Strategic Adaptations in Operational Photovoltaic Projects: Impact of Actions on Photovoltaic Modules and Trackers on Energy Generation

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Abstract

With technological advancements and the discontinuation of certain nominal power outputs of photovoltaic modules, operating solar plants may face the need for unplanned adjustments. In projects that rely on tracking systems to improve power generation curves, a high tracker failure rate can lead to an increase in OPEX. In these cases, replacing modules with higher-power versions can generate similar energy production, potentially eliminating the need for trackers. Furthermore, beyond the source of failure, to optimize the generation of photovoltaic systems, certain strategies can also be used, such as repowering or installing trackers in previously fixed structure locations. Therefore, the objective of this study is to compare workarounds or improvements between investments in photovoltaic modules or trackers to provide a technical basis for more efficient decision-making. This study could support a comparison between the long-term OPEX associated with tracker failures and the CAPEX investment required to upgrade to higher-power modules as a strategy to maximize energy generation, for example. Therefore, the study does not include financial data because they are variable and dependent on each technology chosen. However, it does demonstrate the technical analyses necessary for subsequent correlation with the value of each piece of equipment and technology to be implemented.

Keywords: Photovoltaic Systems, Trackers, Photovoltaic Modules, Technological Advancement, Failure Rate, Repowering

1. Introduction

In recent years, photovoltaic module technology has evolved, enabling the production of modules with power ratings of up to 700 Wp (Danny Song, 2022). These new modules present only slight changes in size and weight compared to 300 Wp modules (common five years ago), while offering significantly higher efficiency. However, due to this technological advancement, the production of 300 Wp modules has been discontinued, forcing existing power plants designed around those specifications to undergo unplanned adaptations.

With the discontinuation of certain photovoltaic module power ratings, in order to maintain a minimum stock of spare parts and ensure failures can be addressed through replacements, it becomes necessary to adapt existing projects to enable compatibility of the new modules with the same inverter. To stay within the voltage range allowed by inverters, it becomes necessary to replace strings with a similar number of higher-power modules, leading to an increased DC/AC ratio.

These actions are adaptation needs arising from technological advancements, resulting in higher installed capacity, which in turn leads to increased energy production up to the inverter clipping limit.

Considering optional adaptations aimed at intentionally maximizing generation, similar levels of energy output can be achieved by increasing the power of photovoltaic modules or by installing trackers on fixed structures, for example. These actions can be implemented either at the end of the project's operational life to extend asset generation or at any point when it is advantageous to invest in adaptations for higher energy and, consequently, financial returns.

On the other hand, when considering adaptations to address existing issues, if a system with trackers has a high failure rate, one possible option to reduce OPEX, maintenance costs, may be to switch to fixed structures. This reduces long-term maintenance costs but also lowers the generation level previously ensured by the trackers. To compensate for the expected drop in energy output, it is possible to adopt fixed structures while increasing

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module power, effectively balancing the reduction in generation.

The objective of this study is, starting from an initial scenario, to compare the generation curves of five different project options, considering: options with and without trackers, and modules with 345 Wp or 575 Wp. This allows for evaluating energy losses and gains arising from potential scenarios of technological adaptation, generation maximization, or maintenance cost reduction.

The results provide a solid foundation for future financial evaluation and strategic decision-making. The final decision will depend on current maintenance costs, the current value of energy, the investment cost of the new project, field adaptation time, potential impact from equipment downtime, and the expected return on investment.

2. Methodology

In order to enable comparison, the 5 photovoltaic systems were analyzed, according to the technical characteristics and annual energies estimated by the PVsyst system, which can be seen below and in Tab 1.

1. Energy output, 345 Wp modules, without a tracker and project total system power;
2. Energy output, 345 Wp modules, with a tracker and project total system power, reference;
3. Energy output, 575 Wp modules, without a tracker and project total system power;
4. Energy output, 575 Wp modules, with a tracker and project total system power;
5. Energy output, 575 Wp modules, without a tracker and total system power exceeds project capacity.

Tab. 1: Technical Characteristics Considered

Systems	Total Modules	Total Strings	Modules per String	Power per Module (Wp)	Total Power DC (kWp)	Total Power AC (kW)	DC/ AC	Module Area (m²)	Tracker ?	Annual Energy (GWh)
1	5040	180	28	345	1739	1473	1.18	9999	No	3.00
2	5040	180	28	345	1739	1473	1.18	9999	Yes	3.99
3	3024	108	28	575	1739	1473	1.18	8175	No	3.12
4	3024	108	28	575	1739	1473	1.18	8175	Yes	4.15
5	4004	143	28	575	2302	1473	1.40	10825	No	4.01

It is worth mentioning that the systems without trackers were simulated with an inclination of 35° and an azimuth of 0°, based on Brazil (Fabiano Perin Gasparin; Arno Krenzinger, 2016). Total Power AC depicts the maximum output power of 1 inverter, the same inverter was considered for all systems.

The meteorological input data in PVsyst were the TMY (Typical Meteorological Year) data from the original project under analysis, ensuring the same meteorological conditions across all projects.

The estimated energy data, E_Grid, Energy injected into the grid (PVsyst, 2025), for each system were extracted from the PVsyst software and compiled in an Excel spreadsheet to enable comparison in a graphical format.

3. Results

Comparing the estimated annual energy curves of each of the 5 systems, it can be seen below and in Fig 1:

1. This system has the same conditions as system 2 (reference), but without a tracker. It exhibits lower analyzed energy compared to the other systems, as well as a steeper curve.
2. Energy is higher than that of system 1 due to the presence of trackers, showing a flatter curve and greater utilization. This serves as the reference for the initial project.
3. The generated energy was expected to match that of system 1, given the same installed power. However, due to technological advances, the 575 Wp modules have a lower temperature loss coefficient and reduced series resistance, resulting in slightly higher energy than reference system 1.
4. Just as a similarity in generation and curves was expected between systems 1 and 3 (without trackers), a comparable expectation exists for systems 2 and 4 (with trackers). The annual curves are similar, but the output of system 4 is slightly higher for the same reason as in item 3: reduced losses due to technological advancements.
5. Installed power was increased by approximately 30% to ensure annual energy generation similar to reference system 2. By raising the DC/AC ratio from 1.06 to 1.40, the resulting curve is steeper and higher than the others in the annual summary.

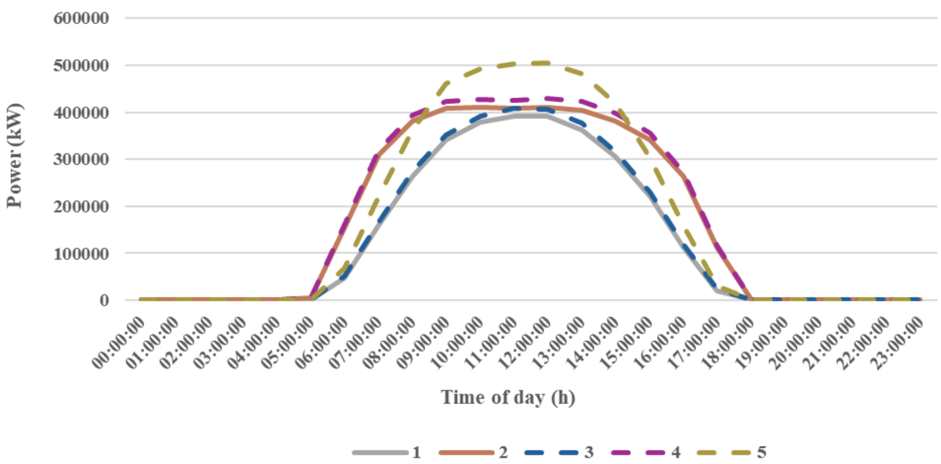

Fig. 1: Comparison of annual energy production between different systems (kWh)

As a conclusion from the annual production curves, it is possible to observe the proximity between the curves of systems without trackers and the same installed power (systems 1 and 3), as well as between systems with trackers and the same installed power (systems 2 and 4). Despite following a curve not so different from the other systems without trackers, system 5 stands out due to its higher installed power and the achievement of a superior peak output.

When analyzing the accumulated annual energy, as shown in Tab. 1, the energy produced by system 5 is closer to that of system 2, which represents the reference of the original project. It is interesting to note that system 4 surpasses the energy of system 2, while requiring fewer adaptations compared to system 5. The latter would demand greater investment in new structures to accommodate the additional photovoltaic modules needed to increase the installed power.

System 4, by maintaining the same tracker structures and only replacing the modules with higher power versions, produces higher annual energy. This represents an advantage in systems with low tracker failure rates. However, in cases where trackers present high failure rates, system 5 may ultimately be more advantageous in the long term, even though it requires greater initial adaptations.

On the other hand, systems 1 and 3 show lower annual energy values, primarily due to the absence of trackers. Nevertheless, system 3 is not far behind the original system 2, as the increase in module power helps mitigate the energy losses caused by the absence of trackers. Therefore, a complementary analysis considering annual energy losses due to failures and the associated maintenance investment is necessary to determine whether such an adaptation would be advantageous.

The curves in Fig. 1 represent an annual sum; therefore, depending on the irradiance level, season, and month analyzed, the curves may invert. Thus, a system that does not generate more energy cumulatively over the year may still produce more energy on a specific day.

To analyze the variation of the curves under different meteorological conditions, Fig. 2 shows that on a day with 7 kWh/m² irradiation, the curve of system 5 (13,9 MWh/day) is limited due to inverter clipping losses. Furthermore, during peak hours, from 10 a.m. to 2 p.m., the curves of systems 1 (10,8 MWh/day) and 3 (11,3 MWh/day), without trackers and with the original installed power, exceed the curves of systems 2 (12,2 MWh/day) and 4 (12,7 MWh/day).

However, although systems 1 and 3 reach higher peak power under maximum irradiance, the daily energy of the systems with trackers (2 and 4) remains higher due to better utilization of the curve in the early morning and late afternoon. On this example day, the system without a tracker only surpasses the system with a tracker when a higher installed capacity is considered, as in system 5, which shows the highest generation curve and accumulated daily energy.

It is worth noting that these curves and energy outputs are based on ideal operating conditions, without failures. If there is a high tracker failure rate, the expected effect that differentiates the curves in the early morning and late afternoon may be minimized, making it potentially advantageous not to have an operating tracker system.

For a more comprehensive analysis, it is recommended to compare the actual production of a system with a high tracker failure rate to the expected production under the same daily or monthly weather conditions simulated in PVsyst. If the actual energy closely matches the PVsyst estimate for the same project installation conditions with trackers, even with a high failure rate, the impact is minimal. However, if the deviation between actual and estimated values is significant, it becomes worthwhile to compare the benefits of adapting the project to operate without trackers but with higher-power modules. Alternatively, it may be evaluated whether the long-term cost of migrating from a tracker-based system to a fixed system is lower than maintaining a high annual fixed cost for tracker maintenance.

In this case, disregarding any financial or cost analysis, one particular requirement for making system 5 viable would be having sufficient available area for the installation of additional photovoltaic modules. Furthermore, a consequence would be an increase in clipping losses, since the inverters were not modified. Therefore, one possible complementary solution would be to store the energy lost to clipping in batteries for later injection into the grid during periods of low irradiance. Including or excluding such complementary measures is essential to determine whether the number of additional panels can be reduced while still ensuring the same expected energy output.

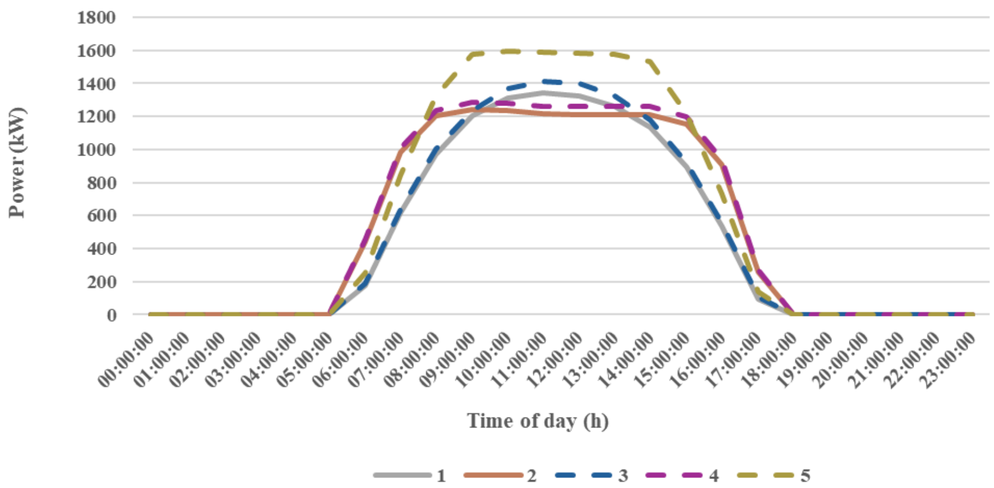

Fig. 2: Comparison of daily energy, on a day of 7kWh/m² of irradiation, between different systems (kWh)

Analyzing a day with lower irradiation, of 3 kWh/m², Fig. 3 clearly shows that all the curves are similar, highlighting the low impact of systems designed to maximize energy production in average low-irradiance scenarios.

From the start of production, between 6 a.m. and 11 a.m., the effect of the tracker is noticeable: although the curves are similar, systems 2 and 4 reach higher power levels. During this period, system 5 starts with a profile more similar to the systems without trackers but reaches the same level as the tracker-equipped systems by 8 a.m.

Between 11 a.m. and 5 p.m. on this example day, all systems except system 5 exhibit the same curve and power level, indicating that if the project adaptation region experiences generally low to medium irradiance levels, the investment may not be justified.

Analyzing the adaptation of simply considering higher-power photovoltaic modules of 575 Wp instead of 345 Wp, while keeping the same installed power, did not highlight significant differences for the systems without trackers—systems 1 (4.9 MWh/day) and 3 (5.1 MWh/day), nor for the systems with trackers, systems 2 (6.4 MWh/day) and 4 (6.7 MWh/day). In both cases, the difference in daily energy generated is less than 1 MWh.

It is worth noting separately that system 5 (6.8 MWh/day) exhibited higher levels than the other systems overall, both in the curve and in energy production. This indicates that on low-irradiance days, higher installed power can be the main differentiator in final energy production. However, although system 5 stands out on this day, its daily energy production does not differ significantly from systems 2 and 4.

For decision-making, it is essential to understand whether the region of the operating system experiences mostly low or high irradiance in order to make the best adaptation choice. In low-irradiance regions, adaptations may have limited impact and may not justify the investment. In regions with consistently high irradiance, adaptations can produce results that even exceed expectations.

In general, an annual analysis is ideal to understand the impact of the adaptations without interference from specific meteorological conditions, as it compensates for variations in annual irradiance levels. Additionally, it is important to compare the ideal results of the adaptation options generated by PVsyst with the real measured scenario on low-irradiance days, since actual losses due to tracker failure rates may not be accurately reflected on such days. Therefore, analyzing the annual impact provides a better characterization of these losses for the specific region where the system is installed.

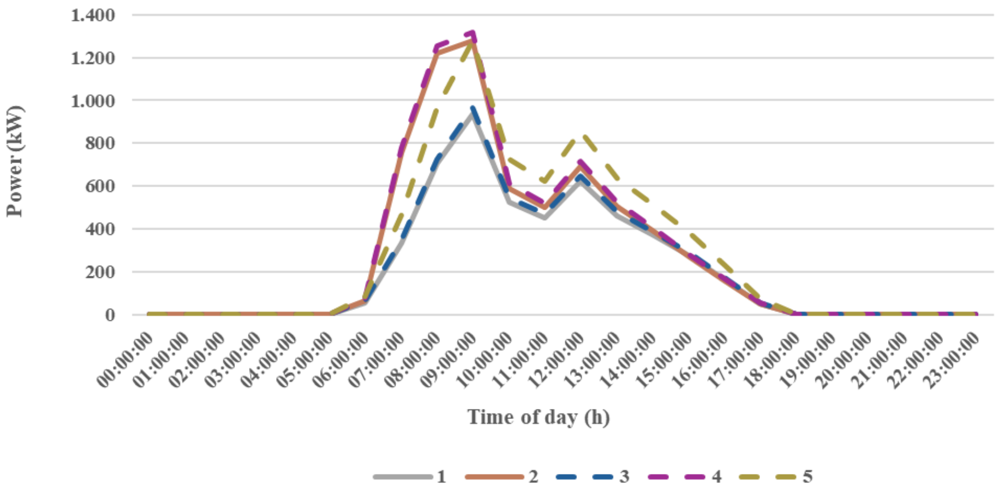

Fig. 3: Comparison of daily energy, on a day of 3kWh/m² of irradiation, between different systems (kWh)

4. Conclusion

The present study demonstrates that technological advancements and the discontinuation of photovoltaic modules of certain power ratings require unplanned adaptations in operational solar power plants. The technical comparative analysis between systems with and without trackers, as well as with different module power ratings, shows that such adaptations can become strategic opportunities to maximize energy generation and even surpass the performance expected in the original projects.

The results indicate that, under ideal conditions, systems with trackers maintain higher utilization of the generation curve, particularly during the early morning and late afternoon hours. However, in projects with high tracker failure rates, alternatives such as replacing modules with higher-power versions and migrating to fixed structures may represent a more advantageous solution, balancing operational costs with increased energy production.

Furthermore, the analysis of low-irradiance scenarios shows that the daily energy difference between systems with and without trackers is reduced, reinforcing that adaptations must consider the solar resource profile of the operational region. The adoption of higher-power modules, regardless of tracker presence, proved to be a decisive factor in increasing daily and annual energy production in regions with high solar availability.

It is important to highlight that each adaptation option presents distinct challenges and complexities. For example, implementing system 5 requires a larger available installation area, additional supporting structures, and adequate time for replacing the photovoltaic modules. Similarly, adapting fixed structures to tracker systems involves technical and logistical complexity. Moreover, adaptations may go beyond photovoltaic modules and trackers; for instance, including batteries to store energy lost due to inverter clipping caused by the installation of additional modules is a relevant example. This topic can be further explored, and it is expected that studies of this nature will increase as the operational lifetime of systems decreases.

Therefore, this work provides a robust technical basis for strategic decision-making in the solar energy sector, allowing managers and designers to more accurately evaluate when and how to implement unplanned adaptations. By correlating potential losses, generation efficiency, and maintenance costs, it is possible to transform challenges arising from failures or technological obsolescence into opportunities for optimization and maximization of electricity generation, contributing to the sustainability and profitability of photovoltaic projects.

This study represents the beginning of a broader analysis that should encompass techno-financial aspects. Only by integrating information on investment costs, maintenance, and expected returns is it possible to consolidate solid strategic decisions, precisely determining which adaptations offer the best balance between economic feasibility and optimization of energy generation.

It is concluded that it is possible to replace one system with another and achieve the same estimated annual global energy results, which will naturally vary throughout the seasons and weather conditions.To make a decision, it is necessary to evaluate OPEX costs in relation to CAPEX, which are dependent on the installed power of the system, current technological developments of the modules and the failure rate of the trackers.

5. References

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