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Performance Evaluation of 119.88 kWp IoT Based On-Grid Solar System at Admin Building Grissik

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Abstract: The global rise in carbon emissions has intensified the urgency of transitioning toward renewable, environmentally friendly and sustainable energy systems, particularly in industrial sectors with high fossil fuel dependency such as oil and gas. Solar panels represent a clean and reliable alternative for electricity generation. This research evaluates the performance of a 119.88 kWp monocrystalline solar panel system integrated with an Internet of Things (IoT)-based on-grid monitoring system at the Grissik Administration Building. Over a 30-day observation period, the solar panels supplied an average of 432 kWh/day, approximately 72.07% of the installed capacity, reducing fuel gas consumption by 0.19 MMSCFD and lowering CO_2 emissions by 10.38 tons. System efficiency exceeded 80% under optimal irradiation conditions. The IoT-based monitoring platform facilitated real-time data and system control, improving operational decision-making and reliability. This research provides novel empirical evidence of field-scale performance of IoT-integrated photovoltaic systems within Indonesia's oil and gas facilities, demonstrating their significant role in enhancing industrial energy efficiency and supporting the national clean energy transition.

Keywords: monocrystalline solar panel, on-grid system, IoT Monitoring, CO_2 emissions, renewable energy systems

Introduction

The global energy transition towards a low-carbon system places photovoltaic (PV) technology as one of the main pillars in renewable energy development. Photovoltaic technology, particularly monocrystalline silicon-based panels, is increasingly being implemented due to its higher energy conversion efficiency compared to other types, with an estimated efficiency range of 15–22% and a relatively short energy payback time (EPBT) of 1.5–3 years [1].

In terms of consumption, Indonesia's national energy demand in 2023 rose by 6.29% to 1,220 million BOE, marking the highest increase in six years. The industrial sector contributed largest share of energy demand at 45.60%, followed by transportation (36.74%), households (12.35%), commercial sector (4.44%) and others (0.87%). The high energy demand in industrial sector is largely driven by significant coal and natural gas consumption in industrial operations. These findings reflect Indonesia's heavy reliance on fossil fuels, underscoring the urgency of energy diversification through renewable energy development to support national energy sustainability [2].

Variations in solar radiation on an hourly and daily basis significantly influence the amount of photon energy absorbed by the photovoltaic system, which is subsequently converted into electrical power through the conversion process of the solar panel [3]. Based on data from Indonesia's National Energy Council, the potential of solar energy averages 4.8 kWh/m²/day, theoretically equivalent to a capacity of 112,000 GWp when considering total land potential in Indonesia. This potential is nearly ten times greater than that of countries such as Germany and most regions in Europe[4].

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The Paris Agreement represents a global commitment to strengthen response against climate change, with primary goal of limiting global temperature rise to below 2°C above pre-industrial levels. As of May 2018, 176 countries had ratified the agreement, representing approximately 88% of total global GHG emissions. Indonesia ratified agreement through Law No. 16 of 2016, committing to a Nationally Determined Contribution (NDC) of reducing GHG emissions by 29% independently and up to 41% with international assistance compared to the business-as-usual scenario by 2030. In the power generation sector, six types of GHGs are typically emitted, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Among these, CO_2, CH_4, and N_2O are most considered in emission reduction strategies [5]. To achieve these reduction targets, efforts to mitigate CO_2 emissions and compensate for the depletion of conventional energy resources are being advanced through the adoption of renewable energy technologies. Renewable fuels such as biodiesel, biogas, hydrogen, liquefied natural gas (LNG), methanol, ethanol, as well as solar and wind energy, and PEM fuel cells can be utilized to supply clean power generation systems [6].

In response, PT Energi, a company operating in oil and gas sector with an electricity demand of approximately 6,000 kW, has taken steps to support the energy transition program and reduce GHG emissions. The company established a 359.64 kWp Solar Power Plant (PLTS) system at Grissik facility, consisting of 119.88 kWp at Administration Building and 230.76 kWp at Camp area, designed to cover 30% of total electricity consumption. The selection of monocrystalline panels was based on their superior efficiency in converting solar energy into electricity [7]. Furthermore, site selection for PV installations requires special and local criteria approaches to ensure optimal system planning [8].

In addition, technological advancements enable integration of Internet of Things (IoT) systems into solar PV operations. IoT allows real-time monitoring and control, providing accurate performance data for analysis and enabling rapid response to technical issues [9]. Smart grids with IoT control can also reduce energy curtailment and enhance distribution efficiency [10]. The integration of IoT into on-grid PV systems is therefore crucial for dynamic grid management [11].

Monocrystalline cells, typically recognized by their uniform dark-blue appearance, exhibit higher conversion efficiency but are associated with higher manufacturing costs [12]. Conversely, polycrystalline cells, characterized by their speckled blue surface, tend to be less efficient, while amorphous thin-film cells offer lower production costs albeit with reduced performance [13], [14].

According to a 2022 research, the monocrystalline solar panel equipped with a Chromel–Alumel sensor achieved the highest power output of 4.62 W at a temperature of 49.7°C (the second-highest recorded temperature) during a one-hour test, with a conversion efficiency of 9.89%. In comparison, the polycrystalline solar panel integrated with Chromel–Alumel exhibited better thermal stability, delaying the voltage drop by maintaining 2.89 W at 51.3°C and 2.84 W at 47.4°C. Interestingly, the polycrystalline panel without Chromel–Alumel achieved the highest efficiency of 8.16%, indicating that although Chromel–Alumel integration enhances thermal responsiveness and stability, it does not necessarily result in higher overall efficiency [15].

Direct sunlight provides approximately 93 lux of illumination per watt of electromagnetic energy, including infrared, ultraviolet, and visible light. On a clear midday, solar irradiance at the Earth's surface can reach about 100,000 lux per square meter. Indonesia, located near the equator, receives abundant solar radiation throughout the year, with an average of 4.8 $kWh/m^2/day$ [16].

Photovoltaic arrays produce direct current (DC) electricity, which can be directly used for battery charging or, through an inverter, converted into alternating current (AC) suitable for household appliances and grid integration. Inverter efficiency typically ranges from 60% to 95%, with most commercial units achieving around 95%. The output power of PV arrays is usually expressed in watts, kilowatts, or megawatts, depending on the size and number of cells in a module. A case study in Turkiye using a 7 MW on-grid PV system achieved an annual output of 10.82 GWh with a capacity factor of 17.6%, demonstrating that climate and weather conditions strongly influence performance [17].

This research addresses three key aspects of solar panel utilization in an on-grid system. First, determining electrical capacity generated by solar panels. Second, assessing efficiency of fuel gas consumption following PV integration to quantify fuel savings. Third, evaluating reduction of CO_2 emissions as a positive environmental impact of system. These aspects form basis for evaluating both technical and environmental benefits of renewable energy integration into electricity grid.

The purpose of this study is therefore to comprehensively assess performance and power generation potential of solar panel system, particularly in the industrial context. Additionally, study evaluates efficiency of fuel gas consumption after system operation (on-stream) and quantifies the

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reduction in CO_2 emissions resulting from implementation of solar panels in company's electricity system.

This study provides a novel contribution by assessing the real-field performance of an IoT-integrated photovoltaic system within the oil and gas sector, a context rarely reported in Indonesian literature.

Materials and Methods

Materials

Solar PV Modules (216 units)

- Brand: Longi Solar Monocrystalline
- Type: LR5-72HPH-555M
- Capacity: 555 Wp
- Efficiency: 21.7%
- Dimensions: 2256 × 1133 × 35 mm
- Junction Box: IP68 rated with three diodes
- Additional info: < 2% First-Year Degradation

Equipments

Inverters (2 units)

- Brand/Type: Sungrow SG50CX
- Capacity: 50 kWac
- Type: On-grid inverter
- Dimensions: 782 × 645 × 310 mm
- Max. Efficiency: 98.7%
- Max. PV input voltage: 1100 VDC
- Max. PV input current: 130 A
- AC Voltage Range: 312–528 V

Combiner Boxes (2 units)

- AC and DC Combiner with polycarbonate enclosure (IP65)
- 1000 VDC

Cables (2,250 meters)

- Type: Solar Cable H1Z2Z2-K
- EN50618 approval
- Flame resistant, EN 60332-1-2 standard
- DC switch disconnector (1000 VDC, 32A)

Procedure

Research Location

The research was conducted at the Grissik Administration Building, South Sumatra, Indonesia. The site is characterized by a tropical humid climate with average daily solar radiation of approximately 4.8 kWh/m²/day and an ambient temperature ranging between 25°C and 45°C. The location was selected due to its high solar potential and the facility's energy-intensive operations within an oil and gas industrial environment.

System Design

The solar panels were installed on the roof of Grissik Administration Building, oriented directly towards sun to maximize solar irradiance absorption. Optimization of tilt angle was considered, as it can increase energy production by approximately 6% [18]. The modules were mounted at an average tilt angle of 15°, adjusted from the site's geographical latitude (5°S) to enhance rainfall-based self-cleaning and reduce dust accumulation. The tilt configuration follows recommendations from SNI 04-6957 (Design Guidelines for PV Systems). The panels were mounted on lightweight steel frames, providing safety and ease of routine maintenance. The layout of solar panels is illustrated in Figure 1.

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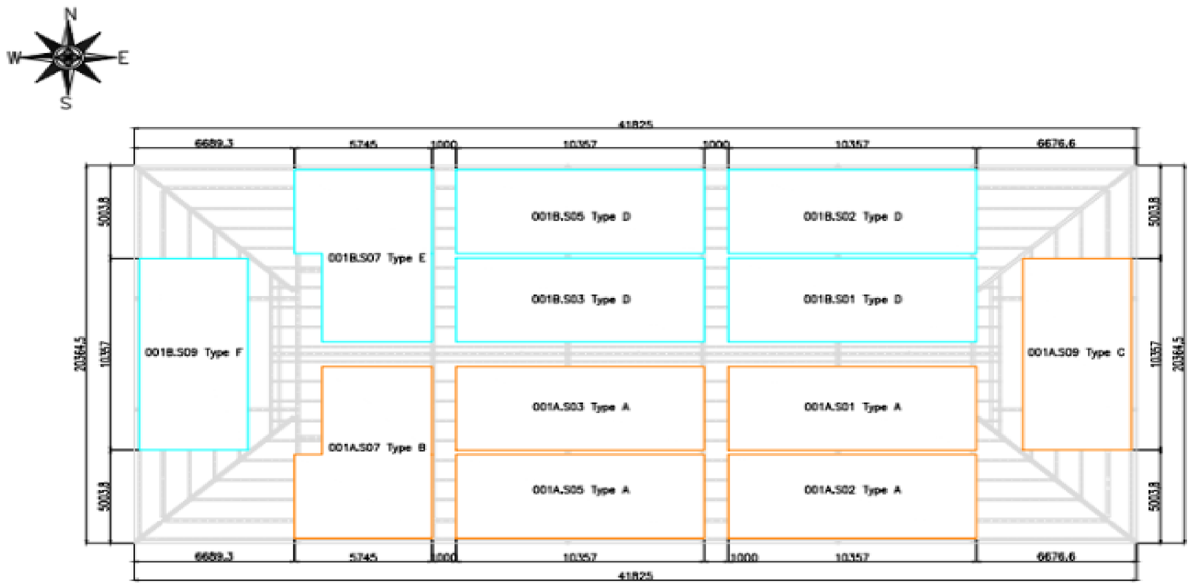

Figure 1. Solar Panel Design on the Roof of the Administration Building

The research procedure included the following steps:

1. Preparation of Personal Protective Equipment (PPE).
2. Ensuring that the PV system was initially in off condition.
3. Activating AC breaker in the AC combiner box to supply inverter with electricity from the PV string.
4. Turning on the DC switch on the inverter.
5. After blue indicator light turned on, switching on the DC switch of second inverter.
6. Waiting for two minutes and confirming that PV system operated normally.
7. Opening the iSolarCloud Application to monitor the operational parameters and performance of PV system in real-time.

Results and Discussions

System Implementation

The installation and data collection were conducted at Administration Building in July 2025. The building features a pyramid-shaped roof resembling traditional South Sumatran houses, with four sides oriented toward the north, south, east, and west (Figure 2). This roof structure was selected for PV installation due to its ability to support the weight of multiple solar panels.

Figure 2. PV Module Placement on the Roof of the Administration Building

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Figure 2. Rooftop configuration showing four-panel orientation toward cardinal directions. The modules were installed at an inclination of 15°, following recommendations from SNI 04-6957 and adjusted from the geographical latitude (5°S) to improve self-cleaning through rainfall and minimize dust accumulation. The increased elevation also enhanced air circulation beneath the panels, reducing module temperature and improving voltage output [19]. Technically, the PV panels were positioned with a tilt of 14° on the east–west axis and 15° on the north–south axis. During the observation period in July, when the sun is located in the northern hemisphere, the south-facing panels received the most optimal solar radiation. Moreover, increasing the installation height significantly enhanced air circulation beneath the modules, resulting in lower panel surface temperatures and consequently higher voltage output [20] PV Output Performance

The performance data collected from installed PV modules were monitored using iSolarCloud application. Table 1 summarizes the daily output, fuel gas savings, CO_2 emission reductions, and system performance percentages for the 30-day period.

Table 1. Daily Electrical System Performance in July

No	**Date**	***Output* PV**	**Fuel Gas**	**CO_2 Emission**	**Performa**
		kWh	**Volume, MMSCF**	**Ton CO_2**	**%**
1	July 1, 2025	499.6	0.0077	0.4003	83.35
2	July 2, 2025	445.1	0.0069	0.3566	74.26
3	July 3, 2025	451.2	0.0070	0.3615	75.28
4	July 4, 2025	444.8	0.0069	0.3564	74.21
5	July 5, 2025	203.0	0.0031	0.1626	33.87
6	July 6, 2025	503.6	0.0078	0.4035	84.02
7	July 7, 2025	386.5	0.0060	0.3097	64.48
8	July 8, 2025	322.4	0.0050	0.2583	53.79
9	July 9, 2025	330.8	0.0051	0.2650	55.19
10	July 10, 2025	417.1	0.0064	0.3342	69.59
11	July 11, 2025	302.1	0.0047	0.2420	50.40
12	July 12, 2025	471.0	0.0073	0.3774	78.58
13	July 13, 2025	475.0	0.0073	0.3806	79.25
14	July 14, 2025	379.2	0.0058	0.3038	63.26
15	July 15, 2025	460.5	0.0071	0.3689	76.83
16	July 16, 2025	557.9	0.0086	0.4470	93.08
17	July 17, 2025	513.6	0.0079	0.4115	85.69
18	July 18, 2025	441.4	0.0068	0.3536	73.64
19	July 19, 2025	523.0	0.0081	0.4190	87.25
20	July 20, 2025	516.7	0.0080	0.4140	86.20
21	July 21, 2025	528.4	0.0081	0.4233	88.15
22	July 22, 2025	438.3	0.0068	0.3512	73.12
23	July 23, 2025	517.5	0.0080	0.4146	86.34
24	July 24, 2025	438.0	0.0067	0.3509	73.07
25	July 25, 2025	394.5	0.0061	0.3161	65.82
26	July 26, 2025	385.8	0.0059	0.3091	64.36
27	July 27, 2025	384.1	0.0059	0.3077	64.08
28	July 28, 2025	457.6	0.0071	0.3666	76.34
29	July 29, 2025	402.1	0.0062	0.3222	67.08

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No	Date	*Output* PV	Fuel Gas	CO_2 Emission	Performa
		kWh	Volume, MMSCF	Ton CO_2	%
30	July 30, 2025	368.0	0.0057	0.2948	61.39
	Total	12958.8	0.1997	10.3822	
	Average	432.0	0.0067	0.3461	72.07

Table 1 presents the research data from solar panels recorded from July 1 until July 30, 2025, including several conversions and calculations based on the PV output generated. The following are the calculation steps used.

On July 1st, PV output was recorded at 499.6 kWh. It is known that Turbine heat rate is 15099 BTU/kWh, Heating value of the fuel gas is 980 BTU/SCF, Emission factor is 53.06 kg CO_2/MMBTU, and PV capacity is 119.88 kWp or 599.40 kWh.

Calculating fuel gas consumption in terms of energy and volume by converting PV output values,

$$\text{Energy} = \text{Output PV} \times \text{Heat Rate} \quad \ldots(1)$$
$$= 499.6 \text{ kWh} \times 15099 \text{ BTU/kWh}$$
$$= 7543460.4 \text{ BTU or } 7.5435 \text{ MMBTU}$$
$$\text{Volume} = \text{Energy} / \text{Heating Value} \quad \ldots(2)$$
$$= (7543460.4\text{BTU})/(980\text{BTU/SCF})$$
$$= 7697.4086 \text{ SCF or } 0.0077 \text{ MMSCF}$$

Next, calculating CO_2 emissions by converting fuel gas volume using CO_2 emission factor for natural gas.

CO_2 Emission Factor

$$= (53.06 \text{ kgCO}_2\text{/MMBTU}) \text{ x Heating Value} \quad \ldots(3)$$
$$= 53.06 \times (980 \text{ MMBTU/MMSCF})$$
$$= 51998.8 \text{ kgCO}_2\text{/MMSCF or } 52 \text{ Ton CO}_2\text{/MMSCF}$$

CO_2 Emission

$$= \text{Fuel Gas Volume x Factor Emission CO}_2 \quad \ldots(4)$$
$$= 0.0077 \text{ MMSCF} \times (52 \text{ Ton CO}_2\text{/MMSCF})$$
$$= 0.4003 \text{ Ton CO}_2$$

The performance can be calculated from PV output data by comparing it to PV capacity.

% Performance

$$= (\text{Output PV} / \text{Capacity PV}) \times 100\% \quad \ldots(5)$$
$$= (499.6 \text{ kWh}/599.40 \text{ kWh}) \times 100\%$$
$$= 83.35 \%$$

The system generated a total of 12958.8 kWh over 30 days, with an average daily output of 432 kWh. The average daily performance was recorded at 72.07%, ranging from a minimum of 33.87% (July 5) to a maximum of 93.08% (July 16).

Daily Performance Fluctuations

Performance fluctuations were closely related to weather conditions:

- **Low output (July 5, 2025)**: Only 203.0 kWh was generated, with PV output above 50 kW for approximately 15 minutes during peak sunlight hours due to overcast skies (Figure 3).

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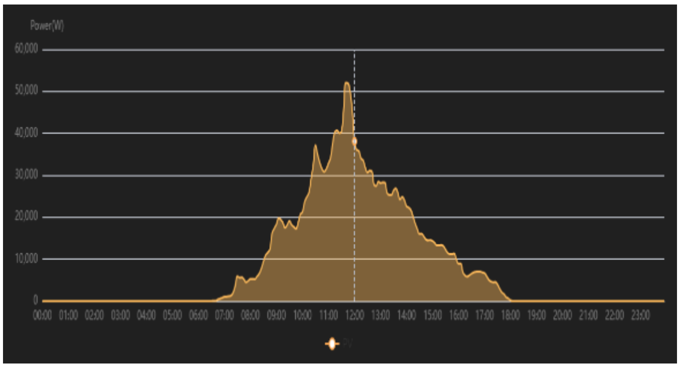

Figure 3. PV Output on July 5, 2025 – Low Performance

Figure 3 shows low performance output. This result confirms that cloud cover significantly reduces irradiance intensity and module temperature uniformity, leading to a decline in power output

- **High output (July 16, 2025):** A maximum of 557.9 kWh was generated under mostly clear skies, with the inverter cooling system functioning optimally, supporting the hypothesis that weather conditions significantly affect PV efficiency (Figure 4).

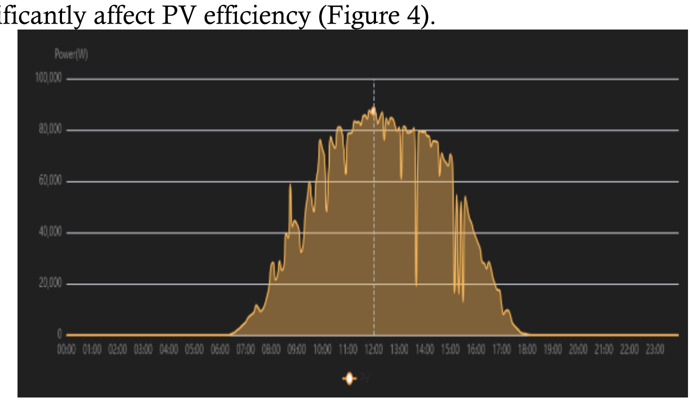

Figure 4. PV Output on July 16, 2025 – High Performance

Polynomial regression was applied to model the PV output curve on July 16, 2025, resulting in the following fourth-order polynomial equation:

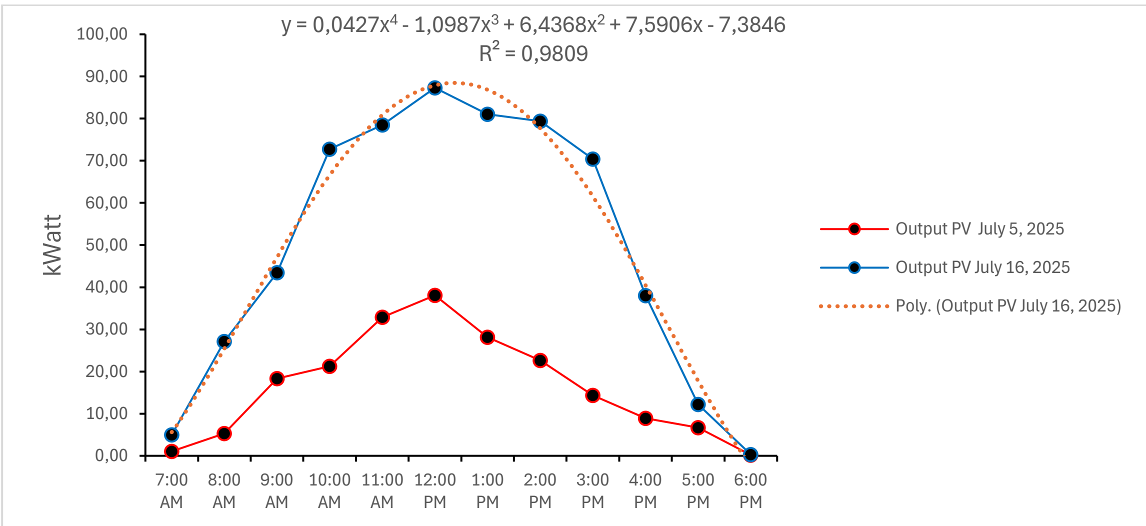

Figure 5. Polynomial Regression Modeling of PV Output on July 5 and July 16, 2025

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This high coefficient of determination indicates a strong correlation between model and actual measured data. Such regression models are valuable for predicting PV performance under varying irradiance conditions. The comparison in Figure 5 highlights significant influence of weather conditions on system performance. On July 16, the output curve exhibited a near-symmetric distribution with a peak of approximately 93 kW at 12 PM. In contrast, on July 5, the peak reached only around 38 kW at same time, demonstrating the substantial impact of cloud cover on energy generation [21].

Environmental and Operational Factors

Environmental conditions such as dust accumulation, shading from nearby buildings, humidity, wind and rainfall were found to significantly influence system performance. For instance, dust accumulation on PV surface (Figure 6) caused a performance reduction of up to 20–25% [22].

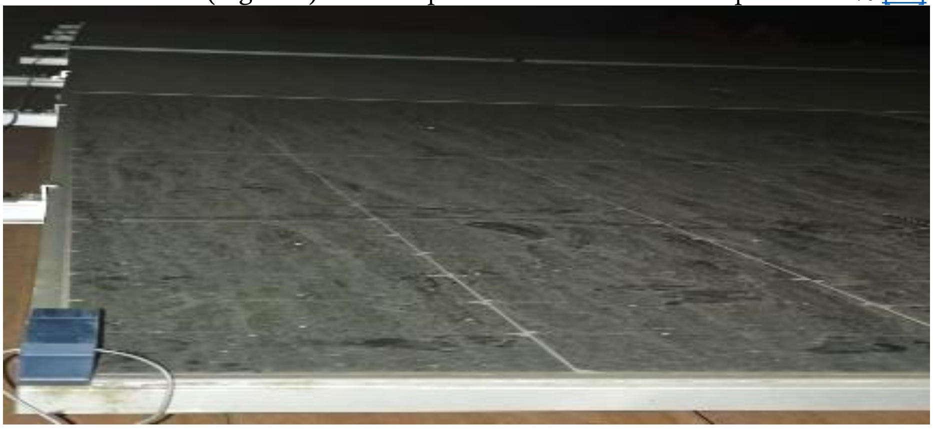

Figure 6. PV Module Surface Covered by Dust at the Site

Figure 6 illustrates the surface condition of the PV modules after two weeks of continuous operation without cleaning. A thin layer of dust and airborne particulates accumulated on the glass surface, forming a semi-opaque film that partially blocked incident solar radiation. This contamination caused a measurable decline in daily energy yield, with performance decreasing by approximately 20–25% compared to cleaned modules [23]. The photograph also reveals that dust tended to concentrate near the lower edges of the modules due to limited rainfall and weak wind flow beneath the roof structure. Regular cleaning schedules and maintaining the 15° tilt angle recommended by SNI 04-6957 help reduce surface soiling and restore optimal optical transmission through the glass layer

The analysis indicates that irradiance intensity and module temperature are among the most significant parameters influencing the conversion efficiency and stability of the photovoltaic (PV) system. Higher module temperatures reduce voltage output due to increased internal resistance, while higher irradiance levels improve power generation up to the module's rated limit. These interactions demonstrate that maintaining optimal thermal conditions is essential for maximizing PV performance, particularly in tropical regions where temperature fluctuations are considerable.

These findings highlight the importance of considering multiple influencing factors such as temperature, irradiance, and panel orientation in evaluating photovoltaic performance. Similar approaches have been demonstrated by Lei et al [24]. Who developed an integrated predictive framework using NSGA-II and ANN models to optimize photovoltaic parameters by combining physical, geographical, and technical variables, achieving high predictive accuracy and convergence. This supports the notion that integrating data-driven optimization and environmental parameters can enhance predictive reliability in PV system evaluation.

Fuel Gas Consumption Efficiency

The PV system contributed directly to reducing turbine fuel gas consumption. The average daily fuel gas savings were 0.0067 MMSCF, totalling 0.1997 MMSCF over the observation period. Extrapolated annually, this represents approximately 2.4292 MMSCF in fuel gas efficiency, providing significant operational benefits for PT Energi.

CO_2 Emission Reduction

The system also demonstrated substantial environmental benefits. Over the 30-day observation period, CO_2 emissions were reduced by 10.3822 tons, with an average daily reduction of 0.3461 tons.

This highlights the potential of PV integration to contribute significantly to corporate sustainability goals and national emission reduction commitments.

Conclusion

Based on the research findings, performance of the IoT-integrated monocrystalline PV on-grid system at Grissik Administration Building demonstrated a stable and reliable contribution to clean energy generation. The system performance ranged between 33.87% and 93.08%, with daily energy production varying from 203.0 kWh to 557.9 kWh and an average of 432.0 kWh/day from installed capacity of 119.88 kWp (599.40 kWh).

The integration of the PV system directly reduced daily fuel gas consumption, with values ranging between 0.0031 and 0.0086 MMSCF, totalling 0.1997 MMSCF over the 30-day period. On an annual scale, this represents an estimated saving of 2.4292 MMSCF. Concurrently, the system achieved a cumulative CO_2 emission reduction of 10.3822 tons within the same period, with an average daily mitigation of 0.3461 tons.

Overall, the study confirms that monocrystalline solar PV panels, when integrated with IoT-based monitoring and control systems, are highly effective in supporting industrial energy transition strategies. The technology not only reduces fossil fuel dependence and mitigates greenhouse gas emissions but also enhances operational efficiency through real-time performance tracking. These outcomes underline the role of IoT-integrated solar PV as a viable pathway toward sustainable and low-carbon energy solutions in the oil and gas sector.

Future research should focus on developing long-term performance and forecasting models that integrate irradiance–temperature correlations, seasonal effects, and system degradation parameters to further optimize PV system design and operational accuracy.

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