Optimizing PV Solar Deployment on Hilly Terrain: Techno-Economic Analysis of Grading and Dynamic Mismatch Losses

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Optimizing PV Solar Deployment on Hilly Terrain: Techno-Economic Analysis of Grading and Dynamic Mismatch Losses.

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Abstract: *After the 2011 Fukushima disaster, which led Japan to take all 54 of its nuclear plants offline for safety checks, the country made a strategic shift towards renewable energy. By the end of 2023, the total installed Photovoltaic (PV) solar capacity approached 87 GWp. PV installations peaked above 10 GW in 2014-2015, followed by a decline in the annual installation pace, stabilizing around 5 GW per year after 2017. Meanwhile, the kWh tariff decreased from 40 JPY under the Feed-In Tariff (FIT) in 2012 to 9.2 JPY in the 2024 Feed-In Premium (FIP) auction. This tariff pressure is pushing solar developers to reduce development and construction costs. One significant cost factor in Japan is civil work grading. While reducing this cost benefits the project capital expenditure (CAPEX), it introduces new technical challenges, including dynamic mismatch losses. In this paper, we will demonstrate how reducing civil work costs leads to dynamic mismatch losses, impacting the energy yield of a PV plant. Subsequently, we will propose a method to mitigate these dynamic mismatch losses with minimal impact on project finances.*

Keywords: Photovoltaic (PV) solar; Dynamic mismatch losses; PVsyst, String wiring, Techno-economic analysis.

1. INTRODUCTION

In response to the 2011 Fukushima disaster, Japan embarked on a strategic pivot towards renewable energy, notably accelerating the deployment of photovoltaic (PV) solar installations. By the end of 2023, Japan had achieved nearly 87 GWp of installed PV capacity, marking a significant shift in its energy landscape [1]. Initially spurred by high Feed-in Tariff (FIT) rates, the pace of PV installations peaked at 10 GW annually in 2014-2015, gradually stabilizing to approximately 5 GW per year post-2017 amidst declining kWh tariffs under the Feed-in Premium (FIP) auctions [2].

This study focuses on the specific challenges faced in PV solar development on hilly terrains such as former golf courses in Japan, where high Ground Coverage Ratio (GCR) conditions prevail. These sites often require substantial civil work grading to achieve optimal PV module orientation and maximize energy yield. However, the costs associated with such grading can significantly impact project economics. This issue becomes particularly critical as Japan strives to integrate renewables and achieve a 36% share of its energy mix by 2030 [2][3].

Civil work grading, typically involves substantial earthworks that can easily exceed billions of (Japanese Yen) JPY for a 100 MWp PV solar plant, translating to at least 1 JPY/kWh in Levelized Cost of Energy (LCOE) [4]. This will also be demonstrated in this paper with case-1 of Table-6. This underscores the critical role of upfront capital expenditures (CAPEX) in determining the financial viability of PV projects, especially in a post-FIT era and kWh target tariffs in the range of 10 JPY [3].

To address these challenges, this paper examines the trade-offs between grading work and wiring configurations, considering their impact on energy yield, financial metrics, and overall project sustainability. Through a detailed techno-economic analysis encompassing four distinct cases, ranging from full grading with I-shape wiring to optimized wiring strategies without grading, the study provides insights into how project developers can navigate cost-effective PV deployment in Japan's evolving energy landscape.

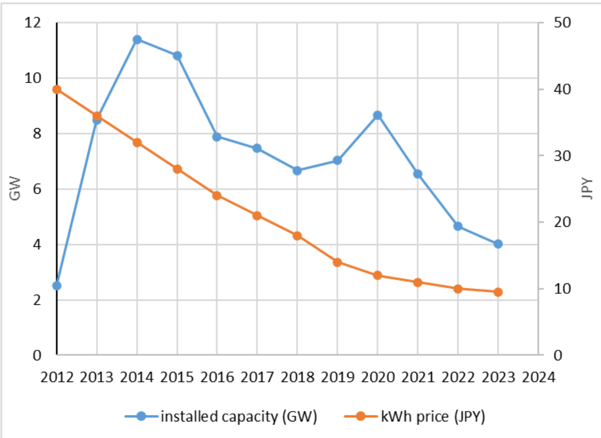


Fig. 1. Evolution of PV installed capacity and FIT/FIP from 2012 to end of 2023.[1],[3]

By leveraging advanced PV system design principles and empirical data from a specific 100 MWp PV solar plant in Western Japan, this research aims to offer actionable recommendations for enhancing project economics, minimizing dynamic mismatch losses, and optimizing LCOE. The findings contribute to the broader discourse on sustainable energy transitions and inform future strategies for maximizing PV solar deployment efficiency in complex terrain environments.

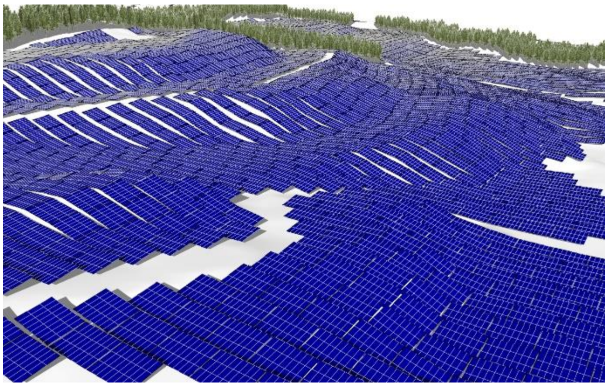
2. DYNAMIC MISMATCH

In a solar PV plant, modules are connected in series and parallel to match the inverter DC input requirement then connected to string or central inverters. However, the Total DC power at any time is lower than the sum of the individual module potential outputs under the same conditions. This discrepancy arises due to static and dynamic mismatches within the system.

Static mismatch refers to the differences in performance characteristics between individual solar modules within the same string. These differences can arise due to variations in manufacturing, partial shading, uneven soiling, uneven aging and degradation rates, and other factors.

Dynamic mismatch refers to the variations in performance characteristics of solar modules within the same string due to changes in environmental conditions over time. Unlike static mismatch, which is relatively constant, dynamic mismatch is caused by transient factors such as changing irradiance conditions, temperature fluctuations leading to uneven module temperatures, moving shadows etc. [5][6].

In the case of high Ground Coverage Ratio (GCR) projects developed on hilly ground without grading work, racks will be non-uniformly oriented, resulting in a 3D layout resembling Fig. 2. This yields the two major issues:



a. 3D layout view

b. View from an actual site

Fig. 2. Non-uniformly oriented racks installed on a hilly topography without grading work.

2.1 Inter-row shading loss

High GCR necessitates using ground space to its maximum potential, resulting in a short row pitch. Consequently, even with low tilt angle the inter-row shading losses are significant, particularly evident during fall and winter when the sun is low, as illustrated in Fig. 3.

In Fig. 4, Fig. 5 and throughout this study, the rack configuration consists of 3 modules in portrait vertical and 8 modules lateral, totaling 24 modules per rack installed at 10-degree tilt.

A typical solar string comprises several modules connected in series, limited by factors such as module specifications, meteorological conditions and inverter input voltage. In our model, we utilized standard 600W PERC modules arranged in strings of 24 modules each. To limit the impact of the inter-row shading to the lowest modules of the rack, connecting the modules in long strings in an I-shape configuration (see Fig. 4) is a common practice. This approach effectively prevents the

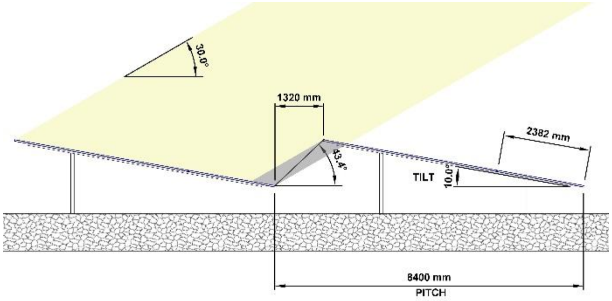


Fig. 3. Inter-row shading loss and its relationship with pitch length and tilt angle.

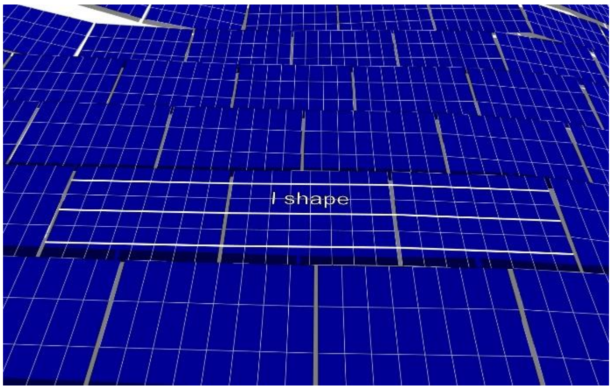


Fig. 4. Racks uniformly oriented in case of flat land. 24 modules string across 3 racks in I-Shape.

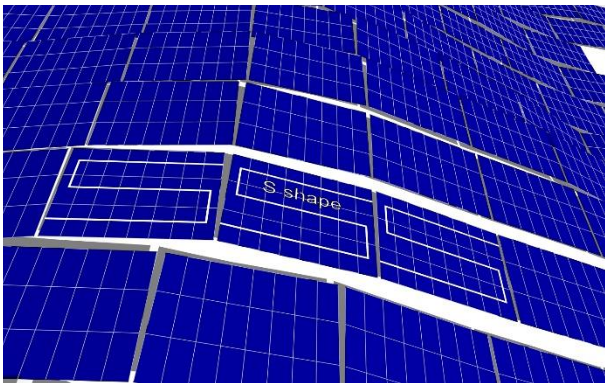


Fig. 5. Hilly land with non-uniformly oriented racks. 24 modules String covers one rack in S shape.

electrical propagation of the inter-row shading to the upper modules.

2.2 Dynamic mismatch loss due to non-uniformly oriented racks

I-shape wiring is ideal for limiting inter-row shading effect. However, as illustrated in the 3D layout and site view in Fig. 2, the site is hilly, and without grading work the racks exhibit non-uniform orientation. In such a case, employing I-shape wiring configuration restricts the string's output current to that of the lowest module, i.e. the rack with the least favorable orientation, at any given time throughout the year. This terrain-induced loss is the specific type of dynamic mismatch addressed in this paper. To mitigate this issue, modules within the same string need to have an identical orientation and therefore be connected in an S-shape configuration, as illustrated in Fig 5.

It is evident from the discussion above that a balance must be struck between mitigating inter-row shading and minimizing the dynamic mismatch. The Methodology to achieve this equilibrium is detailed in the following section.

3. SIMULATION METHOD AND DATA

To determine the optimal design considering various inter-row shading and dynamic mismatch losses for both I-shape and S-shape wiring configurations, a comprehensive Energy Yield Assessment (EYA) was conducted using PVsyst photovoltaic simulation software [7]. The simulations spanned a full year at one-hour intervals for a typical site situated in Western Japan. Key parameters of the site are detailed in Table-1. Meteorological data were sourced from the reliable and bankable solar resource database, Solargis Prospect [8]. Topography was mapped using a thinned grid based on drone scans, representative of the hilly terrain often found in repurposed golf course sites.

It's important to note that as of the present, neither PVsyst nor any commercially available PV solar EYA software fully simulates dynamic mismatch effects. While PVsyst offers advanced module layout options capable of simulating electrical shading mismatch losses for sites up to 5MW, this process necessitates detailed site-wide wiring input. Still, these simulations currently cover only the electrical shading effects and do not encompass dynamic mismatches arising from non-uniform orientation. In this study, dynamic mismatch effects were estimated through individual PVsyst simulations using the Perez transposition calculation model for each orientation scenario [9]. Subsequently, results were analytically combined to ascertain the total string output for each sampling step. Simulation flow chart is presented in Fig.6.

For instance, to compute the output of a 24-module string comprising 8 modules at 0º EW baseline angle, 8 modules at 3º EW baseline angle, and 12 modules at 12º EW baseline angle, each baseline angle scenario is independently simulated across 8,760 hours (24 hours x 365 days) using PVsyst and considering the site Typical Meteorological Year (TMY) data. The string output is computed as 3 times the minimum of the 3 outputs at each sampling step in an Excel application. This calculation approach is accurate since the string current will be limited by the current of the lowest rack for each position of the sun throughout one year.

Inter-row shading losses were evaluated by adjusting the pitch from 8 to 9 meters in 0.2-meter increments, while dynamic mismatch losses were assessed by varying the East-West (EW) baseline angle in 3-degree steps. For educational clarity and analysis facilitation, EW baseline angles were detailed up to 15º in Tables 2, 3, and 4. Table 5 encompassed all actual site rack configurations, further utilized in the techno-economic study.

Table-1. PV Project parameters

Location	Golf course in Western Japan
GHI	1422 W/m^2
DHI	670 W/m^2
Average temperature	15º
Altitude	200m
Module installation area	70 hectares
Required Grading work to flatten the site and eliminate mismatch	1,400,000m^3 (70Hectares@2m)
GCR	0.85%
Module Azimuth tilt	0º, 10º, baseline oriented.
Pitch	8.4m
Rack configuration	Lateral: 8 modules Vertical: 3 modules Orientation: Portrait
EW Baseline angle distribution in 3D layout	see Table-4 column-1
DC capacity	100.3MW
Module power	600
Number of Strings	6,967
String length	24 modules
AC capacity	70MW
String inverter	125kW x 560 unit

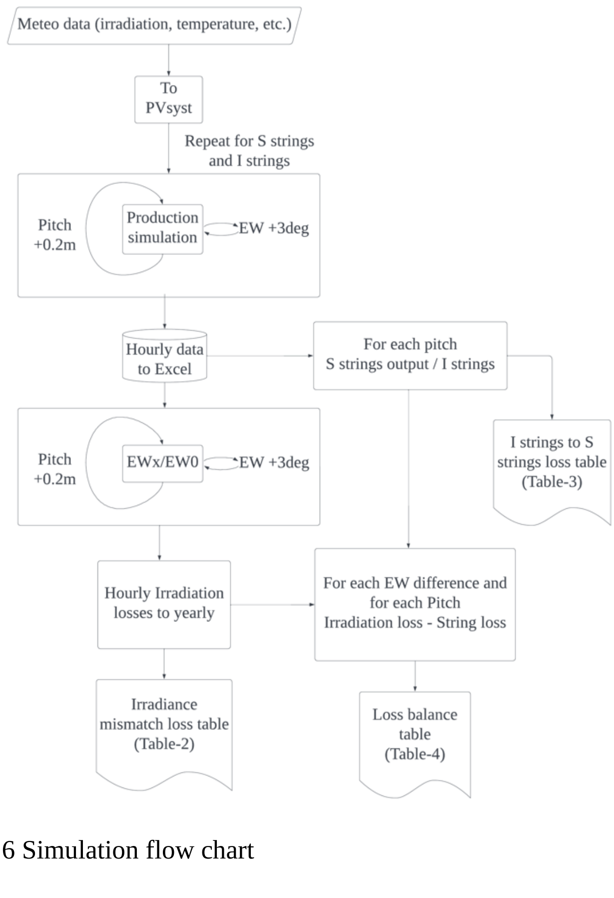


Fig.6 Simulation flow chart

4. TECHNICAL RESULTS DISCUSSION

Table-2 summarizes the dynamic mismatch losses caused by variations in the East-West (EW) baseline angle for different pitches in the case of I-shape wiring. It is important to note that for I-shape wiring, the dynamic mismatch losses are equivalent to the Global In-plane Irradiation (GII) losses. This means the output of a string connected across each set of 3 racks (see Fig. 4) will be limited by the output of the table with the lowest GII at any given moment.

Notably, pitch variation does not affect the dynamic mismatch GII loss, as predicted, since pitch only impacts inter-row losses in the south-north direction (see Fig. 3). Conversely, increasing the EW baseline angle results in an average increase of 1.5% for each 3º step. At a 15º, the dynamic mismatch loss exceeds 7.5%. To contextualize these losses, for the project model analyzed in this study (refer to Table-1), a 7.5% loss translates to nearly 9.5 GWh in annual losses, equivalent to approximately 95 million JPY if we assume an average power tariff of 10 JPY/kWh.

Table-3 presents the same dynamic mismatch losses caused by variations in the EW baseline angle for different pitches when I-shape wiring is replaced by the S-shape wiring depicted in Fig. 5. With S-shape wiring, increasing the pitch reduces the dynamic mismatch losses by an average 0.7% each 0.2m step. This is predictable since I-shape is the optimal wiring configuration for low inter-row spaces as explained earlier. At the opposite, increasing the EW baseline angle causes an average decrease of 0.3% for each 3º step. This is due to the fact that modules from the same strings are located on the same rack and have the same orientation.

For a comprehensive analysis of dynamic mismatch losses for both wiring types, the I-shape to S-shape

Table-2 Dynamic Mismatch Loss

EW baseline angle difference	Pitch: 8	8.2	8.4	8.6	8.8	9
3	1.6%	1.5%	1.6%	1.6%	1.6%	1.6%
6	3.1%	3.1%	3.1%	3.1%	3.1%	3.2%
9	4.6%	4.6%	4.6%	4.6%	4.6%	4.7%
12	6.1%	6.1%	6.1%	6.1%	6.2%	6.2%
15	7.6%	7.5%	7.5%	7.6%	7.7%	7.7%

Table-3 I-shape to S-shape loss

EW baseline angle difference	Pitch: 8	8.2	8.4	8.6	8.8	9
0	5.6%	4.7%	4.0%	3.3%	2.3%	1.7%
3	5.3%	4.5%	3.7%	3.0%	2.3%	1.5%
6	4.9%	4.1%	3.4%	2.8%	2.1%	1.2%
9	4.6%	3.7%	3.0%	2.4%	1.8%	0.9%
12	4.1%	3.3%	2.6%	2.1%	1.4%	0.6%
15	3.7%	3.0%	2.3%	1.8%	1.2%	0.3%

Table-4 I-shape to S-shape Loss balance

EW angle difference	Pitch: 8	8.2	8.4	8.6	8.8	9
3	-3.7%	-2.9%	-2.2%	-1.5%	-0.7%	0.1%
6	-1.8%	-1.0%	-0.3%	0.3%	1.0%	2.0%
9	0.1%	0.9%	1.6%	2.2%	2.8%	3.8%
12	2.0%	2.8%	3.5%	4.0%	4.8%	5.6%
15	3.9%	4.5%	5.2%	5.8%	6.5%	7.4%

Table-5 Wiring pattern selection and weighted gain calculation.

EW baseline angle diff.	Racks number	weight %	change to S-shape?	S-shape gain	S- shape Weighted gain
0º to 3º	2,976	42.72%	NO	-	-
3º to 6º	1,086	15.59%	NO	-	-
6º to9º	852	12.23%	YES	1.63%	0.20%
9º to 12º	653	9.38%	YES	3.46%	0.32%
12º to 15º	557	8.00%	YES	5.23%	0.42%
15º to 18º	359	5.15%	YES	7.16%	0.37%
18º to 21º	240	3.44%	YES	9.01%	0.31%
21º to 24º	118	1.69%	YES	10.83%	0.18%
24º to 27º	56	0.81%	YES	12.70%	0.10%
27º to 30º	29	0.42%	YES	14.57%	0.06%
> 30º	41	0.59%	YES	16.41%	0.10%
		Total yield gain			2.06%

wiring modification loss balance is calculated and summarized in Table-4. The results are self-explanatory: higher pitch favors I-shape wiring, while higher EW baseline angles favor S-shape wiring, consistent with the theoretical explanation provided in Section 2. Orange cells indicate cases where I-shape wiring is recommended, while blue cells indicate cases where S-shape wiring is recommended, with the gradient indicating the level of merit.

It is important to note that, apart from the Meteorological data (TMY) linking the results to a specific site, the results of Tables 2, 3 and 4 are theoretical and can be generalized.

These results were subsequently applied to the solar PV plant detailed in Table-1, located in Western Japan, with a DC capacity of 100MW and an AC capacity of 70MW. The topography and 3D layout reflect characteristics typical of projects developed on 18-hole golf courses.

The 3D module layout was analyzed to identify the East-West (EW) baseline angle and estimate the significance of each pattern. The actual pitch at the site is 8.4 meters, and the results from the loss balance in Table-4 were used to determine when transitioning from I-shape to S-shape wiring was recommended and the associated gains.

As indicated in Table-5, The total number of racks is 6,967. which aligns with the total number of strings detailed in Table-1. This is only because both string length and number of modules per rack is the same; 24 modules. Depending on the design, string length and number of racks per module could be different, but this would not affect the results. Racks with EW base line angles below 6º represent a little more than 58% of the total. Using the loss balance Table-4 at site pitch 8.4m, it is evident that for angles below 6º I-shape wiring offers lower losses. The remaining 42%, will be converted to S-shape wiring. The efficiency gain of S-shape wiring is

Table-6 Technical and financial comparison of different cases

	case 1 (base case)	case 2	case 3	case 4
	grading work + I-shape	No grading work + I-shape	No-grading + I-shape + S-shape (design)	No-grading + I-shape + S-shape (Revamping)
Installed capacity [kWp]	100,339.2			
Pitch [m]	8.4			
Module degradation year-0 [%]	0.8			
Degradation after year-0 [%]	0.5			
Project's lifetime [years]	20			
Annual OPEX [JPY]	120,000,000			
Debt to equity ratio [%]	80			
Loan period [years]	15			
Interest rate [%]	3			
Taxes on profit [%]	20			
Equity IRR	4			
PR	83.9	80.5	82.2	82.2
Specific yield (year 0) [kWh/Kwp]	1,262	1,209	1,234	1,234
Energy Yield (year 0) [kWh]	126,638,104	121,344,632	123,848,489	123,848,489
Yield performance [%]	Reference	-4.18%	-2.20%	-2.20%
CAPEX [Million JPY]	14,047	12,041	12,041	12,241
PPA / FIT / FIP [JPY/kWh]	9.28	8.49	8.32	8.55
ROI [%]	11.57	11.26	11.25	11.32
LCOE [JPY/kWh]	8.72	8.00	7.83	8.05
Financial Performance [%]	Reference	-8.31%	-10.17%	-7.73%

then calculated for each EW baseline angle range, factoring in its weight in the 3D layout and referencing the gain factor from Table-4. The total yield improvement achieved amounts to 2.06%, as depicted in Table-5.

5. FINANCIAL RESULTS DISCUSSION

To assess the financial impact of grading work and various wiring configurations on project finance, a techno-economic study is performed considering four cases:

Case-1: Grading work is performed, and all strings are connected in I-shape.

Case-2: Grading work is not performed, and all strings are connected in I-shape.

Case-3: Grading work is not performed, and string wiring configuration is optimized based on Table-4 during the construction phase, allowing for connections in either I-shape or S-shape.

Case-4: Grading work is not performed, and all strings are wired in I-shape at construction phase. String wiring study and revamping work are engaged at later stage to modify 42% of the strings into S-shape, as per Table-5.

For each case, Solar parameters and financial indicators are calculated as shown in Table-6.

Solar evaluation parameters are Performance Ratio (PR), energy yield and the yield performance compared to case-1. Financial evaluation parameters are the Power Purchase Agreement (PPA), Return On Investment (ROI), Levelized Cost of Energy (LCOE) and the financial performance compared to case-1. The comparison considers a project life cycle of 20 years. All Financial parameters are calculated on the base of a 4% Investment Return Rate (IRR) and a kWh tariff close to the last Feed-in Premium (FIP) auction [2][3]. Other parameters like loan period, interest rates and taxes are just default values, used for illustrative purposes [8].

It should be noted that the LCOE is a crucial metric in energy projects and is used as key comparison factor in this analysis. Fundamentally, it is calculated by dividing the total costs of a project by the production volume over the system's entire life cycle and can be calculated using equation (1).

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}} \quad (1)$$

Where:

I_0	CAPEX
A_t	Annual total cost
$M_{t,el}$	Annual energy yield in kWh
i	Interest rate in %
n	Project lifetime (20 years)
t	Year of lifetime (1, 2,…,20)

Simulation results indicate that case-1 exhibits the poorest financial performance, with an LCOE of 8.72 JPY, despite achieving the highest energy yield due to no dynamic mismatch losses. The higher Capital Expenditure (CAPEX) associated with grading work, amounting to nearly 15%, is the primary factor contributing to this financial underperformance. This outcome is particularly significant when the kWh tariff is below 10 JPY, highlighting the pivotal role of CAPEX in the financial model for projects executed after the high

FIT period. Conversely, during the period of high FIT rates, when kWh tariffs were elevated, energy yield gains outweighed CAPEX considerations, prompting the decision to proceed with grading work.

Case-3 demonstrates the strongest financial performance, with an LCOE of 7.83 JPY. While dynamic mismatch losses slightly exceed 2%, resulting in lower energy yield compared to Case-1, eliminating the heavy grading work CAPEX significantly enhances the financial model, reducing the LCOE by over 10% compared to Case-1.

Case-3 also benefits from selecting the optimal wiring configuration for each rack during the design phase, thereby avoiding post-Commercial Operation Day (COD) revamping or additional costs.

Case-2 represents an actual scenario where all strings were initially connected in I-shape. Despite dynamic mismatch losses exceeding 4%, it ranks as the second-best financial model. This performance was not expected by the Authors, since wiring revamping work after COD (case 4) was expected to perform better since it does occur in real projects.

Case-4 Mirrors the actual case, where string wiring modification was conducted post-COD to mitigate dynamic mismatch and increase energy yield performance. The post-COD wiring modifications did improve energy yield about 2%, but the financial benefits were offset by the revamping costs.

Further investigation revealed that the key differentiator between the actual projects where wiring revamping was performed with our simulation model is the kWh tariff.

Re-evaluating Case-4 with a 15 JPY/kWh tariff reveals a breakeven point in year 9, indicating clear financial merit in conducting wiring mitigation within this timeframe post-COD.

6. CONCLUSION AND FUTURE WORK

The drastic decrease in kWh tariffs of PV solar energy, projects, forces developers to cut the important civil grading cost, leading to significant dynamic mismatch losses due to unevenly oriented racks. In this paper we evaluated the impact of grading work and wiring configurations on the techno-economic performance of a typical 100 MWp PV solar plant located on a former golf course in Western Japan.

The analysis considered four distinct cases, varying from full grading with I-shape wiring to optimized wiring strategies without grading, using the wiring selection lookout table (Table-4) proposed in this work. No grading work combined with wiring mitigation at the design stage (Case-3) emerged as the optimal approach, demonstrating the strongest financial performance with an LCOE of 7.83 JPY. By eliminating grading work and optimizing wiring configurations based on dynamic mismatch analyses during the construction phase, Case-3 achieved over 10% reduction in LCOE compared to the grading work option (Case-1), despite 2.2% dynamic mismatch losses. This underscores the significant impact of upfront CAPEX on project economics, particularly in post-FIT periods with low kWh tariffs.

Post-COD mitigation of dynamic mismatch losses (case 4) was also evaluated. Revamping did improve energy yield about 2%, but the financial benefits were offset by the revamping costs. However, for a 15 JPY/kWh tariff revamping work was shown to be advantageous.

Moving forward, several areas warrant further exploration and development:

Refinement of Dynamic Mismatch Models: Enhance simulations to better capture dynamic mismatch effects, particularly in complex terrain and varying conditions. Developing more sophisticated modeling tools could provide more accurate energy yield predictions and financial performance.

Integration of Advanced PV System Designs: Investigate the integration of advanced PV system designs and technologies to mitigate dynamic mismatch losses. This includes exploring innovative wiring configurations, module-level power electronics, and tracking systems to optimize energy capture in non-uniform terrain [10].

Long-Term Performance Monitoring: Implement robust long-term performance monitoring and data analytics to validate simulation results and optimize operational strategies post-COD. This would provide valuable insights into real-world performance and inform continuous improvement efforts.

Policy and Regulatory Considerations: Evaluate policy frameworks and regulatory incentives to support cost effective PV solar deployment, considering evolving market dynamics and sustainability goals.

Cost Optimization Strategies: Explore additional cost optimization strategies beyond grading and wiring configurations, including procurement practices, supply chain, and operational maintenance strategies.

By addressing these next steps, future research can enhance the competitiveness and sustainability of PV solar projects in Japan and other regions. This will contribute to the global transition towards renewable energy sources by ensuring effective PV solar deployment that aligns with evolving market dynamics and sustainability goals.

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