategies, planning, and re-framing of the current energy policies.
- Imports from the international markets should be decreased, and in the meantime, encourage the local manufacturing units to adopt fast manufacturing to save time and be cost-effective.
- To encourage the local communities to install solar RE sources in the residential complex area by providing loans and an exemption from the tax.
- Training programs from the experts should be initiated for the local communities. They should be implemented for installing, operating, and maintaining, solar RE sources.
- The lack of financial constraints due to the increase in the poverty line in India causes an effect on the budget allocation of solar RE sources.
- The ministry of energy and power resources should continuously engage with experts in solar RE sources from various educational institutes and firms to find potential areas to install PV power plants.

Therefore, such policy implications in India will encourage the local communities and investors to step forward and invest in solar RE sources.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

<table>
<thead>
<tr>
<th>Description</th>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Design [20]</td>
<td>Modules per string in subarray</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Strings in parallel subarray</td>
<td>53,744</td>
</tr>
<tr>
<td></td>
<td>Modules in subarray</td>
<td>64,488</td>
</tr>
<tr>
<td></td>
<td>Strings in $V_{oc}$ at reference condition</td>
<td>772.8 V</td>
</tr>
<tr>
<td></td>
<td>Strings in $V_{mp}$ at reference condition</td>
<td>656.4 V</td>
</tr>
<tr>
<td>Inverter [20]</td>
<td>Model: Yaskawa Solectría Solar: SGI 750 XTMM</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Total number of inverters</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>DC-to-AC ratio</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>Name plate DC capacity</td>
<td>20 MW$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Total inverter capacity</td>
<td>17 MW$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Maximum DC power</td>
<td>0.78 MW$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Power used during operation</td>
<td>3.71 kW$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Maximum DC voltage</td>
<td>820 V$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Maximum AC current</td>
<td>1263.77 A$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Minimum MPPT DC voltage</td>
<td>545 V$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Maximum MPPT DC voltage</td>
<td>820 V$_{dc}$</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>SunPower SPR-E19-310-COM</td>
<td></td>
</tr>
<tr>
<td>Physical Characteristics</td>
<td>Material: Mono-c-Si</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Module length</td>
<td>1.631 m</td>
</tr>
<tr>
<td></td>
<td>Module width</td>
<td>1 m</td>
</tr>
<tr>
<td></td>
<td>Total irradiance</td>
<td>1000 W/m$^2$</td>
</tr>
<tr>
<td></td>
<td>Cell temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td></td>
<td>Maximum power</td>
<td>310.149 W$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Maximum power voltage</td>
<td>54.7 V$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Maximum power current</td>
<td>5.7 A$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Open circuit voltage</td>
<td>64.4 V$_{dc}$</td>
</tr>
<tr>
<td></td>
<td>Short circuit current</td>
<td>6.0 A$_{dc}$</td>
</tr>
<tr>
<td>Lifetime and Degradation [15,56,57]</td>
<td>Annual DC degradation rate</td>
<td>0.5%/year</td>
</tr>
</tbody>
</table>

Figure A1 shows the module characteristics selected for the analysis available in the SAM program. The module was manufactured by an American energy sage company collaborating with the U.S. Department of Energy [57]. The material is used to develop the model technology is Mono-c-si, and the cost used to develop such technology is around 0.40 USD/W$_{dc}$ [20] is obtained from the SAM program.
Figure A1. Module characteristics at reference conditions from the SAM program.

Furthermore, Figure A2 shows the inverter efficiency curve selected for the present study. Thus, Yaskawa Solectria Solar designed an American manufacturing company and the cost of an inverter obtained from the SAM program is 0.06 $/Wdc.

Figure A2. Efficiency curve of the inverter obtained from the SAM program.

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