Enhancing Warehouse Sustainability through Solar Panel Performance Analysis

Master Thesis

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ABSTRACT

In today's world, the growing use of solar photovoltaic (PV) systems especially in the logistics sector has provided companies with new opportunities to produce renewable energy, improve their sustainability performance, and reduce carbon emissions from their operations. Importantly, the deployment of solar systems also helps contribute to broader environmental goals such as the European Green Deal and net-zero emission goals in the long run, since these corporations can decrease their environmental footprints. However, in reality the actual performance of PV systems often differs from their theoretical energy output because of some technical, operational, environmental, and system-level factors that will be explored in this entire study.

The performance analysis of some selected PV installations across the logistic facilities located in Belgium, Sweden, the Netherlands, the United Kingdom, Thailand is presented in this study. The main objective of this study is to evaluate the gaps between expected and actual performance of PV systems, identifying the key root causes behind performance deviations, translate those performance gaps into business opportunities, and recommend measures that support to improve performance. The research uses a multi-case study design using both qualitative and quantitative methods. Initially, With the given production data, performance evaluation is done using standard performance metrics such as Performance Ratio (PR). Then, further analysis is supported by data gathered through questionnaire responses, interviews with site stakeholders, and benchmarking from literature sources. Our root cause analysis groups the causes into four key dimensions like technical, operational, environmental, and contractual /system constraints.

The findings of this study show significant performance gaps between several sites. Even though root causes behind these gaps may vary in local conditions as well as operational practices. While many previous studies have mainly focused more on the impact of environmental and technical dimensions, this study shows that along with technical and environmental losses, operational and contractual / system issues are the most important dimensions behind solar PV systems underperformance. Based on the results, this study suggests further portfolio-level recommendations including improving monitoring systems, Key Performance Indicators (KPIs) based performance monitoring, predictive maintenance, inclusion of proactive cleaning, and improved integration of photovoltaic systems, Battery Energy Storage System (BESS), and grid constraint can significantly enhance the performance.

Overall, the research contributes by giving a broader and more integrated perspective on PV systems, especially within logistics operations. Also, the proposed framework will support structure and scalable decision making for future PV portfolio management. Importantly, study highlights the importance of combining technical, operational and business aspects in order to maximize sustainability benefits.

Keywords: Photovoltaic systems (PV), PV performance analysis, performance loss, root cause analysis, curtailment, energy management systems (EMS), self-consumption, recoverable energy, predictive maintenance, battery energy storage systems (BESS), return on investment (ROI), industrial sustainability, Portfolio, Logistics Sustainability, Installed Capacity

Abbreviations:
PR - Performance Ratio (PR)
EMS - Energy Management Systems
BESS - Battery Energy storage systems
SLA- Service Level Agreements
KPIs- Key Performance Indicators
O&M - Operation and Management
GO - Guarantees of Origins
MWp - Megawatt Peak
KWh - Kilowatt Hour
ROI - Return on investment
PVGIS- Photovoltaic Geographical Information System
PoC- Point of Connection

Important Definition:

- **Recoverable Energy:** It is the amount of energy which can potentially be recovered through some operational as well as technical improvements.
- **Soiling:** It is the depositions of dust, dirt, or other forms of pollutants on solar panel's surface that cause reducing their efficiency and energy output.
- **Curtailment:** It refers to reduction of overall power energy generation by the photovoltaic system due to grid or some operational restrictions.
- **Injection limit / Export Limitation:** It is the maximum amount of electricity supplied from solar PV systems to the electrical grid.
- **Energy Management System (EMS):** This refers to a system for managing energy generation as well as distributions and consumptions within a facility.

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1. INTRODUCTION

This chapter presents the background and motivation of the study together with our main research problems, purpose of the study, and delimitations. Basically, this is supplemented with the importance of studying solar PV system performance analysis within logistics and warehouse sustainability.

1.1. Background

In today's modern world, many business sectors are increasingly starting to adopt low-carbon energy systems. However, this trend of implementing low-carbon energy systems has changed from being moved from a narrow focus to a broad perspective because of rising global concerns about climate change and stricter EU climate policies. According to Kougias et al. (2021), considering the EU Green Deal the EU countries are actively committed to reducing their greenhouse emission (GHG) by 2030 and achieving net zero emissions by 2050. For that it requires a substantial expansion of clean renewable electricity generation. Here in this transition, Solar Photovoltaic (PV) technology plays an important role particularly within commercial and industrial sectors due to their declining costs over the years, scalability, and it can generate electricity closer to distributor generations.

Among all different commercial sectors, logistics and warehousing facilities offer structural advantages for large scale rooftop solar PV installations. According to Lee et al.(2012), Industrial halls typically have large, unobstructed roof areas, and high roof-to-floor ratios which make them technically suitable for installing photovoltaic systems. Large-scale studies of roof-mounted solar PV potential in Sweden indicated that commercial and industrial buildings mostly represent a substantial opportunity for expansion of national solar capacity (Yang et al., 2020). Also, another example based on studies of rooftop PV systems in Europe shows that they generally perform consistently over time. In many European countries, these solar rooftop systems typically achieve around 73% - 74% of their ideal conditions (Schardt and Te. Heesen, 2021).

From an economic perspective, rooftop PV has become increasingly attractive for commercial sectors. These rooftop PV solar in the warehousing industry can definitely help in reducing operational costs, improve long-term asset value, and supporting corporate’s overall decarbonization strategies (UKWA,2022). One notable good example of this transformation can be seen through DSV. They have deployed a large number of rooftop solar PV systems in their Landskrona Site in Sweden. This site further demonstrates how renewable energy assets are being integrated into the warehouse's daily operations while strengthening the company’s long-term decarbonization strategy (DSV, 2024).

Although these solar installations are increasing, having more installed capacity does not automatically translate into its optimal performance. In reality, the actual electricity output generated by solar PV systems may vary from the theoretical expectations. Such variations in output occur due to the effect of the environmental as well as operational factors. Also, the effective functioning and the performance of solar photovoltaic PV systems are highly dependent on the environmental conditions in which they operate (sarmah et al., 2023). However, this research simply shows that key factors such as variations in solar radiation, ambient temperature, humidity, and wind speed also mainly contribute to effective electricity generation by PV systems. Furthermore, factors like cleanliness of the surface, variations in the weather conditions, and the angle of the solar panel (tilt) can also impact on measurable efficiency losses (Cevik and Tirmikci,2025).

Another point is that empirical research based on performance benchmarking studies carried out by Wang and Sueyoshi (2017) clearly indicates that there are many considerable commercial installations that do not operate at their expected efficiency levels. The performance gap, which is the difference between the expected and actual output, has a direct impact on energy efficiency. As a result, it can also affect overall calculation on payback periods, return on investment (ROI), and emission reduction goals.

Against this background, it is really important to study the gap between the theoretical design performance and their actual energy output in real operating conditions. So, by analyzing the rooftop PV systems across multiple dedicated logistics facilities, our study aims to identify the main causes of efficiency losses. Also, provide practical ways to improve system performance and long-term sustainability outcomes in the warehousing sector.

1.2. Problem Statement

The case organization examined in this study is a large global logistics company headquartered in Europe, providing integrated freight forwarding, transportation, warehousing, and supply chain optimization services through an extensive international network. Operating under an asset-light and digitally driven business model, the company has continuously expanded its global presence and service capacity, positioning itself as a major actor within the logistics industry.

Sustainability forms a central component of the organization’s long-term strategy. The company has committed to science-based carbon reduction targets and achieved net-zero emissions across its value chain by 2050. To support this transition, it invests in renewable energy installations, electrified transport solutions, and internally funded emission-reduction initiatives, while also promoting responsible governance, employee development, and humanitarian logistics support. These efforts establish an important foundation for enhancing both the environmental and economic performance of its operations.

Among these sustainability initiatives, rooftop solar photovoltaic (PV) systems deployed across logistics facilities play a key role in reducing emissions and energy costs. However, actual energy generation frequently deviates from theoretical expectations due to factors such as weather variability, installation configuration, panel soiling, equipment degradation, and day-to-day operational conditions. For large organizations operating multiple geographically distributed PV installations, systematically monitoring, comparing, and diagnosing performance differences across sites remains a significant challenge.

Although the company possesses reliable data on installed capacity and electricity generation across numerous facilities, a unified portfolio-level analytical framework to compare expected and actual performance, identify underperforming locations, and determine root causes is currently lacking. Consequently, certain PV systems may continue operating below optimal efficiency, resulting in unrealized energy savings and avoidable operational costs.

Moreover, technical performance data alone is insufficient to support operational and investment decision-making. To effectively prioritize improvement actions and maximize the value of solar investments, identified performance gaps must be translated into clear business implications, including potential energy recovery, cost savings, and return on investment. Developing an integrated framework that links technical PV performance assessment with economic evaluation therefore represents the central problem addressed by this study.

1.3. Purpose

The purpose of this thesis is to assess how solar panels installed across selected buildings of a large global logistics company perform compared to their expected energy output. By comparing theoretical production with actual electricity generation, the study aims to identify where significant performance gaps exist and to understand the underlying causes of these deviations.

Based on the performance assessment, the project further analyzes the main technical and operational factors contributing to underperformance, using site-specific operational data from the company's solar installations. The focus is on identifying practical and implementable improvement opportunities in locations where performance does not meet expectations.

In addition, the thesis seeks to translate analytical findings into concrete business cases that can support organizational investment and operational decision-making. Potential improvement measures are evaluated in terms of their economic impact, including expected cost savings, recoverable energy generation, and overall efficiency improvements.

Ultimately, this research aims to provide practical, scalable insights applicable across multiple facilities, delivering measurable value in both operational performance and sustainability outcomes for the organization.

1.4. Research Questions

In this section, the research questions guiding the thesis are introduced.

RQ1: To what extent do the actual performances of solar panel installations across the company's buildings align with their theoretical energy output?

This question focuses on comparing theoretical energy yield with actual production data across selected sites, utilizing standardized performance metrics such as the Performance Ratio (PR). The objective is to identify whether systematic performance gaps exist and to quantify their magnitude.

RQ2: What technical, operational, environmental, and contextual factors explain significant deviations between expected and actual PV performance?

Where performance gaps are identified, this study aims to diagnose their underlying causes. The analysis will leverage site-specific data and existing literature to examine contributing factors such as system design, operating conditions, maintenance practices, and local circumstances. We will pay special attention to cases with severely substandard performance, as these cases have the greatest potential for improvement.

RQ3: How can the identified performance gaps be translated into actionable business cases to support the case company's investment and operational decision-making?

Based on the analysis results, this question focuses on translating technological insights into management value. The focus is on evaluating potential improvement measures such as operational optimization, retrofitting, enhanced monitoring, or predictive maintenance and assess their economic and environmental impacts. The business cases will support decision-making by quantifying expected benefits using indicators such as return on investment (ROI), payback period, and potential cost and emission reductions.

Together, these questions ensure that the thesis moves from diagnosis to explanation, and finally to actionable recommendations aligned with the company's business and sustainability goals.

1.5. Delimitations

This study is limited in scope to ensure both depth analysis and practical feasibility within the timeframe of a master's thesis. First, the empirical analysis is restricted to a selection of warehouse facilities within a large international logistics company, where relatively reliable and comparable data on photovoltaic capacity and actual electricity generation are available. The study is based on representative case studies and does not aim to provide a comprehensive assessment of all solar installations across the company's global portfolio.

Secondly, the analysis focuses specifically on rooftop photovoltaic systems at the building level and does not consider upstream processes such as solar panel manufacturing, module supply chains, or broader life-cycle environmental impacts. Consequently, the environmental assessment is limited to operational performance and the associated emission reductions resulting from electricity generation.

Furthermore, the identification of underperformance root causes is based on available operational data and reported information. In some cases, site-level data may be incomplete, inconsistent, or subject to reporting limitations, which may affect the precision of performance comparisons. While technical, operational, and environmental factors are considered, no on-site field inspections are conducted at each location. Therefore, the causal explanations remain analytical rather than experimental in nature.

Finally, the business cases developed in this study are intended to support managerial decision-making rather than to provide final investment solutions. The cost–benefit and return on investment calculations are based on assumptions and scenario analyses derived from available data and literature and therefore cannot substitute for detailed technical or financial feasibility studies required for real-world implementation.

These delimitations allow the study to remain focused on its core objectives: assessing photovoltaic performance, identifying significant deviations, and translating analytical findings into scalable management recommendation

2. LITERATURE REVIEW

This chapter discusses the overall theoretical background behind the solar PV system's performance, key root causes of solar PV systems underperformance, and the valuation of renewable energy investments. Furthermore, it also reviews previous literature and concepts relevant to the theoretical foundation of this study.

2.1. Solar PV Performance & Performance Ratio

In today's contemporary world, the need for a transition towards sustainable logistics systems has become a prominent issue in modern supply chain and operation management studies. As energy-intensive nodes within supply chains, these warehouses have been found to be major contributors to overall carbon emissions due to electricity consumption for ventilation, material handling systems or in day-to-day operations (Faccio et at., 2013). Also, improving warehouse sustainability has become a strategic priority especially through renewable energy integration and energy efficiency optimization.

The performance of a solar photovoltaic system (PV) is nothing but the ability to convert incident solar radiation into usable electrical energy under real operational conditions. The actual system output is influenced because of some environmental, operational, and technical factors. In order to evaluate real-world operating system effectiveness, the performance ratio (PR) is a widely accepted metric for this purpose (SMA,2011). According to SMA (2011), the performance ratio is the ratio between the actual measured production output and the theoretical energy output that is based on incident radiation and installed solar capacity (MWp). This solar Performance Ratio (PR) can be expressed in Percentage (%). Performance Ratio shows how the available energy solar resource is converted into usable electricity by considering losses caused by factors such as inverter inefficiencies, wiring losses, shading, high temperature and dust on panels (soiling) (CHROSIS, 2019).

According to Chen et al. (2016), PV performance is significantly influenced by environmental conditions, and it includes solar irradiance, ambient temperature, wind speed and humidity. These factors are directly proportional to power generation. Empirical studies by Sarmah et al. (2023) highlighted that solar panels efficiency increases particularly with the good amount of solar irradiance and wind speed, but it decreases because of ambient temperature and humidity. The temperature effect is particularly important for crystalline silicon modules. Also, these modules typically exhibit a negative temperature coefficient of around 0.4% per Kelvin (Skoplaki and Palyvos,2009). As module temperature increases, open-circuit voltage and fill factor decreases. Hence, resulting reduces maximum power output. In the large commercial sector, especially warehousing rooftop infrastructure may experience seasonal PV performance variability due to heat accumulation.

Over the extended period, empirical research also confirms that PR is a very useful indicator for benchmarking PV system performance. As per Schardt and te-Heesen (2021), a study of more than 32,000 rooftop PV solar installations in different regions of Europe and further reported a consistent average performance ratio of approximately 0.73 over five consecutive years. Furthermore, their finding indicates that there is limited correlation between system size and PR. Also, suggesting that performance is strongly affected by design quality, installation standards, and operational management instead of installed capacity alone.

Apart from climate related and technical losses, there are some external factors such as dust accumulation and degradation that affect long term performance. The absence of strong timely maintenance practices such as poor surface contamination can reduce the efficiency of overall output. Besides, the long-term degradation of a module's surface materials can lead to gradual reduction in energy yield, which must be considered in lifecycle performance assessments. From a policy perspective, the overall expansion of rooftop PV systems plays a very strategic role in achieving targets as per the European Green Deal framework.

In summary, the performance of solar PV systems is dependent on environmental conditions, designs of systems, operational efficiency, and long-term surface degradation factors. The performance ratio helps as a reliable and climate-independent metric for easy evaluating and comparing PV system performance over time.

2.2. Causes of Underperformance in PV Systems

As we discussed earlier, solar photovoltaic PV systems are widely considered as a reliable renewable energy technology. However, in practice sometimes this real-world performance often differs from the expected output. So, it is necessary to understand the causes of PV underperformance for improving system reliability. However, this becomes more important especially for industrial applications such as warehouse operations where economic viability and sustainable objectives can be achieved through a stable and consistent generation of output.

In simple terms, the underperformance by photovoltaic systems is the difference between the actual gap and the expected energy yield, and the actual electricity generated under real operating conditions (CHORSIS,2019). Also, as per Dawood et al. (2023), one of the noticeable major causes is temperature variations. The photovoltaic modules have a negative temperature coefficient, which clearly shows that the efficiency of the module will reduce as the temperature of the cell increases. For example, the crystalline silicon modules have a loss of power of around 0.40 - 0.45% for every 1 °C temperature rise (CSIRO, 2021). Even if temperature rises, then those of internal resistance will also rise. Also, the open-circuit voltage will decrease and result in lower energy production. One of the empirical studies by Eze et al. (2024) shows that the higher irradiance increases current generation but it also raises module temperature. As a result of this, it potentially offset gains in overall output. Having poor ventilation, rooftop mounting constraints, and high ambient temperature causes the underperformance of PV systems.

Another important cause is the soiling and dust accumulation on Photovoltaic panels, which can reduce their efficacy and lead to underperformance (CSIRO, 2021). Most of the time, dust, moisture, and other airborne particles can block the amount of irradiance reaching the surface of solar cells. This leads to measurable efficiency losses. Also, experimental studies reveal that an increased amount of dust decreases the system efficiency particularly in dry or industrial zones (Dawood el al., 2023). The impact of soiling is climate-related and easily influenced by tilt angle, rainfall frequency, and frequent maintenance routines (Chen et al., 2016).

Variability in irradiance is also considered as a critical factor. According to Chen et al. (2016), solar output is directly proportional to incident irradiance. These kinds of fluctuations occur due to seasonal changes, cloud cover, and geographical location lead to irregular production rate. According to one of the recent studies by Eze et al. (2024) mentioned that solar panels produce maximum efficiency at an optimal level of irradiance. However, if the intensity of sunlight is too high or low, then this performance always drops in a non-linear manner, mostly because of increased temperature within the system (Eze et al., 2024).

Shading and geometric misalignments are also major contributors to energy losses. As such modules in the string are electrically connected in series. Therefore, even partial shading of one single module can reduce the performance output of the entire string (CSIRO, 2021). Lastly, various operational as well as system-related inefficiencies could also lower the overall efficiency. For example, losses in inverters, degradation of components, and inefficient monitoring can also reduce output gradually. According to Chen et al.(2016) stated that real-world monitoring studies have found that many installed rooftop systems do not perform as per expected output because of undetected or overlooked faults as well as maintenance shortcomings.

In summary, the main causes of underperforming PV systems usually arise from combined effects of high ambient temperature, variations in irradiance, soiling, shading, design-constraints and overlooked regular operational shortcomings. In the case of warehouse rooftop installed systems, consistent performance monitoring and climate-specific designs are very important in order to reduce these losses. This will help to enhance the reliable output as well as long-term sustainability outcomes.

2.3. Cost-Benefit & ROI in Renewable Energy Investments

The literature consistently explains that it is important to translate technical performance improvements into economic terms to support managerial decision-making. So, some recent studies in industrial and warehouse buildings by Lee et al. (2012) illustrate that improving energy efficiency and reducing energy demands can generate higher economic returns than just increasing photovoltaic (PV) capacity, especially when it is evaluated through cost-benefit and ROI analysis. Also, research on energy-efficiency investments conducted by Catherine Cooremans (2012) in “Investment in energy efficiency: do the characteristics of investments matter?” explained that sustainable investments are often undervalued within many organizations. This is because core decision-making processes are always influenced by strategic and organizational factors that extend beyond profitability alone.

Cost–benefit analysis is extensively used in environmental impact and sustainable development studies and has become a key analytical method for evaluating investment decisions in renewable energy infrastructure (Asirin, Siregar, Juanda, & Indraprahasta, 2023). In photovoltaic economic assessments, system revenue is commonly defined as the reduction in electricity purchase costs and the resulting cost savings are typically calculated using local electricity tariff rates (Zhou et al., 2025). In addition, when PV generation exceeds on-site electricity demand, surplus electricity exported to the grid may generate additional revenue, depending on the applicable feed-in tariff or market-based pricing mechanism. The cost depends on the identified root causes of poor performance and the corresponding performance improvement measures. These may include inverter replacement or upgrading costs, operation and maintenance (O&M) expenses, panel cleaning and inspection costs, engineering and technical service fees, monitoring system upgrades, and potential retrofit or system optimization investments. Performance diagnostics, data management improvements, and temporary operational disruptions during maintenance activities may also incur additional costs. Taking into account economic benefits and related implementation costs, a comprehensive assessment of the financial feasibility of the proposed improvement measures can be conducted.

Cost-benefit analysis provides an overall evaluation framework, while return on investment and payback period serve as supplementary financial indicators to assess profitability, return on investment, and long-term economic value. Return on investment (ROI) assesses the financial return of a photovoltaic system over its entire lifespan relative to total investment and operating costs, typically calculated by dividing net income by total costs (Zhou et al., 2025). While ROI provides an indicator of profitability, the payback period reflects investment risk and capital recovery speed. Simple payback period (SPT) is the shortest time required for the savings generated by cash flow (excluding debt repayment) to be proportional to the total investment (Datta, Kalam, & Shi, 2020). Dynamic payback period overcomes the drawback of simple payback period, which does not consider the time value of capital. Specifically, it needs to consider the project's investment costs, expected returns, inflation rate, and other factors, and then use these factors to calculate the project's dynamic payback period (Ren & Chen, 2023). Both ROI and payback period are commonly applied in renewable energy investment assessments to provide complementary insights.

Beyond financial evaluation, environmental indicators are also essential when assessing performance improvement measures in existing photovoltaic systems. Enhancing system efficiency not only increases economic returns but also contributes to additional emission reductions. Environmental assessments typically include quantifying the amount of greenhouse gas emissions avoided, particularly carbon dioxide, as well as the reductions in air pollutants such as sulfur dioxide and nitrogen oxides. These emission reductions are usually estimated by applying emission factors to the additional electricity generated by performance improvements, reflecting the substitution of fossil fuel grid electricity (Zhou et al., 2025).

3. METHODOLOGY

Now, this chapter includes an overview of the research design, data collection process, and methodological approach used in this study. In addition, it also describes the different phases of analysis that were done during this study in order to develop PV system performance and further develop business case recommendations.

3.1. Research Design

This study adopts empirical case-based research methodology to thoroughly examine and analyze how solar panel analysis contributes to warehouse sustainability within logistics company's warehouse operations. The research follows a mixed-method approach, combining quantitative analysis of operational data and qualitative insights from the sites. The unit of analysis for this study is the individual warehouse facility equipped with solar photovoltaic PV systems. The case organization is a logistics company managing these installations across their global network. Also, in order to support the empirical investigation, a systematic literature review will be conducted for this study to establish a clear and appropriate theoretical foundation. Basically, this study is based on the examination of real-world operational and energy performance data within an organizational context.

As this study is theoretically grounded in case study research and mixed-method research methodology. The case study approach is suitable for this research because it focuses on investigation of real-world photovoltaic system performance within the operational context of a logistics company. Also, the mixed-method approach is useful and combines quantitative operational data with qualitative data (questionnaires response, interviews) provides a broader understanding of root causes behind solar PV system's underperformance.

As mentioned before, this study follows a mixed-method research approach that combines quantitative and qualitative in order to analyze the performance of solar photovoltaic installations across 26 warehouse facilities. This mixed method approach is important because quantitative data helps identify the difference between actual and expected performance while qualitative data provides insights for deeper understanding of the underlying technical, operational, and environmental factors. Considering this mixed-method approach, it can be incorporated to provide proper contextual understanding and help to explain observed performance differences that cannot be explained using numerical data alone itself. The logistics company is responsible for providing the real-world actual production dataset for solar photovoltaic installations. This study research is in accordance with ethical standards that involve confidentiality and ensure responsible data handling. In study, the company name, company-specific provided actual operational data and all shortlisted site-specific data are kept completely anonymized when needed. Also, data obtained through interviews and questionnaires will be used only for academic purposes only. However, expected energy output data obtained by conducting simulation through the PVGIS simulation tool. It means doing this step ensures that all required datasets are available for preliminary analysis and comparison across locations.

After the initial data collection, a portfolio-level performance screening (Phase1) of solar PV systems will be conducted across the different warehouse facilities locations. This phase directly addresses our research question Q1, which closely focuses on the degree to which the actual performance of solar PV systems aligns with their theoretical energy output. Hence, the main objective of this step is to compare the actual solar electricity generation with the expected energy generation in order to identify the potential solar PV performance gaps at various locations. On the basis of the results obtained from the above preliminary analysis, a smaller number of representative sites will be selected for further investigations. These include sites such as a benchmarking site with expected performance, Underperforming site, and critically underperforming site. This stage represents Phase 2 of the study and directly addresses research question Q2, which seeks to identify operational, and contextual factors that explain deviations between expected and actual PV performance. In this study, phase 2 also supports a more detailed investigation of site-specific conditions that causes the solar PV system's underperformance. It includes system design characteristics, maintenance practices, and environmental factors affecting energy generation. Additionally, questionnaires are designed to collect more information that is not captured in the operational dataset. This questionnaire was distributed with relevant stakeholders as well as site-specific managers at the logistic company. Also, information on unanswered questions from this questionnaire will be collected through semi-structured interviews with site-specific representatives.

The insights obtained from both qualitative and quantitative analysis will be used to develop practical business case scenarios, considered as Phase 3. This Phase of the study addresses research question Q3, which focuses on how identified performance gaps can be translated into actionable business cases to support company's investments as well as operational decisions. This business case study includes financial indicators such as return on investments (ROI) and payback period. These results aim to support the logistic company in improving the overall performance of their solar PV systems and provide evidence-based recommendations for sustainable investment decisions.

Also, as mentioned above in order to improve methodological quality, this research study uses both qualitative and quantitative analysis through data triangulation. The reliability of the data is supported by using standardized questionnaires and the calculations of performances across all sites are involved. Secondly, validity is supported and strengthened through the comparison of operational data, site-specific interview data, and based on literature sources. Since, our study is based on selected sites within one logistics company, the finding may not be generalized directly to all organizations. However, these findings and insights can be useful for similar logistics organizations and situations.

This research methodological steps and phases of analysis will be discussed in more detail in the following subsections.

3.2. Data Collection

This study focuses on a mixed-method approach combining quantitative real-world operational data along with qualitative information collected from selected warehouse sites. The dataset that was used in this research was provided by Logistics Company, as they are responsible for monitoring and managing solar photovoltaic (PV) installations across their global warehouse network. These warehouses are especially located across regions like Europe, the United Kingdom, USA, the Middle East, and South Asia. Considering such installations across a diverse set of geographical and climate conditions, provide a useful and strong basis for analyzing PV performance.

Basically, the dataset used in this study includes real-world operational data from more than 26 warehouse locations from 2023 to 2025. Also, this dataset contained the key variables related to the solar PV systems installed at each warehouse site. The data includes the name of the site, geographical location, geographic coordinates (longitude and latitude), Installed solar capacity (MWp), operational date, and the quarterly actual production data. These variables are crucial as they provide the foundation for evaluating the performance of rooftop solar installations and allow to do further in-depth root cause analysis as well as sustainability analysis. Additionally, the theoretical energy output data for each site obtained by performing simulation using PVGIS tool. Based on this available data, basic data preparation procedures were applied. This includes verification of quarterly cumulative data, verification of site coordinates, checking and requesting missing values, and furthermore standardizing data formats where it is actually necessary.

Also, to support the quantitative dataset, further qualitative information will be collected by designing site specific questionnaires. These questionnaires are designed to gather contextual information that cannot be captured in the given operational dataset such as solar installation characteristics, operational and maintenance challenges, and local energy usage pattern. Considering this a standardized questionnaire consisting of 36 questions was distributed across all five selected sites. The responses to this questionnaire were provided by site-level representatives, especially Sustainability Manager or Facility Manager, which resulted in five complete questionnaires responses. In cases where certain questions were not answered or required further clarification, follow-up semi-structured interviews were scheduled with the respective site representatives. This combined approach of a standardized questionnaire and semi-structured interviews ensured both consistency and flexibility in this data collection. Hence, it was important to collect this qualitative data that will support a more comprehensive understanding of the factors influencing the overall solar PV performance across different warehouse environments.

This study clearly aims at developing a more holistic understanding of solar PV performance analysis in typical warehouse operations by combining quantitative performance data and qualitative site-specific insights. This mixed method helped the research to capture both measurable performance outcomes and operational factors. As a result, it helps to improve the reliability and robustness that supports this overall analysis.

3.3. Phase 1 – Portfolio Performance Screening

The first phase of our research focuses on a high-level performance screening of solar systems across selected warehouse facilities in different countries. The objective of this phase is to systematically compare the actual energy production of installed PV systems with their expected energy output in order to identify potential performance gaps and select representative cases for deeper analysis.

The analysis begins with defining the scope of the dataset, including the selection of sites and the relevant time period for evaluation. Only sites with available information on installed capacity, operational status, and electricity production data are included in this phase.

To estimate the theoretical energy production of each PV installation, the study uses the PVGIS simulation tool developed by the European Commission. Based on the geographic coordinates of each site and the installed system capacity (MWp), PVGIS provides an estimate of the expected annual electricity generation under typical meteorological conditions. This theoretical value represents the expected specific yield of each system.

Next, the reported solar electricity production data are cleaned and standardized. Since the available data are reported on a quarterly or year-to-date basis, the dataset is structured to ensure comparability across sites and time periods.

To enable cross-site comparison, the study normalizes energy production by system size. The actual specific yield (kWh/MWp/year) is calculated by dividing the reported electricity production by the installed capacity of each system. This normalization allows installations of different sizes to be evaluated on a comparable basis.

Based on these values, the Performance Ratio (PR) is calculated as:

$$PR_y = \frac{ASY_y}{ESY_y}$$

where y denotes the year, PR_y represents the performance ratio in year y, ASY_y is the actual specific yield in year y, and ESY_y is the expected specific yield in year y.

PR represents the ratio of actual system performance to theoretical system performance and is a key indicator for evaluating the efficiency of photovoltaic systems.

Finally, the calculated PR values are used to classify system performance into different categories (e.g., excellent, normal, underperforming, and critical). It should be noted that there is no universally accepted PR classification standard in photovoltaic performance literature, and the reported benchmark ranges vary depending on system type, climatic conditions, monitoring boundaries, and study objectives. The classification thresholds are defined based on commonly reported performance ranges in photovoltaic system assessment literature. While there are slight differences in the definition of the scope of PR across different literatures, the general scope is quite consistent. In 2012, a study of 100 PV system installations in Germany found that their annual PRs ranged between 70% and 90% (Woyte et al.,2013). According to a study by Reich et al. (2012), the typical range of PR has reportedly risen from 50-75% in the late 1980s and 70-80% in the 1990s to over 80% today. Regarding the European PV guidelines, a good PR value range is between 0.8 and 0.85 while a value below 0.75 indicates a problem (Khalid, Mitra, Warmuth, & Schacht, 2016). Schardt and te-Heesen (2021) studied more than 32,000 rooftop photovoltaic solar installations in different parts of Europe and found that the average performance ratio remained stable at around 0.73 for five consecutive years.

Based on the synthesis of these literature benchmarks and considering the need for comparative screening across a diverse international PV portfolio rather than for strict technical certification purposes, the PR classification thresholds shown in Table 1 were applied in this study.

Table 1：Performance Ratio Category

Category	**PR Range**	**Description**
Excellent	> 90%	Close to expected performance

Normal	75-90%	Slight deviations from expected
Underperforming	50-75%	Significant performance gaps
Critical	< 50%	Severe underperformance

These thresholds provide a practical framework for identifying systems that may require further investigation and enable the selection of representative case studies for deeper analysis in Phase 2.

Figure 1 shows the flowchart of Phase 1 (Portfolio Performance Screening).

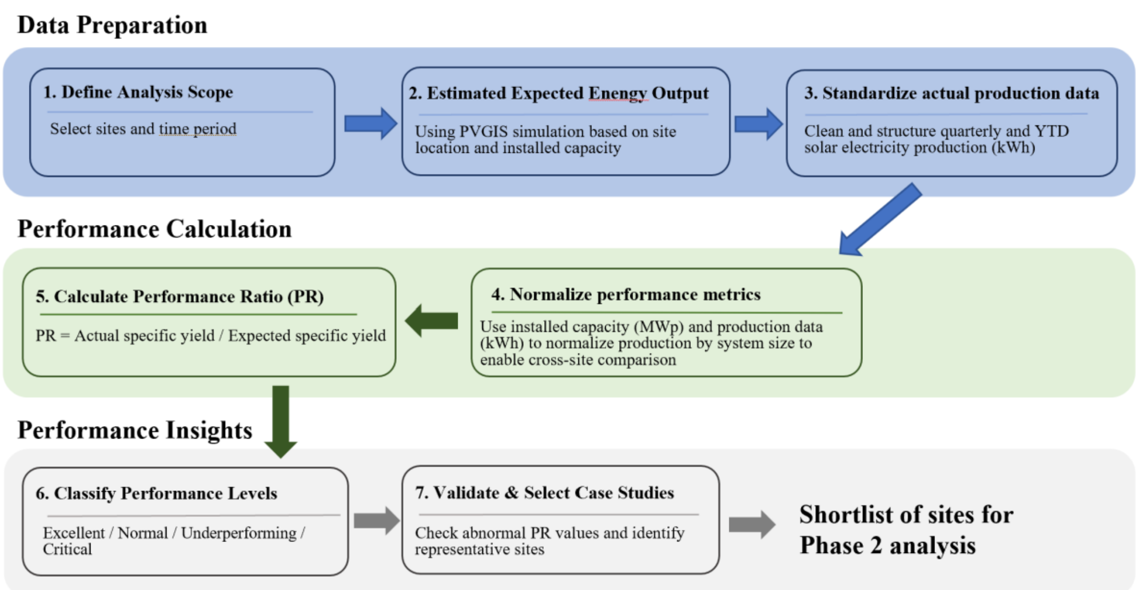

Figure 1：High-Level Portfolio Performance Screening-Method Overview

3.4. Phase 2 – Root Cause Analysis (Case Studies)

As discussed in section 3.3, following the preliminary portfolio analysis of solar performance across the logistics company's warehouse facilities, a total five sites were shortlisted for further root cause analysis. Included sites such as Belgium (Benchmarking Site), Sweden and the Netherlands (Underperforming), the UK, and Thailand (Critically Underperforming). These sites were selected to represent different performance categories such as benchmarking site / best performance, an underperforming site, and critically underperforming site. However, the reason for selection of these sites is to understand how benchmarking-site operate and to identify best practices or technical configurations that could also be replicated at underperforming sites or at critically underperforming sites. For example, the Belgium site is considered as our benchmarking site due to its high-performance ratio. By analyzing this site, this study aims to identify and replicate their best practices to other underperforming sites such as the Uk or Thailand. This will help to improve solar PV performance at underperforming sites by providing clear understanding of the underlying causes of solar system underperformance.

To support our quantitative analysis, a qualitative methodology-based questionnaire was developed to collect more detailed site-level data. Accordingly, the questionnaire consists of approximately 36 questions organized into 8 structured sections. These sections were constructed in a way that moves from general information to more technical aspects. This questionnaire includes sections such as Site characteristics, Technical Configuration, Operations and Maintenance, Data Quality and Monitoring, Environmental factors, Solar energy production and Consumption. For example, the section such as “Site characteristics” collects information on installed solar capacity, system type, and module technology. Also, sections like “Operation and Maintenance" helps understand practices such as frequency of Solar PV cleaning, labour hours, and maintenance responsibilities. The environmental factor section investigates site-specific conditions such as shading, dust, snow, or external factors that may affect the overall solar PV performance.

Accordingly, this questionnaire was distributed to all 5 shortlisted sites. These 5 sites were as follows: Benchmarking Site (Belgium), Underperforming site (Sweden and The Netherlands), and critically underperforming sites (Thailand and the UK). The site's Sustainable Manager was responsible for providing the response to this questionnaire. Also, if in the case of site-specific responses were incomplete, then additional missing information collected through follow-up interviews with responsible site personnel. The collected qualitative data supported our further analysis of performance differences and helped to identify the underlying root causes of solar PV underperformance. The questionnaire used in this study is provided in Appendix 1 for your reference.

3.5. Phase 3 – Business Case Development

To extend the analysis from performance diagnosis to business case evaluation, a structured framework is applied to translate identified performance gaps into economic and environmental value.

The first step focuses on quantifying performance losses based on the results of Phase 1 and Phase 2. The estimated percentage of losses was derived from a combination of location-specific data, simulation results, semi structured interviews, and literature benchmarks. These losses were then converted into energy values and further allocated to self-consumption and output based on location-specific energy use patterns. This distinction helps to more accurately estimate the economic impact, as the value of electricity varies depending on whether it is used to offset grid purchases or exported to the grid. The following are the formulas involved in the first step.

$$LE_y^{self} = LE_y \times S_y$$

$$LE_y^{self} = LE_y \times S_y$$

$$LE_y^{export} = LE_y \times E_y$$

$$LC_y = LE_y^{self} \times P_y^{purchase} + LE_y^{export} \times P_y^{export}$$

where the subscript y denotes the year. LE_y represents the loss of energy in year y, AG_y is the annual generation, L_y is the loss percentage, S_y is the self-use percentage, E_y is the export percentage, LC_y is the cost of energy loss, $P_y^{purchase}$ is the electricity purchase price, and P_y^{export} is the export price.

The second step is to estimate recoverable energy. For each root cause, we estimate recoverable energy by applying scenario assumptions that reflect actual operational improvements. This analysis focuses on the extent to which identified performance losses can be reduced through improvements in system operation, maintenance practices, and control strategies, thus deriving an achievable energy recovery estimate, rather than a theoretical total loss. This step ultimately yields an estimate of recoverable energy (KWh).

The third step is to translate the estimated recoverable energy into economic benefits. Similar to loss assessment, the recovered energy is allocated to both self-consumption and export based on the specific location's electricity usage patterns. The economic value is then calculated by applying relevant electricity prices (including avoided grid purchase costs and export revenue). Electricity prices are determined based on local market conditions, reflecting regional price differences. This ensures that the financial assessment reflects the actual value stream of photovoltaic power generation.

Finally, the feasibility of the improvement measures is assessed by comparing the projected economic benefits with the expected implementation costs. Quantitative comparisons are made if detailed cost data is available. If cost information is limited, a qualitative assessment is conducted based on typical cost ranges and the relative magnitude of expected benefits. This step helps identify high-impact and cost-effective improvement opportunities across different locations and root causes, thus supporting the prioritization of improvement measures.

In addition to the financial assessment, environmental benefits are considered by estimating the carbon emission reduction from energy recovery. This allows the analysis to take into account both economic and sustainability aspects, providing a more comprehensive basis for decision-making.

However, this study only considers the self-consumed portion of recoverable energy as a direct environmental benefit. While exported PV power may indirectly reduce emissions by replacing grid-generated electricity, it was not included in the calculation to avoid uncertainty regarding marginal grid displacement effects.

The calculation method for CO2 Reduction is as follows:

$$CO_2\, R_y = RE_y \times S_y \times EF_y$$

where y denotes the year, $CO_2\, R_y$ represents the CO_2 reduction in year y, RE_y is the recovered energy in year y, S_y is the self-used percentage in year y, and EF_y is the emission factor in year y.

4. EMPIRICAL RESULTS

Now, the results obtained from the analysis conducted at both portfolio-level screening and site-specific investigations are discussed within this empirical results chapter. These results mainly focus on identifying performance gaps and key root causes behind performance deviations. Furthermore, the identified real-world challenges are classified across four perspectives(technical, operational, environmental, and contractual).

4.1. Portfolio-Level Performance Overview

This study initially screened a portfolio of 54 photovoltaic (PV) warehouse sites located across 22 countries and regions spanning six continents, including Europe, Asia, North America, South America, Africa, and Oceania using available production and system information.

Due to missing key data (e.g., production data, installed capacity, or operational information) and limited access to relevant site contacts, only 26 sites with sufficient data quality were retained for portfolio-level performance analysis. The total installed PV capacity across the 26 analyzed sites is approximately 41.5 MWp.

Finally, five representative case sites were selected for detailed investigation based on their performance characteristics, geographical diversity, and availability of site-specific operational information.

To ensure comparability across systems of different sizes, performance was assessed using specific yield (kWh/MWp) and Performance Ratio (PR).

4.1.1. Overall Performance Distribution

Based on the PR classification thresholds defined in Section 3.3, sites are grouped into four performance categories according to their average PR over the period 2023–2025.

It is important to note that a small number of sites exhibit PR values exceeding 120%, which is not physically realistic. These cases are therefore considered data quality issues and are excluded from performance interpretation, pending further validation.

The distribution of sites across performance categories is illustrated in Figure 2. Out of the total 26 sites:

- 5 sites fall into the excellent category
- 9 sites are classified as normal
- 4 sites are underperforming
- 5 sites show critical underperformance

- 3 sites need to further check data accuracy

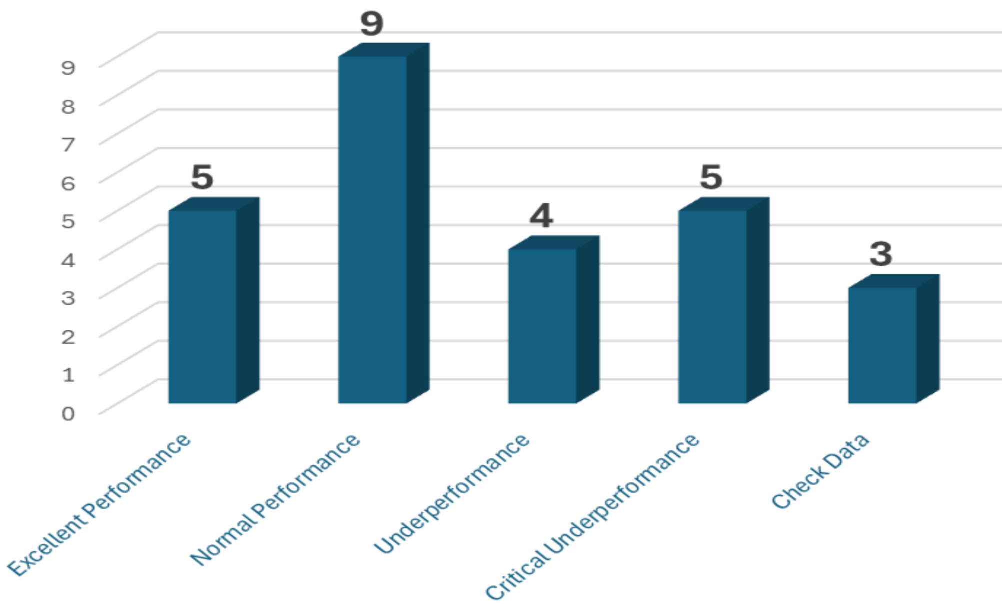

Figure 2: Overall Distribution of PR-Based Performance Categories Across the Analyzed PV Portfolio

Figure 3 illustrates the distribution of PV system performance categories across the 26 analyzed sites, highlighting significant variations in operational performance and data quality between countries within the portfolio.

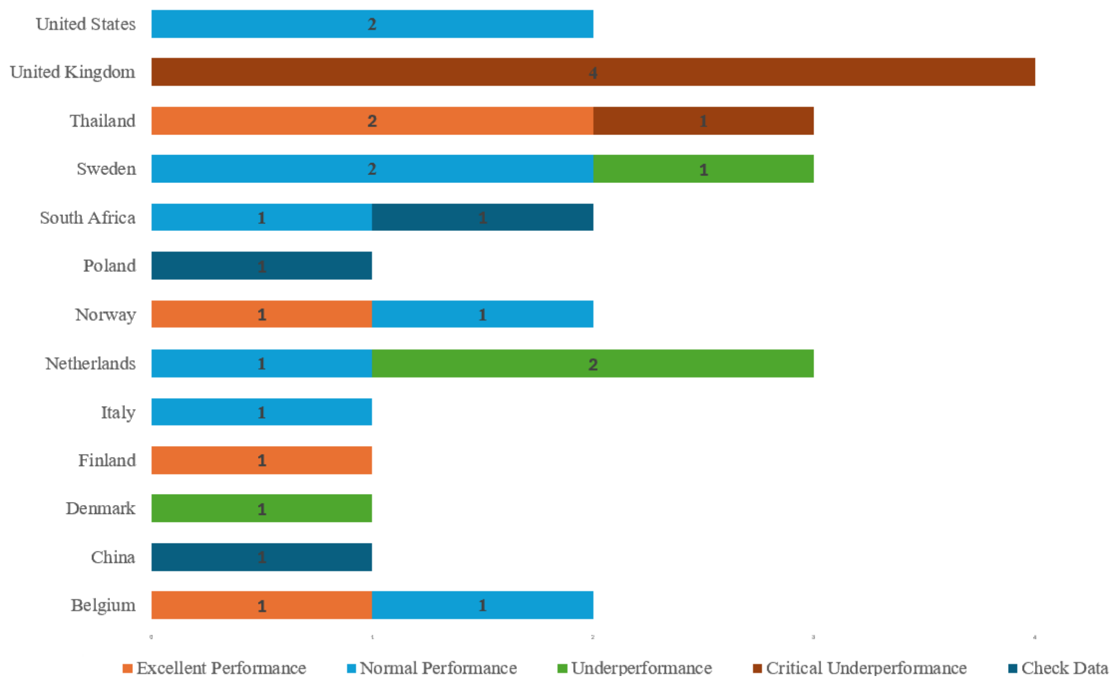

Figure 3: Distribution of PV System Performance Categories Across the Selected Portfolio

4.1.2. Key Observations

Several key observations can be drawn from the portfolio-level analysis:

- A number of sites perform close to theoretical expectations, suggesting that the applied estimation method based on EU's Photovoltaic Geographical Information System simulation (PVGIS) provides a reasonable benchmark for performance evaluation.
- There is significant variation in performance across sites, indicating that factors beyond geographical conditions influence system output.
- Sites located in Belgium, Norway, and Sweden generally show performance levels close to expected values, with relatively stable PR across the analyzed period.
- In contrast, some sites exhibit extremely low PR values (below 20%), indicating critical underperformance. This is particularly evident across the UK sites, where consistently low performance is observed.
- Certain sites show substantial year-to-year variation in PR, suggesting instability in system performance or potential data inconsistencies. For example, the Poland site demonstrates significant fluctuations over the analyzed period.

- Within the Thailand portfolio, performance varies considerably: while two sites perform at or above expected levels, one site shows significantly lower performance compared to the theoretical benchmark.
- A small number of sites exhibit unrealistically high PR values (above 120%). Since PR compares actual generation with theoretical expected generation, values far above 100% are unlikely under normal PV operation. Therefore, PR values above 120% were treated as potential indicators of data reporting, metering, installed capacity, or system boundary issues rather than genuine overperformance.

These observations suggest that further investigation into operational and technical factors is needed to determine the specific causes of the performance gap.

4.1.3.Implications for Further Analysis

Based on the portfolio overview, representative sites are selected for in-depth case studies:

- One site in Belgium representing excellent performance
- One site in Netherlands and one site in Sweden - representing underperformance
- One site in the UK and one site in Thailand – representing critical underperformance

These case studies will be used to identify root causes of performance gaps and evaluate potential improvement measures in the following sections.

4.2. Case-Specific Root Cause Findings

As discussed and outlined in the Methodology section, the site-specific questionnaire was distributed to the 5 shortlisted sites (Belgium, Sweden, Netherlands, UK and Thailand) to collect detailed qualitative information. As explained before, this questionnaire aimed to capture technical, operational, contextual, and environmental factors that influence the overall solar PV performance that cannot be easily identified by the number itself. Accordingly, some positive responses were received from all 5 sites-specific representatives. In some cases, for instance sites located in the Netherlands and Belgium certain questions remained unanswered due to their limited technical knowledge or data availability.

In order to address these lack of information gaps, and ensure the completeness of root cause analysis, follow-up online interviews were planned with responsible representatives from all 5 sites. Considering this purpose, a set of site-specific questions was developed based on the questionnaire responses provided by respected sites. The additional questionnaire for these follow-up interviews is added into appendix 2 section: Interview

Questions. These questions were focused on clarifying key performance issues and identifying the underlying root causes of performance deviations.

By keeping this in mind, finally on average 11-12 targeted questions were prepared for each site. Also, these questions were shared with them in advance to help guide a more structured and well-informed discussion during the interviews. Based on the findings from interviews, the case-specific analysis indicates that the solar PV underperformance across the selected sites is mostly influenced by a combination of technical, operational, environmental, and contextual factors. This section will focus on the all root causes identified through questionnaire and interview responses across the five sites. Keeping this in mind, our study summarizes the site-specific root causes in the following table 2. Furthermore, referring to this summary, we have elaborated on each of these factors in detail.

Table 2：Key Root Cause Summary

Site	Technical	Operational	Environmental	Contractual / Ownership
Sweden	•Suboptimal tilt (~10°, constrained by roof load) •Inverter failures (fire damage, multiple units disconnected) •BESS not optimized	•No KPI-based performance tracking •Monitoring not fully automated (manual/monthly evaluation) •Cleaning not data-driven	•Snow accumulation (multi-day coverage, major financial impact) •Bird droppings	•Grid curtailment (14MW → 7MW PoC limit) •BESS participation requires PV curtailment (Dynamic limitation)
Netherlands	•No major hardware issue identified	•No PR tracking • No automated alerts •Maintenance/cleaning unclear and undocumented	•High temperature impact (summer efficiency drop)	•50% injection limit •Energy return fees discourage export •Grid capacity constraints

UK	•Tilt chosen for density (not performance) •Electrical and system design failure • Installation and construction quality issues • System downtime due to safety shutdown	•Limited monitoring (monthly only) •No KPI tracking •Reactive maintenance (no preventive strategy)	•Weather variability / modeling mismatch •Dust/soiling •Bird droppings	•No performance management process
Thailand	•Low tilt (<10° due to roof constraint)	•Cleaning fixed (quarterly, contract-based) •Monitoring exists but landlord-controlled •No SLA / KPI	•Dust/soiling	•Zero-export restriction (cannot sell electricity)
Belgium	•Tilt not optimized (roof constraint)	•Cleaning 2×/year (contractor-controlled) •No structured monitoring or alerts •No KPI tracking	•Dust and bird droppings	•Ownership split (limited control) •No clear SLA

4.2.1. Technical Perspective

Firstly, from a technical perspective, several design and system-related factors limitations were identified. One key root cause is related to suboptimal system design particularly in terms of tilt angle and panel's orientation. Many previous studies have shown that tilt angle and orientation significantly influence the overall photovoltaic system performance. Considering that one of the studies by Baranayi et al. (2025) explained that if panels are not properly oriented or tilted, they can also further contribute to lower energy output by about 3-10%. To quantify tilt-related performance losses, a comparative PVGIS simulation approach was applied. For each selected site, the installed PV capacity, actual site orientation (azimuth), and existing tilt angle configuration were used as baseline conditions. The annual PV generation under the existing tilt angle was then compared with the simulated annual generation obtained using the PVGIS-recommended optimal tilt angle while maintaining the same site orientation. This approach allowed the impact of tilt angle alone to be isolated without altering other system-design conditions.The annual tilt-related loss percentage was calculated as:

$$Tilt\ Loss(\%) = \frac{Optimal\ Generation - Simulated\ Generation}{Optimal\ Generation} \times 100\%$$

The analysis showed that tilt-related annual losses varied across sites depending on climatic conditions, roof design, and existing installation configurations. For example, the Thailand site, where the installed tilt angle was below 10°, showed estimated losses ranging between 1% and 3% compared with the PVGIS-recommended optimal tilt angle of 17°. Similar simulation procedures were applied to the Sweden, Belgium, and UK sites. The summarized results are presented in Table 3.

Table 3：Estimated Annual Loss % against solar panel's tilt angle

Sites Name	**Installed Capacity (MWp)**	**Tilt Angle at site**	**Optimal Tilt Angle based on PVGIS simulation**	**Azimuth**	**Optimal Annual Generation (MWh)**	**Simulated Generation (MWh)**	**Annual Loss (%)**
Thailand	0.28	< 10°	17°	South Facing	458	444-456	1-3%
Sweden	14	8°	0°	East-West	13,201	12,860	0.5%
UK	0.2	10°–20°	0°	East-West	185	184-182	1-2%
Belgium	1.52	20°–30°	38°	South & Southwest	1,765	1,709-1,754	1-3%

It should be noted that the PVGIS simulation values presented in the tilt-angle analysis differ slightly from the theoretical generation values used in the broader performance and economic assessment sections. For the tilt analysis, site-specific orientation (azimuth) conditions were maintained in order to isolate the impact of tilt angle alone. In contrast, the theoretical generation values applied in the PR and business-case calculations were based on optimized PVGIS simulation settings using both optimal tilt and orientation assumptions. In addition, slight differences may also arise from the use of different PVGIS simulation configurations and default parameters across analysis stages.

Based on quantitative data, it is clear that a suboptimal tilt angle can reduce the solar PV energy yield.

Unlike tilt angles, orientation-related performance impacts were not quantified separately in this study, as rooftop PV orientation is generally fixed by building layout and was therefore considered a non-adjustable boundary condition rather than a practically recoverable performance factor.

Secondly, equipment-related breakdown was identified as one of the main factors causing this poor PV system performance. For example, in Sweden, some inverters were not operating due to malfunctions. As mentioned during the interview, inverter breakdown has reduced PV production during peak price periods. So, the primary cause of inverter breakdown was identified as a fire incident which further led to the disconnections of six inverters. Also, in analysis of utility-scale PV systems, it clears that equipment (inverter) downtime is typically responsible for approximately 2%-3% of total energy losses (Veiga,2022). Due to the lack of data availability on inverter downtime, it is difficult to estimate the exact annual loss caused by system downtime. Thus, based on the literature reviews, the annual loss due to inverter downtime can be estimated to lie between 2%-3%.

According to the inspection report provided by the UK site, several key technical problems have been identified. As it highlighted problems such as non-conforming AC cables, lack of protection for DC connections, incorrect fuse sizing, and the use of non-durable cable materials. These above observations show clear shortcomings in both system design and installation defects. As a result, the PV system was taken out of operation due to safety precautions, and that led to significant downtime and loss of electricity generation. Hence, the performance gap at this site is mainly due to system unavailability instead of just efficiency-related factors. Now, since there is no operational data related to the exact duration of system downtime at this UK site. Therefore, a scenario analysis method is used in order to estimate the potential effect of such incidents. In this case, instead of relying on fixed assumptions, three scenarios for possible amounts of downtime are developed. If it is short-term downtime (<1 month) due to minor faults or quick repairs, then annual loss corresponding to 5%-10%. Similarly, medium-term downtime (1 to 3 months) is linked to more complicated technical issues that require either components or system replacements which contribute to 10%-25% annual loss. And from a long-term perspective (3 - 6months) which corresponds to 25%-30% annual loss, as it could be because of major technical corrections or safety compliance measures. Therefore, these findings clearly suggest that having installation errors and design shortcomings at the initial stage can also directly limit system efficiency. So, it was challenging to quantify the breakdown loss due to the downtime issue for this site because of the absence of data regarding annual energy production. Furthermore, system constraints such as the non-optimized battery energy storage system (BESS) in Sweden also limit the effective utilization of generated solar energy, which reduces the overall efficiency.

4.2.2. Environmental Perspectives

Environmental factors include snow accumulation, soiling (e.g., dust and bird droppings), and temperature effects. However, due to a lack of field data, the impact of these factors is difficult to quantify precisely. Therefore, literature benchmarks are used to provide a reference range for potential losses.

At the Sweden site, snow accumulation is expected to contribute to performance loss during winter periods. The reduction in power generation from snow cover by photovoltaic (PV) systems has been quantified in numerous studies, varied significantly depending on climate conditions and system configuration. A large-scale analysis of 263 PV systems in northern Sweden found that annual snow losses typically range between 1.5% and 6.2%, with extreme cases reaching up to 20% (van Noord et al., 2021). In addition, the Sweden site operates with a relatively low tilt angle of approximately 8°, which may increase snow retention on the panel surface and delay natural snow shedding. However, during our on-site visit, we also learned that the solar panels will be covered by snow for a relatively short period of time in 2025, only 1 to 3 days. Therefore, we predict that the average annual impact of snow cover on the Swedish site will be approximately 1-2%. In spite of that, snow-related forecast uncertainty was identified as a more significant operational challenge. According to site feedback, inaccurate predictions of snow-related PV production reductions created imbalance costs within the energy trading process and affected EMS scheduling accuracy.

For the Dutch site, we analyzed the impact of high summer temperatures using normalized power generation (power generation/irradiance) under high irradiance (>700 W/m²). The results showed no significant correlation between temperature and performance. This suggests that temperature-related efficiency losses are relatively small and may be masked by stronger operational constraints. This finding highlights the limitations of using actual operating data, as we cannot isolate the temperature factor due to constraints such as electrical resistance. Numerous studies have shown that rising temperatures significantly reduce the performance of crystalline silicon photovoltaic modules. Using 25°C as a baseline, the efficiency of crystalline silicon solar cells decreases by approximately 0.4–0.5% for every 1°C increase in temperature, while the temperature coefficient for polycrystalline silicon modules is even greater, at approximately 0.35–0.8%/°C (Alaas, 2024). To further quantify the impact of temperature, a simplified estimation was conducted using hourly temperature data. The questionnaire revealed that the person in charge was unaware of the PV solar module type at the Dutch site; therefore, a temperature coefficient range of 0.35–0.8% per °C above 25°C was applied. The hourly losses were weighted by actual power generation to reflect the relative contribution of each period to total energy production. The estimated annual temperature-related loss ranges between approximately 0.1% and 0.3%, indicating that temperature has a negligible impact on overall performance at this site compared to other factors.

Based on questionnaire responses and interviews, cleaning practices vary across the five sites and are generally not optimized. Sweden follows a trigger-based approach, while the Netherlands lack clear or structured cleaning strategies. The UK, Thailand and Belgium apply fixed schedules (e.g., quarterly or twice per year), but these are not linked to performance monitoring. Due to the absence of before/after cleaning performance data, site-specific quantification was not possible. Therefore, a literature-based estimate was applied. According to IEA PVPS (2018), soiling losses typically range between 3–5% under normal conditions, which is used as a general benchmark. Another study indicated that cleaning every six months results in an average loss of 9.1%, while cleaning every two months results in an average loss of 4.4% (Zuñiga-Cortes et al., 2023). Therefore, we will also estimate the annual loss based on the different cleaning frequencies for each site. However, for the Thailand site, interview feedback suggests that annual soiling losses are relatively low (approximately 2%), which is attributed to the clean environment and frequent rainfall. It should also be noted that the observed impact of soiling may be partially masked by system-level constraints, such as the zero-export condition, which limits the utilization of generated electricity. As a result, the actual effect of soiling may be underestimated in the operational data. The table below shows our estimates of the cleaning frequency and annual soiling loss for each site.

Table 4：Cleaning frequency vs annual soiling loss

Site	**Current cleaning frequency**	**Suggested annual soiling loss**
Sweden	assumed 2 times/year	5-10%
Netherlands	assumed 2 times/year	5-10%
Thailand	4 times/year	2%
Belgium	2 times/year	5-10%

UK	4 times/year	3-5%

In the UK case, part of the performance gap may be influenced by the use of GIS-based irradiation data, which represents average values over large spatial grids and may not accurately capture local rooftop conditions. As a result, its impact is difficult to quantify and is treated as an indirect source of uncertainty rather than a direct performance loss.

4.2.3. Operational Perspective

Operational factors are also equally important in explaining this performance loss. A common root cause across multiple sites was the lack of structured, data driven maintenance practices. Based on interviews with Thailand and Belgium, the cleaning activities were infrequent (E.g. twice a year or quarterly) and also usually not supported by performance data (before vs after cleaning). Add on to this, for the Sweden site, cleaning was performed on a trigger-based basis without any systematic monitoring. So, these can lead to increased soiling losses (dust accumulation) over time. In support of this, particular studies by IEA (2022) and NREL (2022) have clearly indicated that the losses from soiling in PV systems typically fall in the range of 3-5%, especially under normal operating conditions. Also, a scientific study by Brahma (2023) clearly mentioned that the soiling losses can be increased up to 8%-13% depending on the cleaning frequency and environmental conditions.

Additionally, absence of clearly defined maintenance schedules and preventing strategies, service level agreements (SLA), and optimization practices can contribute to overall PV system performance especially in the Netherlands and UK. Furthermore, one of the important causes behind the solar PV systems' underperformance is the lack of real-time monitoring and performance tracking. For instance, in the Netherlands and Belgium, there were no proper monitoring systems or alerts system in place, contributing to undetected solar PV system underperformance and system faults in a timely manner. As per the interview insight from the UK site, delayed detection was linked to the lack of monitoring systems which also lead to prolonged system downtime and reduce the overall actual energy output. Moreover, most sites do not have well-defined key performance indicators (KPIs) and timely performance reviews which limit the ability of site operators to actively monitor and improve system performance. As a result of this, it leads to inefficiencies and underperformance.

4.2.4. Contractual & Ownership Perspective

Contractual and ownership-related factors are identified as the primary drivers of performance loss across multiple sites, mainly due to grid constraints and system-level operational objectives.

This paper employs a data-driven model based on actual photovoltaic (PV) power generation data to estimate curtailment losses. PV power generation curves are scaled to represent systems of different sizes and locations, and curtailment is assessed using a constraint function applied hourly. Curtailed energy is defined as the difference between total PV power generation and the allowable output under system constraints.

At the Swedish site, curtailment is primarily driven by point-of-connection (PoC) constraints limiting the combined export capacity of the PV and BESS system. Although the site has 14 MWp of installed PV capacity and 11 MW inverter capacity, the combined PV-BESS operation is subject to an export limitation of approximately 7 MW behind the PoC in order to avoid exceeding grid connection limits. In addition, the BESS is operated for ancillary services and energy trading, which can further reduce the available export capacity for PV generation under certain operating conditions. As a result, PV curtailment occurs dynamically depending on irradiance conditions, BESS dispatch, and market participation, rather than as a constant fixed limitation throughout the year. Based on the applied curtailment model, the annual curtailment level is estimated at approximately 35% of theoretical PV generation. Figure 4 illustrates the estimated annual PV curtailment at the Sweden site, where TPO (Theoretical Power Output threshold) represents the maximum allowable PV output level used in the curtailment model before excess generation is assumed to be curtailed due to system or grid limitations.

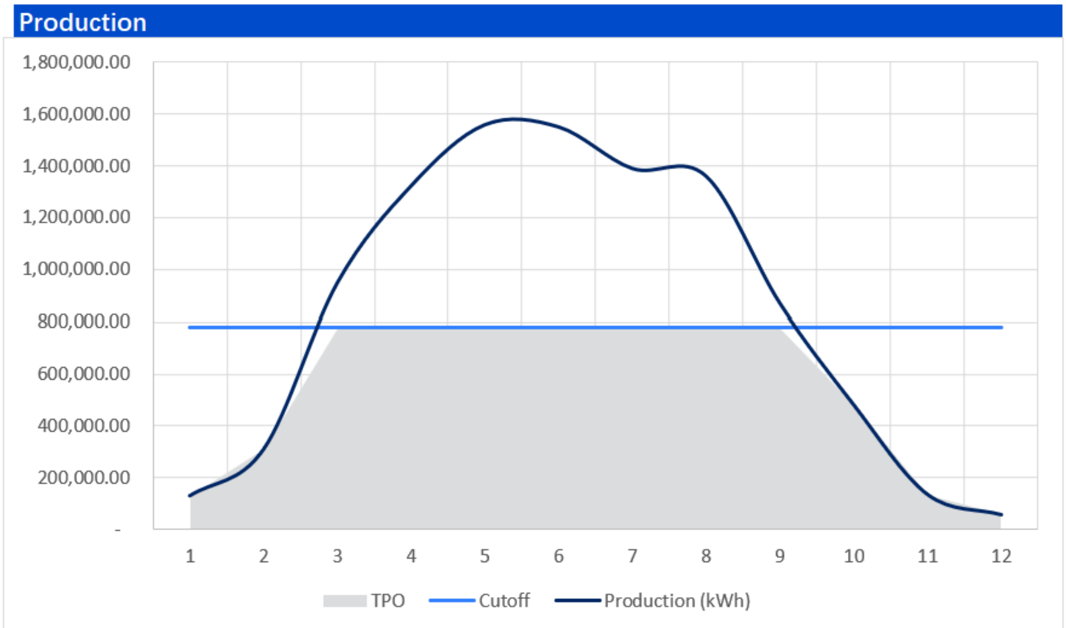

Figure 4： Estimated Annual PV Curtailment Model for the Sweden Site

At the Thailand site, curtailment is caused by a zero-output policy, which limits PV power generation to on-site demand, preventing excess energy from being fed into the grid. According to stakeholder interviews, instantaneous curtailment of up to 50% can occur when PV power generation exceeds local electricity consumption. However, due to the time-varying nature of PV power generation, this situation only occurs during peak power generation periods. In the absence of high-resolution data, the annual curtailment rate is estimated to be between 35% and 50%, with 35% being a model-based estimate and 50% represents a short-term peak curtailment condition rather than a continuous annual average. Figure 5 illustrates the estimated annual PV curtailment at the Thailand site.

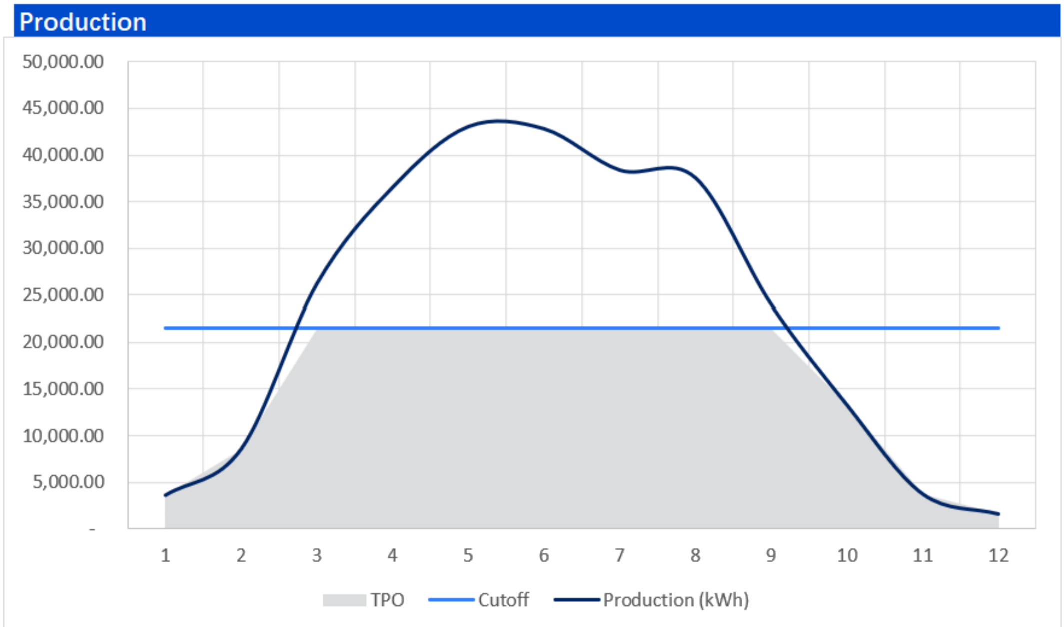

Figure 5： Estimated Annual PV Curtailment Model for the Thailand Site

In the Netherlands, a 50% injection limit and energy return fees suppress the export of all generated electricity, thus limiting system utilization. To quantify the impact of curtailment on PV performance at the Netherlands site, an empirical, data-driven approach was applied based on hourly generation profiles.

First, days affected by curtailment were identified using the hourly generation data. These days are characterized by abnormal drops or plateaus in generation during high irradiation periods, deviating from the expected smooth bell-shaped production curve. In contrast, non-curtailed days exhibit a typical PV generation pattern with a gradual increase in the morning, a stable peak around midday, and a symmetric decline in the afternoon (as illustrated in Figure 6 and Figure 7).

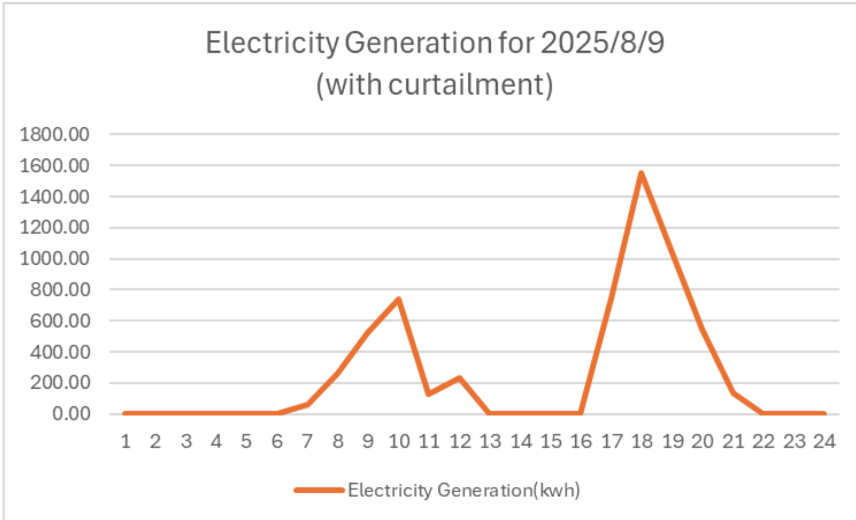

Figure 6：Example of Daily PV Generation Profile under Curtailment Conditions

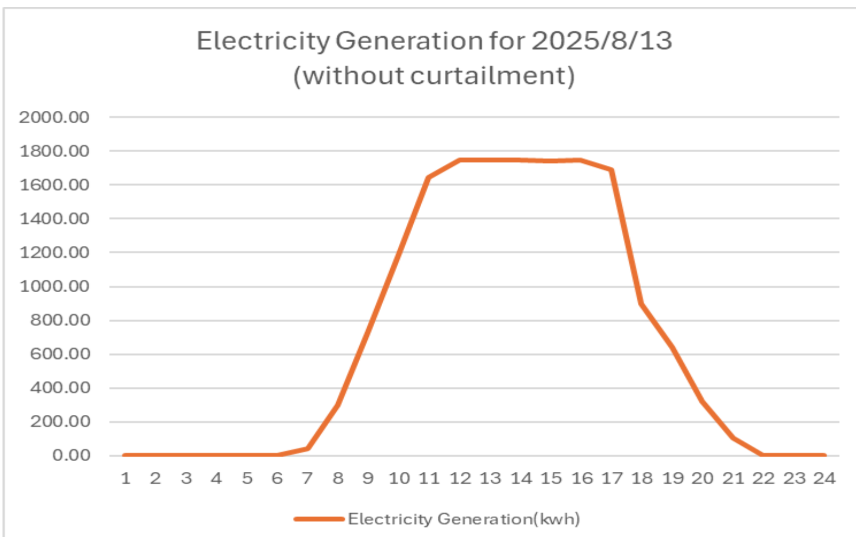

Figure 7：Example of Daily PV Generation Profile without Curtailment Conditions

To estimate the theoretical (non-curtailed) generation, each curtailed day was matched with the closest non-curtailed day in terms of seasonal proximity and irradiation conditions. The hourly production profile of the selected reference day was then used as a proxy for the expected generation without curtailment. This approach assumes that, under similar weather conditions, the PV system would follow a comparable generation pattern in the absence of operational constraints.

Figure 8 presents representative comparisons between curtailed days and their corresponding reference days. The dashed line indicates the expected generation (non-curtailed), while the solid line represents the actual generation under curtailment.

Significant deviations are observed during peak production hours, where generation is artificially reduced despite favorable solar conditions, confirming the presence of curtailment.

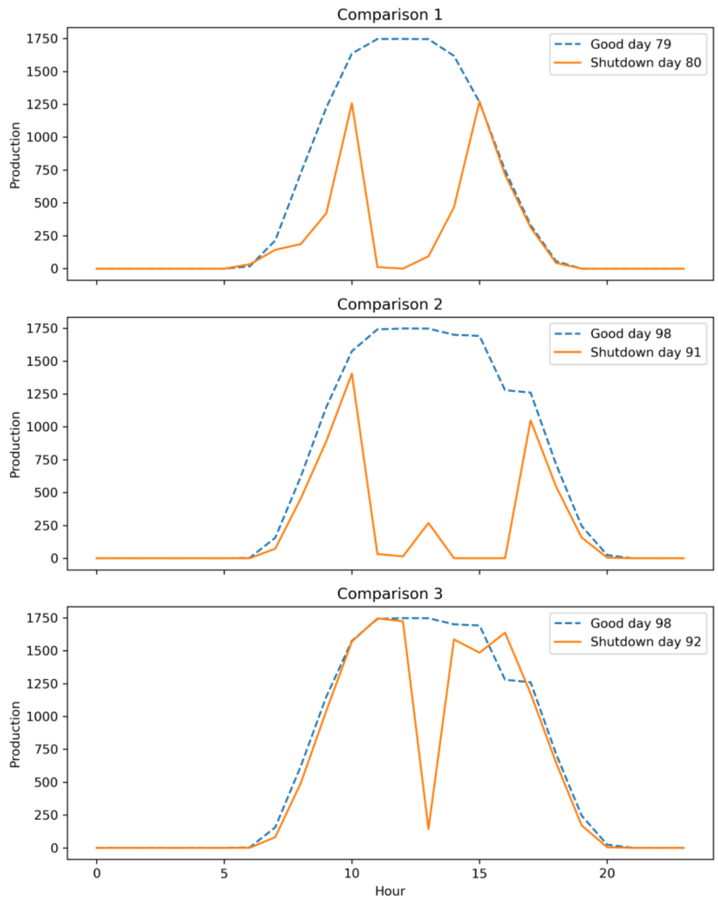

Figure 8：Curve-Fitting Method for Estimating Daily PV Curtailment Losses

The energy loss due to curtailment is calculated as the difference between the expected and actual generation, aggregated across all affected hours and days.

Based on this methodology, the total curtailed energy in 2025 is estimated to be approximately 24% of the theoretical annual generation. This indicates a substantial performance loss primarily driven by grid export constraints rather than environmental or technical inefficiency.

Overall, these findings suggest that curtailment is not merely a technical limitation, but is primarily influenced by grid constraints, regulatory policies, and market conditions, making it one of the main causes of system performance loss.

In the Belgium site, the performance gap appears to be influenced by ownership and contractual structure. The split ownership model limits direct operational control, resulting in unclear responsibility for system performance. In addition, the absence of a formal Service Level Agreement (SLA) means that no performance KPIs or penalties are defined, reducing accountability for maintenance quality and response time. At the UK site, there is no structured performance management process in place, meaning that system performance is not systematically monitored, evaluated, or optimized.

4.2.5. Performance Loss Breakdown by Root Cause

To summarize the relative importance of different factors, a breakdown of performance loss by root cause is provided for each site. Where quantitative estimates are available, annual loss values are reported. For factors where data is insufficient, the impact is acknowledged but not quantified. Table 5 shows the annual losses of different root causes at each site

Table 5：Annual Loss Breakdown

Site	**Annual Loss**	**Root Cause**	**Estimated Annual Loss**	**Basis**
Sweden	46%	Curtailment (PoC + BESS interaction)	35%	Interview + Simulation model based
		Soiling	5%-10%	Literature
		Snow	1%-2%	Literature + Interview
		Tilt & Design	0.5%	PVGIS Simulation
		Inverter issues	2-3%	Literature
Netherlands	32%	Curtailment (50% export limit)	24%	Interview + Python
		Soiling & Bird Dropping	5%-10%	Literature

		Temperature	0.1–0.3%	Literature
		Monitoring / Operational	Not quantified	
UK	91%	Maintenance / Operational issues	Not quantified	
		Tilt & Design	1-2%	PVGIS Simulation
		Electrical and system design failure	Not quantified	
		Installation and construction quality issues	Not quantified	
		System downtime due to safety shutdown	5%-50%	Scenario Assumptions
		Weather variability / modeling mismatch	Not quantified	
		Soiling & Bird Dropping	3–5%	Literature
Thailand	59%	Export constraint (zero export)	35% -50%	Interview + Simulation model based
		Soiling & Dust	2%	Literature
		Tilt & Design	1-3%	PVGIS Simulation
Belgium	8%	Soiling & Bird Dropping	5%-10%	Literature
		Tilt & Design	1-3%	PVGIS Simulation
		Operational / Monitoring	Not quantified	

5. BUSINESS CASE & DECISION ANALYSIS

This section converts the identified performance gaps into the real-world practical business improvements opportunities. Also, it examines the economic and environmental impacts of proposed measures together with a scalable decision-support framework.

5.1. Improvement Measures per Root Cause

5.1.1. Technical Perspective

As discussed in section 4.2, technical issues such as inverter breakdown were identified as an important contributor to solar PV systems' performance losses. As noted during the site-specific interviews, especially at the Sweden site where multiple inverters stayed non-functional for extended periods, which had an immediate impact on the total energy produced. Also, from the analysis of utility-scale PV systems, it clears that equipment (inverter) downtime is typically responsible for approximately 2%-3% of total energy losses (Veiga,2022). Considering this is an improvement opportunity, inverter reliability represents a feasible short-term improvement. This can be positively achieved by introducing clearly defined service level agreements (SLA) with guaranteed response times. Also, it is important to ensure the availability of critical spare parts, and conduct regular preventive maintenance, especially Monthly or Quarterly. On the other hand, the long-term perspective, as suggested by Kull et al.(2025), a transition toward the predictive maintenance approach through real-time monitoring and data analytics is used to detect early signs of inverter breakdown issues and will help to prevent unexpected breakdowns. These inverter-related issues are not the common cause of underperformance across all sites, but it is important to address them so it will help to reduce unwanted downtime and improve overall system performance.

Another key improvement area as per technical perspective is tilt angle of solar PV systems. It is one of the most important factors that causes the underperformance of PV systems, as it directly affects the amount of solar irradiance received by the solar panel's surface. As mentioned earlier, if panels are not properly oriented or tilted, they can reduce energy output by about 3-10 % (Baranayi,2025). Keeping this in mind, tilt angle optimization can be implemented through both short-term and long-term perspective strategies. In this context, a research study carried out by Sharma et al. (2020) clearly suggests that, regardless of whether solar panels are fixed or adjustable, but still the optimal tilt angle is generally close to the latitude of the installation site. Another study has indicated that by rotating the tilt angle of the solar panels occasionally (for example, monthly or seasonally) will increase their overall performance by 6.9% as compared to fixed installations (Peter, 2025). In this context, long term solutions like utilization of advanced solutions such as adjustable mounting or solar trackers that will help align these solar panels with the orientation of the sun. As a result of this, it can help to produce more energy throughout the year. The tilt angle optimization may not always be feasible for all rooftop systems due to structural constraints; it remains a highly effective and low-cost technical improvement that can boost overall PV system's generation.

5.1.2.Operational Perspective

Operational inefficiencies are related to the limited continuous system monitoring, and the absence of structure performance tracking were observed across multiple sites, especially in the Netherlands and the UK. Basically, for these sites, overall solar PV system performance is mainly reviewed on a periodic basis rather than monitoring it continuously. As a result, it limits the ability to detect deviations in real time. Also, having a reactive approach can lead to ongoing inefficiencies, as performance deviation may not be easily noticed. To do effective photovoltaic (PV) system operation requires the proper use of key performance indicators (KPIs) such as performance ratio (PR), tracking of expected vs actual energy production supported by automated monitoring systems. According to International Energy Agency PVPS guidelines (2022), continuous monitoring with automated alerts can help to quickly detect performance deviations and enable faster decision-making. Based on this, a feasible short-term improvement is the quick introduction of a structured KPIs framework along with threshold-based alerts in order to identify performance deviations promptly, But, for long-term perspective, this could be extended to more use of data-driven monitoring systems that can integrate real-time analytics.

Adding to monitoring limitations, another improvement area is the absence of structured maintenance strategies that contribute to performance variability. This point is more relevant to sites where maintenance is mainly schedule-based or follows a reactive approach (for example, sites such as Netherland and the UK). This approach does not consider the actual condition of system or real-time performance tracking that often leads to delayed detection or unnecessary maintenance actions. Recent studies show that PV systems perform efficiently when maintenance moves from reactive maintenance to predictive maintenance strategies. As per International Energy Agency PVPS guidelines, in order to run effective PV system operations, require continuous monitoring, fault detection, and clearly defined maintenance procedures linked to system performance (IEA PVPS, 2022). Also, some reliability studies also proved that data-driven maintenance supported by monitoring systems can reduce downtime and improve system performance reliability (Köntges, 2017). In the short-term perspective, improvements include well-defining clear maintenance procedures, setting response times, and linking maintenance strategies to performance deviations. In the long-term perspective, these practices can evolve into frameworks supported by forecasting and advanced intelligent monitoring. For example, in the Sweden site, implementation of such a system would allow them earlier identification of issues such as inverter inefficiencies or performance drops. As a result, it will help to reduce system downtime and improve operational efficiency. These improvements may require gradual implementation; they provide a practical pathway toward more reliable and efficient solar PV systems operations.

5.1.3. Environmental Perspectives

As mentioned in Section 4.2, environmental factors such as soiling, bird droppings, and snow accumulation represent a significant source of performance loss of photovoltaic (PV) systems across all selected sites. Basically, these environmental factors restrict the amount of solar radiation reaching the solar panel surface and leading to lower generation output. According to Ilse et al. (2019), soiling can reduce global solar power production by approximately 3%-4% with at least 3-5 billion € annual revenue losses. Furthermore, this impact might go up to 5%-10% due to the infrequent cleaning, resulting in larger economic loss. Moreover, the study also highlighted that soiling is not uniform and may involve various kinds of pollutants like dust, pollen, and bird droppings that prevent sunlight from reaching to the surface of PV systems. These factors vary by geographical location and conditions, hence environmental losses are difficult to quantify accurately, but they still have a noticeable impact on system performance.

From a practical point of view, improving cleaning strategies is one of the most effective short-term measures to reduce these losses. Instead of cleaning panels according to fixed cleaning schedules, such cleaning should be performed depending on actual performance data and soiling levels. Also, some papers have even proven that optimizing cleaning schedules can help to significantly improve performance of PV systems. For example, more frequent cleaning of PV panels can increase overall output generation by approximately by 4.73%-5%, as compared to less frequent cleaning (Abdallah,2022). With such data-driven cleaning supports us to ensure a good balance between cleaning costs as well energy gain making sure that cleaning is only done when it is actually needed (Ilse,2019). Apart from that, technology such as automatic cleaning methods and anti-soiling coatings can also help to reduce the impact of soiling. Looking at the big picture, site-specific solutions include designing the solar plants better, minimizing dust and introducing advanced automated cleaning robots that can further improve cleaning performance and reduce costs.

On the other hand, in colder regions, environmental losses are coming through snow accumulation, moisture, and changing weather conditions, which again block sunlight and reduce the overall energy production. Unlike dust accumulation, snow-related losses are more seasonal, but they still have a high impact on system performance if not managed properly. In addition, Ilse et al. (2019) indicate that sometimes moisture and dew formation lead to buildup of dust through capillary action on panels, thereby making soiling worse over time. In order to solve these challenges, short-term measures would be the need for effective monitoring of environmental conditions such as snowfall, dust, and weather changes. Basically, it helps operators to take rapid actions like cleaning or adjusting operations. Moreover, removal agents may be used in the short run to prevent snow accumulation on the surface of solar PV panels. Such an approach could be beneficial for sites which are located in colder regions like Sweden and Netherland. These snow removal agents can support the faster snow melting process and allow panels to receive sunlight after snowfall. Also, a recent study mentioned that the use of snow removal agents can potentially increase solar PV system's generation (Ruan 2024). From a long-term perspective, setting up higher tilt for PV panels is beneficial, as such an option would ensure snow will fall off faster and prevent snow accumulation (Marion, 2013). It is also helpful, if advanced monitoring systems are connected with weather forecasting, to further support operational decisions making by identifying snow-related losses in real time. In order to improve snow-related forecast accuracy, the energy management system (EMS) and trading system should use local weather information such as snowfall duration, temperature, irradiance, and snow cover. This will make more accurate forecasting of how much PV power generation is expected during snow events. Also, it will support smarter energy management decisions and helps to reduce imbalance and curtailment costs. In high impact regions, more advanced solutions such as solar panels heating or surface treatments such as hydrophobic coating can reduce snow adhesion and improve natural cleaning effects. However, these improvements always require careful economic evaluation due to their additional cost.

5.1.4. Contractual & Ownership Perspective

Contractual and ownership factors such as grid limitations and market-based operations are seen as the main contributors in performance loss of solar photovoltaic (PV) systems. As previously discussed in section 4.2, these constraints occur when grid capacity is limited and also if there are restrictions concerning export capacity and requirements for curtailment due to the generation surplus. Curtailment is an effective means of controlling and maintaining stability in the power grid in case of high PV penetration, but it could possibly result in huge losses of energy and monetary (Dellaly, 2023). On the other hand, the current findings on hosting capacity show that the grid limits may also impose an upper limit to the amount of PV energy that can safely be supplied to the grid, despite the possibility of additional generation (Aydin,2025). Based on these findings, it is fair to say that curtailment is not only a technical issue but rather a matter of the overall system design and limitation of the system itself.

To address these issues, the following steps may be taken to improve upon the problem of curtailment. One of the noticeable approaches is improving coordination between PV systems, battery energy storage systems (BESS), and grid operations. According to research, it is shown that integrating the generation of photovoltaic PV systems with battery energy storage systems (BESS) makes it possible to store surplus electricity instead of curtailing it and allowing it to be stored and used later (Wang, 2024). Hence, it facilitates reducing curtailing and increasing the value of the entire system. There are other advanced control strategies such as data-driven or reinforcement learning schemes that can enhance coordination through real-time changes in energy consumptions. This can give opportunities to reduce curtailment and improve economic performance. In the short-term perspective, practical approaches include optimizing battery charging during curtailment and aligning energy export to the grid during high-price periods.

Secondly, in the long-term perspective, solutions such as smart energy management systems including forecasting-based planning as well as dispatch, and digital twin models can support better scheduling. The use of Digital twin models can support the simulation of energy management systems (EMS) under different operating conditions which support better monitoring, prediction, and optimization of performance (Dellaly, 2023). Furthermore, the deep learning approach to solar forecasting will improve the prediction of energy productions, which will again improve synchronization between generation, energy storage, and export to the grid (Lalbiakhlua,2025). Also, it will aid in systematic scheduling of battery storage, thus allowing for easy storage and used later when demand or prices are higher.

Overall, as a result of these integrated approaches, improve grid utilization, reduce reliance on fixed limits, and further improve economic performance. For example, at the Netherlands site, such improved coordination between PV generation and storage could help proper utilization of excess energy locally instead of curtailing it. For Sweden, using smarter control strategies could help to reduce unnecessary curtailment caused by fixed operational limits. Hence, overall these improvements can help transform curtailment from an unavoidable loss into a more systematically manageable operation.

5.2. Economic Evaluation

5.2.1. Electricity Price Assumptions

To convert energy values into economic impacts, electricity price assumptions were defined for both self-consumed and exported electricity. These assumptions are based on publicly available market data and are aligned with typical industrial electricity price ranges in the respective regions.

For self-consumed electricity, the value is represented by the avoided cost of purchasing electricity from the grid. For exported electricity, the value corresponds to the market price or feed-in compensation received for electricity supplied to the grid.

Based on available literature and recent European energy market trends, the following assumptions are applied:

Table 6：Purchase Price Assumptions

Site	Purchase Price (€/kWh)	Export Price (€/kWh)
Sweden	0.059 (Eurostat, 2025)	0.0397 (Nord Pool, 2026)
Netherlands	0.101 (Eurostat, 2025)	0.075 (FfE, 2025)
Thailand	0.1 (interview)	No export allowed
Belgium	0.1025 (Eurostat, 2025)	0.075 (FfE, 2025)
UK	0.3(Gov.UK, 2025)	0.042(ELEXON, 2022)

5.2.2.Electricity Utilization Assumptions

To assess the financial impact of photovoltaic power generation performance, it is necessary to determine the allocation ratio of generated electricity between self-consumption and export. These ratios are derived based on annual demand and generation comparisons, as well as qualitative analysis through interviews and questionnaires. The final assumptions are summarized in Table 7 and are consistently used in financial analysis to distinguish between electricity priced at the avoidance purchase price (self-consumption) and electricity priced at the export market price.

Table 7：Self-consumption % vs Export %

Site	Annual Demand (MWh)	Expected PV Generation (MWh)	Actual PV Generation (MWh)	Demand vs PV	Estimated Self-consumption	Estimated Export
Sweden	6,500	14,157	7,624	PV > Demand	10%	90%
Netherlands	2,786	4,029	2,504	Demand ≈ PV	67%	33%
Thailand	450	391	158	Demand > PV	100%	0%
Belgium	1,300	1,641	1,507	PV > Demand	39%	61%
UK	220	200	17	Demand > PV	100%	0%

It should be noted that the estimated self-consumption rate does not represent the theoretical maximum field utilization potential based solely on a comparison of annual demand and power generation. Instead, they reflect the estimated operational self-consumption under current site-specific operating conditions, considering factors such as temporal mismatch between PV generation and warehouse demand, export-oriented energy management strategies, BESS operation, and participation in ancillary service and electricity trading markets.

5.2.3. Monetization of Energy Loss by Site and Root Cause

Following the electricity utilization assumptions, the next step is to quantify the economic value of energy losses across different sites and root causes.

This step translates the estimated performance losses (in %) into monetary terms by combining expected PV generation, loss ranges, and location-specific electricity price assumptions. For each site, the value of lost energy is calculated by allocating the lost generation between self-consumption and export, based on the utilization shares defined in Section 5.2.2.

Electricity that would have been consumed on-site is valued using the avoided purchase price, while electricity that would have been exported is valued using the corresponding export price. This distinction ensures that the economic impact reflects real operational conditions and market structures.

For each root cause, a range of minimum and maximum loss values is provided where uncertainty exists (e.g., soiling, snow, and downtime), allowing a more realistic representation of potential economic impact.

Minor loss contributors such as tilt deviation and temperature effects are included for completeness but are considered to have limited economic significance.

The results are summarized in Table 8.

Table 8：Energy Loss by Site and Root Cause

Site	Root Cause	Expected PV Generation (MWh)	Minimum Loss %	Maximum Loss %	Purchase Price (€/kWh)	Export Price (€/kWh)	Self-consumption	Export	Minimum Loss of Cost (€)	Maximum Loss of Cost (€)
Sweden	Curtailment	14,157	35%	35%	0.059	0.0397	10%	90%	206275	206275
	Snow (physical loss)	14,157	1%	2%	0.059	0.0397	10%	90%	5893	11787
	Snow (forecast error)	—	—	—	0.059	0.0397	10%	90%	—	—

	Soiling	14,157	5%	10%	0.059	0.0397	10%	90%	29467	58935
	Inverter issues	14,157	2%	3%	0.059	0.0397	10%	90%	11787	17680
	Tilt	14,157	0.50%	0.50%	0.059	0.0397	10%	90%	2947	2947
Netherlands	Curtailment	4,029	24%	24%	0.101	0.075	67%	33%	89373	89373
	Soiling	4,029	5%	10%	0.101	0.075	67%	33%	18619	37239
	Temperature	4,029	0.10%	0.30%	0.101	0.075	67%	33%	372	1117
Thailand	Zero-export curtailment	391	35%	50%	0.1		100%	0%	13685	19550
	Soiling	391	2%	2%	0.1		100%	0%	782	782
	Tilt	391	1%	3%	0.1		100%	0%	391	1173
Belgium	Soiling	1,641	5%	10%	0.1025	0.075	39%	61%	7034	14067
	Tilt	1,641	1%	3%	0.1025	0.075	39%	61%	1407	4220
UK	Technical failure → downtime	200	5%	50%	0.3	0.042	100%	0%	3000	30000
	Soiling	200	3%	5%	0.3	0.042	100%	0%	1800	3000
	Tilt	200	1%	2%	0.3	0.042	100%	0%	600	1200

Overall, the table shows that the largest economic losses are mainly associated with system-level constraints, particularly curtailment at the Sweden and Netherlands sites and the zero-export condition at the Thailand site. In comparison, environmental and design-related factors such as soiling, snow, temperature, and tilt deviation generally show smaller economic impacts, although they remain relevant for operational improvement. The UK site also shows a potentially significant economic loss related to technical downtime and system availability. However, due to the absence of detailed downtime records, this value should be interpreted as a scenario-based estimate rather than an exact measurement. Therefore, Table 8 should be understood as an indicative comparison of the relative economic importance of different root causes, providing the basis for the subsequent recoverable energy and feasibility assessment.

5.2.4. Recoverability Assumptions

Based on the technical feasibility and operational practicality of the improvements discussed in Section 5.1, the recoverability of the identified performance losses was assessed. Recoverability does not assume the complete elimination of all losses, but rather reflects the proportion of losses that can be realistically reduced under actual conditions.

Losses associated with soiling, inverter issues, and suboptimal tilt are considered largely recoverable. Existing literature demonstrates that performance losses due to soiling can be significantly reduced through optimized cleaning strategies and monitoring-based maintenance by increasing around 5% of annual generation. Similarly, inverter-related losses and system inefficiencies can be mitigated by improving maintenance practices, service level agreements (SLAs), and predictive maintenance methods.

Losses caused by snow accumulation are subject to climatic conditions and have limited recoverability. Literature indicates that the use of snow removal agents and improved operating strategies can increase annual photovoltaic power generation by 0.1%-2.3%. Compared to annual snow impact loss in Sweden, which is 1%-2%, the recoverable proportion is set at 50%, representing a limited but measurable potential for improvement. This is because snow removal agents cannot guarantee the complete elimination of snow impact, and their effectiveness is highly dependent on weather, snowfall, temperature, and roof accessibility. Due to the lack of location-specific comparative data on predicted and actual power generation, snow accumulation-related prediction errors cannot be quantified and are therefore not included in the quantitative analysis.

In the UK, performance losses are primarily caused by system downtime due to critical technical failures. As mentioned earlier, we defined different downtime scenarios to reflect varying degrees of system unavailability. In terms of recoverability, these losses are considered largely recoverable because they are not inherent efficiency losses but rather caused by temporary system downtime. Once the identified technical issues are resolved and the system is back online, performance is expected to return to normal levels. Therefore, recoverability is considered directly related to downtime duration, with overall recoverability ranging from 5% to 50% of annual losses, depending on the severity of the scenario. This reflects the fact that downtime-related losses can be significantly reduced through technical remediation, but the exact recoverable percentage remains uncertain due to limited operational data.

Losses associated with curtailment were assessed based on site-specific grid constraints, operating conditions, and future improvement potential. In Sweden, curtailment has historically been driven by grid constraints and operational limitations associated with the point of connection (PoC). However, recent data shows that the site is now operating at near full capacity. This suggests that curtailment is largely a temporary constraint, thus assuming a recoverability of 80%–90%. In the Netherlands, curtailment is structurally linked to a fixed 50% capacity export restriction. Because this restriction is enforced by grid regulations, it cannot be fully recovered without additional system modifications such as battery storage systems or energy management systems (EMS). Based on literature on storage-based curtailment mitigation measures, a recoverability range of 40%–60% is assumed. In Thailand, curtailment is primarily driven by a zero-export policy, meaning excess generation cannot be integrated into the grid. However, its recoverability remains high due to factors such as increased on-site electricity demand, load shifting, and system optimization. Given that this constraint is demand-driven, we assume that the recyclability ranges from 40% to 60% as well.

Table 9 lists the assumptions for recoverability for different root causes at each site.

Table 9：Recoverability Assumptions

Site	**Root Cause**	**Recoverability**
Sweden	Curtailment	80–90%
Sweden	Snow(physical loss)	50%
Sweden	Soiling	50%-100%
Sweden	Inverter	100%

Sweden	Tilt	100%
Netherlands	Curtailment	40–60%
Netherlands	Soiling	50%-100%
Netherlands	Temperature	Negligible
Thailand	Curtailment	40–60%
Thailand	Soiling	100%
Thailand	Tilt	100%
Belgium	Soiling	50%-100%
Belgium	Tilt	100%
UK	Technical downtime	5–50% (scenario)
UK	Soiling	100%
UK	Tilt	100%

5.2.5. Estimated Recoverable Energy by Site and Root Cause

Based on the loss quantification method presented in Section 4.2 and the recyclability assumptions defined in Section 5.2.2, we calculated the estimated recoverable energy for each site and root cause. Only the primary loss factors were included, while secondary factors such as temperature effects were excluded due to their negligible impact.

For each category, the theoretical annual energy loss was first derived using the estimated percentage of loss and the site-specific annual generation. Then, the recoverable share was applied to estimate the amount of energy recovery achievable under practical improvement schemes.

The results are summarized in Table 10, which lists the estimated recoverable energy for all sites and root causes.

Table 10：Estimated Recoverable Energy by Site and Root Cause

Site	Root Cause	Expected PV Generation (MWh)	Loss %	Recoverable Assumption	Recovered Energy (MWh)
Sweden	Curtailment	14,157	35%	80–90%	3964-4459
	Snow (physical loss)	14,157	1-2%	50%	71-142
	Snow (forecast error)	—	—	—	Not quantified
	Soiling	14,157	5–10%	50%-100%	708
	Inverter issues	14,157	2–3%	100%	283-425
	Tilt	14,157	0.50%	100%	71
Netherlands	Curtailment	4,029	24%	40–60%	387-580
	Soiling	4,029	5–10%	50%-100%	201
Thailand	Zero-export curtailment	391	35%-50%	40–60%	55-117
	Soiling	391	2%	100%	8
	Tilt	391	1–3%	100%	4-12
Belgium	Soiling	1,641	5–10%	50%-100%	82
	Tilt	1,641	1–3%	100%	16-49

UK	Downtime due to technical failure	200	5%-50%	100%	10–100
	Soiling	200	3–5%	100%	6-10
	Tilt	200	1–2%	100%	2-4

Overall, the results indicate that the majority of recoverable energy is concentrated in losses associated with curtailment and system downtime. In Sweden and the Netherlands, curtailment is the largest component of recoverable energy, but the extent of recovery depends on structural constraints such as grid output limitations. In Thailand, recoverable energy is also primarily driven by curtailment due to the zero-output policy, but the potential for recovery is significant through increased on-site consumption and demand growth.

In contrast, environmental and technical losses (e.g., dust accumulation, inverter inefficiency, and insufficient tilt angle), while resulting in smaller energy losses, are more stable and easier to recover. These losses are generally easier to address through operational improvements and maintenance strategies. At the UK test site, estimated recoverable energy is highly dependent on system downtime. Therefore, the observed potential recoveries range widely, reflecting uncertainty due to a lack of detailed operational data.

It is important to note that the estimates represent achievable recoveries under real-world conditions, not theoretical maximums. In cases of insufficient data, results are presented as ranges or labeled as unquantified to ensure transparency in the analysis.

5.2.6. Economic Value of Recoverable Energy

Cost savings reflect the potential economic benefits that could be realized if improvements were implemented and recoverable energy were utilized. The calculation is based on the average recoverable energy for each root cause, combined with location-specific electricity prices and electricity utilization patterns. It is worth noting that although tilt angle optimization may offer relatively high theoretical recoverability, its practical implementation is often limited by installation density requirements, row spacing considerations, wind loading effects, and potential interactions with shading and snow accumulation. Therefore, large-scale tilt adjustment was not considered a highly feasible improvement measure for most sites in this study.

For each root cause, recyclable energy was allocated to self-use and export based on the location-specific utilization assumptions (Table 7). The economic value was then calculated using the corresponding purchase and export electricity prices defined in Section 5.2.1. The results, summarized in Table 11, indicate that curtailment represents the largest source of potential cost savings, particularly in Sweden and the Netherlands, due to the significant volume of recoverable energy. In contrast, soiling and inverter-related improvements provide moderate but consistent economic benefits across all sites.

Table 11：Estimated Annual Cost Savings by Site and Root Cause

Site	Root Cause	Average Recovered Energy (MWh)	Purchase Price (€/kWh)	Export Price (€/kWh)	Self-consumption	Export	Annual Cost Saving (€)
Sweden	Curtailment	4212	0.059	0.0397	10%	90%	175,346
	Snow (physical loss)	107	0.059	0.0397	10%	90%	4,454
	Soiling	708	0.059	0.0397	10%	90%	29,474
	Inverter issues	354	0.059	0.0397	10%	90%	14,737
Netherlands	Curtailment	484	0.101	0.075	67%	33%	44,731
	Soiling	201	0.101	0.075	67%	33%	18,576
Thailand	Curtailment (zero-export)	86	0.1		100%	0%	8,600
	Soiling	8	0.1		100%	0%	800

Belgium	Soiling	82	0.1025	0.075	39%	61%	7,029
UK	Downtime (technical)	55	0.3	0.042	100%	0%	16,500
	Soiling	8	0.3	0.042	100%	0%	2,400

It is worth noting that for the Netherlands site, due to the lack of precise site-specific cost information, grid-related export fees and recycling charges were not included in the calculations, therefore the economic value of exported electricity may be slightly overestimated. According to interview feedback, the exact amounts of these fees were not available during the analysis. Therefore, the calculated export-related economic benefits should be considered as reference estimates, not precise financial figures.

5.2.7. Investment Feasibility and ROI

The investment feasibility of performance improvement measures was evaluated by comparing the estimated annual cost savings with the corresponding implementation costs.

Operation and maintenance (O&M) costs were estimated based on European benchmarks. An assessment of solar costs at the EU level shows that the average operating and maintenance costs for utility-scale solar installations in the EU range from €6.8/kW peak power/year to €14.8/kW peak power/year (Joint Research Centre, 2023). The operation and maintenance costs, approximately 10% to 12%, are spent on inverter replacement (Mackenzie, 2020). For the Sweden site, survey data indicates that inverters have been replaced twice within a three-year period, which is significantly below the typical inverter lifetime of 10–15 years. This suggests abnormal failure rates. Based on the average EU benchmark of approximately €10.8/kWp/year, the estimated annual O&M cost for the 14 MWp Sweden PV system is approximately €151,000/year. Considering that inverter replacement typically represents 10–12% of total O&M costs, the indicative inverter-related maintenance cost is estimated at approximately €15,000–18,000/year. Given the reported abnormal inverter replacement frequency at the Sweden site, this mid-to-upper benchmark range was considered appropriate for the feasibility assessment.

For the UK site, reported maintenance costs are approximately £5,000 per year(around €5,800 for a 2 MW peak power system in another site, equivalent to only €2.90 per kilowatt per year). This is significantly lower than European benchmarks and reflects only routine maintenance under normal operating conditions. Given the observed system downtime and technical issues, it can be inferred that increased maintenance investment is needed to bring it closer to industry benchmarks in order to improve performance. Applying the upper range of the EU benchmark (€14.8/kWp/year) results in an estimated annual O&M requirement of approximately €2,960/year for the 0.2 MWp system. This suggests that an additional maintenance investment of approximately €2,400/year may be required to improve operational reliability and align maintenance practices more closely with industry standards.

Cleaning costs were estimated using a combination of site-specific information and industry-based benchmarks. For the UK and Thailand sites, site-specific cleaning cost information was available and was therefore applied directly. The UK site reported approximately £3,000 per year for four cleaning cycles, corresponding to approximately €870 per cleaning cycle. For Thailand, the reported cleaning cost was approximately €650 per cleaning cycle. For the remaining European sites, cleaning costs were estimated using an industry-based per-panel benchmark. Industrial and large rooftop PV cleaning prices can start from approximately €0.40 per panel, depending on system scale, accessibility, and cleaning method(Solarco, 2025). In this case, a conservative lower-bound benchmark of €0.40 per panel per cleaning cycle was therefore applied to reflect the large scale of the analyzed industrial rooftop systems.

Since detailed module specifications were not consistently available across all sites, the approximate number of PV modules was estimated using a representative commercial PV module capacity of approximately 550 W per panel. This assumption is consistent with commonly reported commercial and industrial PV module capacities in recent industry literature and market reports, which typically range from approximately 500–600 W per panel for commercial and industrial (C&I) installations (Shravan Chunduri, 2025). The Netherlands site provided the exact number of panels, which is 7136, and the capacity of each panel is 555W, which strongly supports our assumption.

Based on this approach, the corresponding estimated cleaning costs per cleaning cycle are summarized in Table 12.

Table 12：Cleaning Cost Estimation Basis

Site	Installed Capacity (MWp)	Estimated Panels	Cost Basis	Estimated Cost per Cleaning (€)
Sweden	14	25,455	€0.40/panel	10,182
Netherlands	3.96	7,136	€0.40/panel	2,854

Belgium	1.52	2,764	€0.40/panel	1,105
UK	0.2		Site-specific data	870
Thailand	0.28		Site-specific data	650

Based on literature recommendations for an optimal cleaning interval of one to three months, our assumptions about increasing cleaning frequency and the corresponding increase in costs are shown in the table below:

Table 13：Cleaning Cost Estimation for Each Site based on Cleaning Frequency

Site	Current Cleaning Frequency	Target Frequency	Additional Cleanings	Cost per Cleaning (€)	Additional Annual Cost (€)
Sweden	2	6	4	10,182	40,727
Netherlands	2	6	4	2,854	11,418
Belgium	2	6	4	1,105	4,422
UK	4	6	2	870	1,740
Thailand	4	6	2	650	1,300

It should be noted that reliable cost data is unavailable for curtailment-related improvements at the analyzed locations. While potential energy recovery and associated economic benefits can be estimated, the required investments（such as grid upgrades, BESS or EMS) will vary significantly depending on location-specific conditions and infrastructure constraints. Therefore, this study cannot quantify the rate of return and payback period of emissions reduction and mitigation measures. Consequently, these measures are classified as "uncertain" in terms of investment feasibility, requiring further site-specific technical and economic assessments

The results of the ROI assessment are summarized in Table 14.

Table 14：ROI and Investment for Each Site & Root Cause

Site	Root Cause	Annual Saving (€)	Cost Assumption	Estimated Cost (€)	Payback	Feasibility
Sweden	Curtailment	175,346	Not available	–	–	Uncertain
	Snow (physical loss)	4,454	Not available	–	–	Uncertain
	Soiling	29,474	Estimated Cleaning Cost	40,727	>1 year	Low priority
	Inverter issues	14,737	High O&M	15,000–18,000	~1 year	Medium priority
Netherlands	Curtailment	44,731	Not available	–	–	Uncertain
	Soiling	18,576	Estimated Cleaning Cost	11,418	<1 year	Highly feasible
Thailand	Curtailment	8,600	Not available (grid constraint)	–	–	Uncertain
	Soiling	800	Estimated Cleaning Cost	1,300	>1 year	Low priority
Belgium	Soiling	7,029	Estimated Cleaning Cost	4,422	<1 year	Highly feasible
UK	Downtime (technical)	16,500	Increased O&M toward benchmark	2,400	<1 year	Highly feasible

	Soiling	2,400	Estimated Cleaning Cost	1,740	<1 year	Highly feasible

5.3. Environmental Benefits

The environmental benefits of performance improvements were assessed by estimating the reduction in carbon dioxide (CO_2) emissions associated with recoverable PV energy identified in the previous sections was assumed to offset grid electricity consumption at each site. Assuming that the recovered photovoltaic power generation can offset the grid power consumption, and using the grid emission factor of a specific country to calculate the amount of emissions avoided. Country-specific emission factors were collected from internationally recognized and governmental sources, including the European Environment Agency (EEA), UK Government greenhouse gas conversion factors, and Thailand's Energy Policy and Planning Office (EPPO), summarized as Table 15 below. In this study, environmental benefits are expressed as carbon dioxide equivalent (CO_2e) reductions. CO_2e represents the combined global warming impact of multiple greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), converted into an equivalent amount of CO_2 based on their relative global warming potential. Therefore, the emission factor expressed in kg CO_2e/kWh represents the total greenhouse gas emissions associated with the generation or consumption of one kilowatt-hour of electricity.

Table 15：Emission Factor for Each Country

Country	**Emission Factor (kg CO_2e/kWh)**
Sweden	0.08(EEA, 2023)
Netherlands	0.256(EEA, 2023)
Thailand	0.418(EPPO, 2026)
Belgium	0.15(EEA, 2023)
UK	0.177(Gov.UK, 2025)

The environmental value of recovering photovoltaic (PV) energy varies geographically, as its environmental benefits depend on electricity utilization rates and the national grid's carbon intensity. In this study, only the self-consumed share of recovered PV electricity is included in the main CO_2e reduction calculation. This is because self-consumed PV electricity directly offsets electricity that the site would otherwise purchase from the grid, making the avoided emissions more clearly attributable to the site. Exported electricity may also contribute to wider grid decarbonization, but its actual emission reduction effect depends on marginal grid displacement, market conditions, and whether the exported electricity replaces fossil-based generation or other renewable electricity. Therefore, exported electricity was excluded from the primary calculation to avoid overestimating the direct environmental benefit of site-level PV performance improvements. Regions with high self-consumption rates and high grid carbon intensity, such as Thailand and the Netherlands, have relatively high potential for CO2 reductions per kilowatt-hour of recovered PV energy. In contrast, Sweden has relatively limited environmental benefits because most of the recovered electricity is fed back into the grid, and Sweden's power structure itself has a relatively low carbon intensity. Strategically, this means that improvement measures that increase on-site self-consumption, such as load shifting, EV charging, flexible operations, or storage, can strengthen both the financial value and the certainty of reported CO_2e reductions.

The final CO_2e Reduction for different countries is shown in the table below.

Table 16：CO_2e Reduction for Each Country

Country	**Emission Factor (kg CO_2e/kWh)**	**Self-consumption**	**Average Recovered Energy (kWh)**	**CO_2e Reduction（tCO 2e/year）**
Sweden	0.08	10%	5,381,000	43
Netherlands	0.256	67%	685,000	117.5
Thailand	0.418	100%	94,000	39.3
Belgium	0.15	39%	82,000	4.8
UK	0.177	100%	63,000	11.2

In conclusion, the results indicate that improving PV system performance can bring not only economic benefits but also significant environmental value through reduced greenhouse gas emissions. However, the magnitude of these environmental benefits largely depends on local power characteristics and on-site energy utilization patterns.

5.4. Scalable Decision Framework for the Logistics Company

From the results obtained from our muti-site analysis, it is suggested that a framework for scaling decisions be put in place to support consistent and data-driven decision making in relation to company's photovoltaic portfolio. This standards framework is designed to provide a comprehensive structured and repeatable approach that can be easily applied across different sites irrespective of their geographical location or operational context. However, this framework is based on observed performance gaps and combines site-specific findings from existing literature.

Step one in this proposed framework involves performance screening using standardized metrics like the performance ratio (PR). It ensures consistency while comparing actual performance vs theoretical performance across the selected sites such as Belgium, Sweden, UK, Netherlands, and Thailand, where there are differences in their monitoring capabilities. So, applying Performance Ratio (PR) screening ensures that poorly underperforming systems are detected at the early stages of analysis, even when detailed technical data is limited.

The second stage of this framework focuses on root cause identification of solar PV underperformance, where performance losses in different dimensions such as technical, operational, environmental, and contractual / system issues. Basically, each dimension is considered to align with the patterns that are identified from the case study sites. For example, Inverter breakdown, Suboptimal tilt angle in Sweden (Technical Perspective), Limited Monitoring, lack of maintenance strategies in UK and Netherland (Operational Perspective), environmental losses due to soiling, bird dropping and snow accumulation in Belgium and Sweden. Losses due to curtailment driven by grid and market in Sweden, Thailand, and the Netherlands (contractual / system). Hence, such a structured classification approach will ensure that any problems with performance are not just analyzed in isolation but are understood within a broader system context.

Then, the third step in the process where quantification of losses is done using available data and literature benchmarks. In case, when there is no way to conduct measurements directly, it would help to use relevant literature-based estimates (for example, for soiling, snow accumulation or Inverter downtime loss) to quantify the amount of loss in the respective dimensions. Basically, this step would provide an objective way of determining what the most important issues have the greatest impact, even under data limitation. Furthermore, it supports better comparability across sites with different data quality levels.

Lastly, this framework includes prioritization of improvement measures based on impact and feasibility. At first, improvement measures that have high-impact and are feasible to implement will be addressed. For example, the curtailment and system constraints issue especially in Sweden, and the Netherlands will be addressed through strategic actions. It includes strategies such as improving coordination of Photovoltaic PV-BESS (battery energy storage systems) and energy management. At the same time, improvement measures that are inexpensive and quick-win measures, such as implementation of KPI, upgrading monitoring systems with alert, and improved cleaning or maintenance practices can be implemented across sites such as the UK and Belgium. Hence, this approach ensures a complete balance between short-term and long-term operational improvements by equally prioritizing long-term strategic investments. Overall, the proposed framework helps achieve transformation for the logistics company by moving away from a reactive model, site-specific approach towards a more standardized and scalable decision-making process. Also, it provides a platform where performance monitoring, structured analysis, and prioritization of actions will be done in order to ensure continued growth of PV projects. Hence, such an approach allows flexibility in order to adapt to site-specific conditions.

Figure 9 presents a structured framework for identifying, quantifying, and prioritizing photovoltaic (PV) performance improvement opportunities across multiple operational sites using standardized technical, operational, and business-oriented evaluation steps.

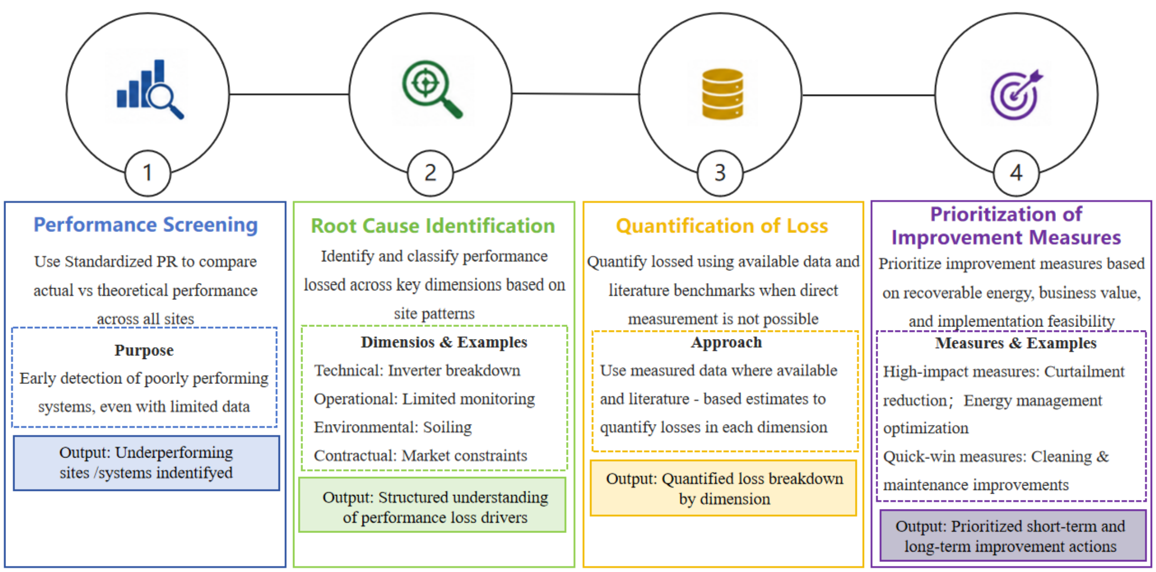

Figure 9: Proposed Framework for Scalable PV Performance Improvement and Decision-Making Across Multi-Site Portfolio

6. DISCUSSION

In this section, the major findings of this study are presented in relation to previous literature studies and the research questions. Moreover, it includes some reflections on the broader implications for logistics sustainability as well as methodological limitations of the research.

6.1. Interpretation of Results

The study results indicate that the poor performance of the PV systems across different sites of this logistics company was not caused by a single dominant technological factor, but rather by a combination of factors including operations, infrastructure, and site-specific conditions. Although all selected sites operated their PV systems within the same corporate sustainability framework, significant differences remained in performance levels, root causes, and recovery potential.

One of the most important findings is that energy losses due to curtailment and operational system constraints are more significant than those caused by traditional technical and environmental efficiency losses such as dust or temperature effects. At multiple sites, the performance gaps were significantly correlated with system-level operational constraints rather than photovoltaic module inefficiencies. This was particularly evident at the Swedish site, where the PV and storage system combination was constrained by PoC limitations and operational strategies controlled by the EMS. According to interview feedback and follow-up discussions during the site visit, although the system has 14 MWp of installed PV capacity and 11 MW inverter capacity, the practically utilized export capacity was estimated by site personnel to be approximately 6 MW under typical operating conditions due to combined PV-BESS operational constraints. Similar operational constraints were observed at sites in the Netherlands and Thailand, with export restrictions and power utilization conditions reducing the effective utilization of power generation. Overall, the results indicate that PV underperformance in industrial systems is typically influenced by curtailment and operational energy management conditions, rather than simply by technical efficiency losses.

The study also indicates that traditional PV performance metrics, such as performance ratio (PR), should be interpreted with caution in industrial photovoltaic systems. A lower PR does not necessarily indicate poor module performance or equipment defects. On the contrary, the PR may reflect factors such as power curtailment, export restrictions, operational downtime, energy management system (EMS) control strategies, or electricity trading conditions.

Another important interpretation involves the role of electricity utilization patterns in determining the practical value of PV performance improvements. Sites with high self-consumption rate typically gain more significant economic and environmental benefits from recovered solar energy, while export-oriented systems, despite potentially large amounts of recoverable energy, have relatively low direct value. This suggests that simply maximizing power generation is insufficient. Effective integration between power generation, electricity demand, and operational flexibility is also important.

Overall, the findings indicate that improving PV system performance should not be viewed only as technical optimization. Instead, effective performance enhancement requires comprehensive consideration of operational strategies, power utilization, grid interaction, energy management system configuration, maintenance practices, and site-specific operating conditions. Therefore, this study emphasizes the importance of integrating technical, economic, and operational factors when evaluating the solar performance and improvement potential of industrial PV systems.

6.2. Comparison with Literature

The previous studies on photovoltaic (PV) system performance commonly identified factors such as temperature effects, soiling, and irradiance variability have been highlighted as major factors responsible for performance losses. Temperature effects have been found to reduce module efficiency, with typically losses of around 0.4% per degree increase in module temperature (Skoplaki and Palyvos, 2009). Similarly, the soiling that occurs because of the dust accumulation, pollen, and dirt is generally believed to lead to an estimated energy loss, particularly in dry and industrial zones (Dawood, 2023). Moreover, the impact of soiling due to dust accumulation and surface contamination can also reduce energy generation when proper maintenance or cleaning is not done. Also, according to Ilse et al. (2019) clearly stated that soiling can reduce the solar power production by 3%-4% annual energy loss. Furthermore, variability in the intensity of solar irradiation becomes another important influence in energy yield and system performance. As a result, the current literature focuses on reducing losses by optimizing system design, maintenance and cleaning practices. These studies provide key insights and help to understand both technical as well as environmental issues regarding the performance of PV systems.

Unlike the results shown in the literature, the results from our study suggest that environmental factors like temperature and soiling are not the dominant drivers of performance loss across the analyzed sites. As discussed, in the case of the Netherlands, temperature-related losses were found to be negligible throughout the year because of temperature being moderate, where ambient temperatures are generally lower compared to hotter regions. In this case although soiling is present, its impact is limited due to minimal rainfall and lower dust intensity. Hence, these favorable conditions ensure that the solar panels are clean. Therefore, it can be said that such environmental losses in this context do not play a major role in the observed performance gaps. The analysis of this study shows that operational and contractual /system-level constraints have a greater influence. For the Netherlands, technical limitations on the grid such as the maximum amount of energy that may be injected (capped export capacity) and some economic factors like energy return fees that directly limit the how much generated solar energy can be used or exported. Consequently, the energy generated by solar PV systems is not fully consumed at sites or sold and leads to curtailment losses. Similar situation observed in Sweden, it is seen that dynamic curtailment due to limited grid capacity (7MWp), and the requirement for battery use limits the useful energy generated from the PV system. Overall, this clearly shows that real-world photovoltaic (PV) systems performance is strongly dependent on the system integration, grid infrastructure, and operational strategy, instead of just only environmental or technical factors.

Additionally, lack of operational efficiencies was another factor which contributed to the reducing PV system performance, particularly in sites such as the UK and Belgium. With the limited monitoring systems available, it would be difficult to track real-time PV system's performance and delay the identification of exact issues such as inverter faults or drops in energy generation. Moreover, the absence of required KPIs-based performance tracking like Performance Ratio (PR) evaluation. It means that deviations from expected performance were not completely identified or analyzed. As a result, many issues often remain unnoticed for long periods of time. Also, maintenance practices were more of reactive than proactive, which meant that required corrective actions were only taken only after system breakdown occurred, instead of being prevented in advance. As result to this, delays in resolving issues and increased downtime resulted in decreased overall generation. Together, these factors prove that apart from technical problems, lack of operational practices can still result in significant performance losses.

These results clearly show that the actual performance of a photovoltaic system is determined by a combination of factors, where the contractual and operational factors have more weightage than traditional losses due to environmental factors. To sum up on this, the study findings extend existing literature knowledge by showing that operational and contextual factors play an equally, if not more important role in PV system performance in logistics applications.

6.3. Implications for Logistics Sustainability

The findings of this study clearly suggest that sustainable development through the use of photovoltaic (PV) systems requires more than just installations itself. Basically, it depends on effective operational and contractual optimization. In the real world, in logistics operations where energy demand is very high (E.g. warehouse, transportation), need the help of proper energy management and strong system coordination. Further, the inclusion of renewable energy in logistics operations plays an important role especially in minimizing the environmental impact while at the same time increasing operational efficiencies and cost savings (Smith, 2024). This means that with proper management of PV systems, can contribute not only to emissions reduction but also to sustainable development across a logistic network.

For big logistics companies, this underscores the importance of the need for energy management practices to be incorporated in logistic operations. Several studies show that the implementation of energy management systems (EMS) and renewable energy solutions in logistics operations improves self-consumption and further decreases energy consumption and emissions. As such, implementation of energy management strategies was helpful in increasing the rate of self-consumption by 25%, and helpful for reducing the level of CO2 emissions (Cannava, 2024). On the other hand, studies on logistics sites using photovoltaic (PV) technology have highlighted that data-driven digital solutions offer real-time decisions making and hence improve productivity and lower costs. Furthermore, a study by Pan et al. (2023) mentioned that logistics sites that use these photovoltaic (PV) systems support data-driven decisions and help to improve asset utilization.

From a practical point of view, these findings are directly relevant as well as useful to the sites that we studied in this study. For example, sites like Sweden and the Netherlands, where PV production has been limited due to curtailment issues. But if photovoltaic PV systems are coordinated properly with energy storage systems along with operational strategies, then it helps to increase energy utilization by minimizing losses. Similarly, in sites like the UK and Belgium, improving monitoring and maintenance practices could help them to improve overall efficiency and maximize sustainability benefits for respected sites. Therefore, considering these findings clearly indicate that logistics companies need to go beyond reliance on PV technology for energy savings and further they need to develop an integrated strategy wherein energy management, optimization, and contract design align. Basically, doing this would allow photovoltaic (PV) technology to reach its full potential in terms of sustainability and efficient logistics operations.

6.4. Methodological Reflections

This study applied a mixed-method approach combining quantitative PV performance analysis with qualitative operational insights collected through questionnaires, follow-up site specific interviews, and a site visit. The combination of literature-based benchmarks, operational observations, and site-specific data provided a practical framework for evaluating PV underperformance across different geographical and operational conditions.

A key methodological reflection is that it is difficult to isolate the root causes of photovoltaic underperformance individually. In real-world operating environments, performance losses are often interrelated rather than independent. For example, curtailment, inverter limitations, weather conditions, energy management system (EMS) operation, and electricity trading strategies can affect system performance at the same time. Therefore, some performance losses may overlap, making it difficult to accurately distinguish the impact of each factor. Thus, the quantitative values presented in this study should be considered indicative estimates rather than absolute measurements.

Another important reflection is the value of incorporating the operational and organizational environment into photovoltaic technology analysis. Site interviews significantly enhance the interpretation of performance data and help distinguish between purely technical losses and operational constraints. For example, in the cases of Sweden, the Netherlands, and Thailand, we found that the main performance bottlenecks were not due to the inefficiency of photovoltaic modules, but rather to export restrictions, the operational interaction of PV-BESS, and energy trading conditions. Without qualitative operational insights, these factors could be misinterpreted as conventional performance deficiencies.

This study also demonstrates that photovoltaic system evaluation should not rely solely on traditional technical indicators such as performance ratio (PR) or annual electricity generation. Practical performance improvement potential is also influenced by economic value, electricity utilization patterns, curtailment conditions, operational feasibility, and environmental impacts. In addition, simplified assumptions were required in several parts of the analysis, including self-consumption allocation, export pricing, and the use of representative average electricity prices instead of hourly market prices in the economic assessment. These simplifications were applied to ensure comparability across sites and maintain a practical portfolio-level analysis framework, although they may not fully capture short-term operational and market dynamics.

Furthermore, not all identified performance losses were considered equally recoverable in practice. Some factors, such as soiling, monitoring improvements, and inverter maintenance, were regarded as operationally recoverable with relatively high implementation feasibility. In contrast, factors such as tilt-angle optimization may offer theoretical performance improvements but were considered less practical due to installation density requirements, wind loading considerations, shading interactions, and snow-related operational impacts. Similarly, orientation-related effects were treated as fixed design boundary conditions rather than recoverable operational losses, since rooftop orientation is generally constrained by building layout.

In summary, although simplifications and assumptions are required in some parts of the analysis, the methodology demonstrates its ability to effectively identify key performance drivers and assess the improvement potential of different photovoltaic systems.

7. CONCLUSIONS AND RECOMMENDATIONS

Lastly, this chapter highlights the main results and answers the research questions of the thesis study. Furthermore, it presents the theoretical contribution of the study, the limitations in conducting this research and also provides recommendations for future studies in the field of PV performance and logistics sustainability.

7.1. Answers to Research Questions

7.1.1. RQ1 – Portfolio-Level Performance Alignment

In the beginning of the study, three main research questions were introduced. As per Research Question 1, as it investigated to what extent the actual performance of solar PV systems across this chosen logistics company's sites align with their theoretical energy output. Considering this first question, the findings of the analysis were performed using standardized metric Performance Ratio (PR). Using the Performance Ratio (PR), the results indicate that even though many systems perform satisfactory, but notable differences in performance are observed across several sites. Hence, differences in PR values highlights that performance is not consistent across the portfolio. Some sites perform relatively stable and with expected performance levels, such as Belgium, whereas others sites show noticeable performance deviation between actual and the expected energy output level (The UK, Spain, and Thailand).

This variation in performance can be clearly observed across the case sites. For example, Sweden and the Netherlands have less efficient performance because of curtailment and system constraints. While sites like the UK and Belgium experience inefficiency that have been caused by operational as well as environmental issues. This research shows that the issue of performance misalignment also depends on specific circumstances that could be site-specific conditions or system characteristics. By applying a proper structured PR-based evaluation procedure, this study was able to pinpoint underperforming systems and calculate the extent of deviations, which helps to address a direct answer to research questions Q1.

7.1.2. RQ2 – Root Causes of Performance Deviations

Now, the second research question explored the key factors that account for the gap between expected and actual PV performance. For this question, this study adopted a muti-factor analytical framework and further categorized root causes into four main perspectives (technical, operational, environmental, and contractual). Such a structured approach supports detailed understanding of the exact root cause of performance gaps instead of relying on only technical explanations. The study findings indicate technical issues like inverter downtime and system design can cause performance differences, but they are generally not the key drivers at most locations. Instead, operational inefficiencies that include limited monitoring, lack of maintenance practices, and absence of performance-based tracking (KPIs) can play a significant role, particularly in sites such as the UK and the Netherlands. Environmental perspectives root causes for systems underperformance includes factors such as dust accumulation, soiling, snow accumulation, especially for locations like Belgium, Sweden. Apart from these, the major effect comes from contractual and system-level constraints, which have common root causes such as grid limitations and market-driven operational strategies. Such situations are observed in Sweden, Thailand, and the Netherlands because of the limitation on energy export of energy due to government regulations and grid capacity.

Overall, this study shows the performance differences are the result of interconnected factors instead of just a single cause, and that addressing these root causes always require a more comprehensive outlook. Keeping in mind, through the integration of site-specific information (questionnaires responses), interview findings, and literature-based benchmarks, the study provides an explanation of performance gaps and points out areas where the greatest impact can be made. This directly answers our research question Q2 by identifying and prioritizing the key root causes of underperformance of photovoltaic systems across the portfolio.

7.1.3.RQ3 – Business Case and Decision Support

The third research question focused on how identified PV performance gaps can be translated into actionable business cases to support investment and operational decision-making within the company. To address this question, we developed a structured evaluation framework that links technical performance losses to economic and environmental impacts.

This analysis follows step-by-step logic, first translating identified performance gaps into projected energy losses, and then analyzing recoverable energy potential, financial impact, and environmental benefits. This framework enables the transformation of PV underperformance into measurable business metrics, including annual cost savings, potential CO_2 emission reductions, investment feasibility, and projected payback period. The results indicate that not all performance gaps have the same commercial significance. Implementing relatively low-cost operational measures, such as clean optimization and improved inverter maintenance, typically demonstrate the strongest investment feasibility and the shortest payback period. In contrast, losses associated with curtailment often represent the greatest potential for recoverable energy, but their feasibility for improvement is highly uncertain due to limited cost data and dependence on grid infrastructure, energy management system operation, and electricity market conditions.

The study also highlights the importance of electricity utilization patterns in determining business value. Sites with higher self-consumption rates typically gain more significant economic and environmental benefits from recovered solar energy, while export-oriented systems, despite potentially large amounts of recoverable energy, offer lower direct economic and environmental returns. This is particularly evident in the Swedish site project, where, despite identifying substantial recoverable energy, its overall firm value was impacted by low self-consumption rates and a relatively low-carbon electricity structure.

Overall, the findings suggest that translating PV performance gaps into financial metrics provides a practical and feasible foundation for prioritizing improvement measures and aligning PV technology management with the company's operational and sustainability goals.

7.2. Practical Recommendations for the Logistic Company

7.2.1. Portfolio-Level Recommendations

This section is about turning our findings into clear, actionable portfolio-level recommendations for the logistics company. The first and most important key recommendation in order to improve photovoltaic PV system performance across the portfolio of the company includes introduction of standardized monitoring systems and performance tracking of systems on the basis of KPIs. In this context, it should be pointed out that use of the performance ratio (PR) as a common metric would allow consistent comparison of expected performance vs actual production across all sites. Such KPIs based monitoring allow earlier detection of underperformance and supports faster corrective actions. Also, as per guidelines by IEA PVPS (2022), continuous monitoring is very important to ensure proper operation and maintenance of PV systems. To the company, this would be particularly advantageous in locations like the UK or in Belgium, where limited monitoring currently delays fault detection. In the long run, such KPIs based monitoring would allow for more proactive management and increase overall system efficiency.

Another suggestion would be the implementation of KPIs-based service level agreements (SLAs) and maintenance improvements. As per finding of the study, the current approach in most sites is reactive instead of proactive, and that causes delays in fixing faults and unnecessary loss of performance. By clearly specifying response times, availability targets, and defining performance benchmarks within SLAs, organizations guarantee better maintenance consistency across their different sites. Research study already suggests that effective maintenance plans and data-driven have potential to minimize downtime and maximize system reliability (Köntges, 2017). This will assist in addressing issues such as inverter downtime observed in Sweden or in the UK. With proper service level agreements (SLAs) in place, it would be possible to resolve issues on time without delays over an extended period and to help to control systems losses coming through downtime. In the long term, a combination of SLA and predictive maintenance strategies can further improve system reliability and reduce operational risks.

Further improving data standardization and availability across within the PV portfolio would be crucial as well. As identified in this work, data inconsistencies have an impact on conducting strong analysis and making informed decisions. It is necessary for this logistics company to implement data collection standardization practices, including high-resolution data regarding generation, irradiation, system downtime, and load profiles. For instance, improving quick access to the right data would surely allow more accurate quantification of losses related to curtailment in Sweden and the Netherlands, and environmental impacts such as soiling in Belgium. With time, the improvements in data infrastructure would definitely facilitate more advanced analytics and performance management of the portfolio.

Lastly, it is recommended that this organization implement a structured process of making decisions across all PV sites as developed in this study. This framework follows the stepwise approach: performance screening using KPIs such as PR, identification of root causes, quantification of losses using data and literature benchmarks, and prioritizing improvement actions. By following the framework described above, a company can easily move from a reactive approach to a more consistent and scalable one. Such an integrated and data-driven approach can be effective in coordinating and decision-making for PV systems. In reality, it would push this company to systematically address the high-impact issues such as curtailment in Sweden and the Netherlands. Additionally, it will allow some easy quick-win improvements such as monitoring and maintenance in other sites. Overall, this will help in long-term continuous performance improvement, improved resource usage, and greater sustainability results across the portfolio.

7.2.2. Site-Specific Recommendations

Based on the identified root causes and business case analysis, several specific on-site operational and investment recommendations can be made for the logistic company. These recommendations prioritize measures that are highly recoverable, have strong investment feasibility, and are practically implementable under current operating conditions.

Recommendations for each site are summarized in the table below.

Table 17：Recommendations for each site

Site	Main Issue	Recommended Action	Priority	Expected Benefit
Sweden	Curtailment / PV-BESS operational limitation	Improve EMS coordination and increase flexible local electricity consumption (e-trucks, charging infrastructure, controllable loads)	High	Reduce curtailment and improve effective PV utilization
	Inverter reliability	Strengthen preventive maintenance strategy and maintain spare inverter components	Medium	Improve system reliability and reduce downtime
	Soiling	Optimize cleaning schedule based on seasonal performance monitoring	Low	Moderate recoverable energy improvement
	Snow forecast uncertainty	Integrate snow-aware forecasting into EMS and electricity trading strategies	Medium	Reduce forecast deviation and imbalance costs
Netherlands	Curtailment and export dependency	Improve local load shifting and EMS-based self-consumption optimization	High	Increase self-consumption and reduce export losses
	Soiling	Increase cleaning frequency based on performance-loss monitoring	High	Cost-effective performance recovery

Thailand	Zero-export limitation	Evaluate local energy utilization opportunities and optimize operational scheduling	High	Improve on-site PV utilization
	Soiling	Adjust cleaning frequency and optimize cleaning intervals	Low	Limited recoverable energy improvement
Belgium	Minor soiling-related losses	Maintain current maintenance strategy with periodic performance review	Low	Maintain stable benchmark-level performance
UK	System downtime / technical failure	Prioritize corrective maintenance and technical compliance upgrades	High	Restore system availability and improve operational performance
	Soiling	Increase cleaning frequency where economically justified	Medium	Moderate recoverable energy recovery

Overall, these recommendations suggest that the improvement measures with higher priority are not necessarily the largest-scale technical interventions, but rather those that combine high recoverability with low implementation complexity. In particular, operational optimization measures such as improved cleaning programs, corrective maintenance, EMS optimization, and dynamic power consumption have strong practical application potential in those selected sites.

7.3. Theoretical Contributions

Firstly, this study contributes to existing knowledge by proposing an additional approach for the assessment of the performance of solar panels PV systems which is not based solely on technical aspects. Basically, the majority of existing literature studies focus on system efficiency, reliability of components, or on improving overall energy production. However, this study additionally explores factors such as operational, environmental, technical, and contractual / system-level factors. Hence, this helps to provide a more complete understanding of performance gaps, especially when analyzing scenarios in real-world such as logistics facilities. For instance, apart from just technical factors such as inverter downtime, the study highlights the importance of operational practices (E.g., monitoring and preventive maintenance), environmental factors and their effects (E.g., soiling, snow accumulation), and mainly contractual constraints like grid-related restrictions or curtailments. This combined holistic approach is more consistent with recent studies showing the significance of monitoring as well as optimization in order to increase solar PV system performance.

Secondly, this study's contribution in linking technical as well operational performance to business value, which remains mostly unexplored in many available PV system studies. Instead of just assessing such losses from a technical angle, our current study converts them into economic and environmental considerations. For example, those losses related to curtailment or grid capacity restrictions, downtime, and soiling are not only just identified but also further explained based on the effect on energy usage, cost efficiency, and importantly on sustainability development impacts. Also, this study approach supports the development of improvement strategies with both operational and environmental performance. Hence, the study bridges the gap between technical analysis and managerial decision-making by linking technical findings with business-level outcomes.

Lastly, the final contribution of this study is an empirical contribution through multi-site study based on warehouse-based PV systems across different geographical coordinates. It includes sites from Sweden, the UK, Thailand, Belgium, and the Netherlands. As it must be noted that while other studies focus on single-site or simulation-based analysis. But this current study makes use of real-world operational data along with stakeholder insights. Considering this, our study combines quantitative analysis (E.g. primary analysis and performance loss analysis) along with the support of qualitative inputs including site-specific interviews and observations. In this way, this study offers a more holistic approach to evaluating the performance of photovoltaic systems provided. The proposed methodology contributes to the identification of context-specific issues such as curtailment in Sweden and the Netherlands, operational issues in United Kingdom and Belgium sites, but also supporting the development of decision-making framework. Overall, the study contributes to the limited body of research that focuses on application of PV technology in logistics operations. Furthermore, it highlights the importance of adopting technical, operational, environmental perspectives with business perspectives in order to manage energy for sustainable development.

7.4. Limitations

The first and most important limitations of this study involve data availability and consistency across selected sites. As the preliminary analysis was performed using data provided by the company. However further in-depth analysis was conducted based on data collected from site-specific locations. Further all required data for this study was collected using both quantitative and qualitative approaches such as site-specific questionnaires followed by interviews with personnel responsible for PV systems. However, it needs to be stated that the degree of detail of collected data varies significantly and depends on the source. In some cases, only aggregated production generation data was available, while detailed required information like hourly generation data, data on irradiance, system downtime and load profile was limited or sometimes unavailable. Hence, this made it difficult to conduct a thorough and standardized comparison of all the sites. Accordingly, results from this study should be taken into consideration in light of these limitations in data.

Secondly, the scope of this study is limited only to selected case sites within the company's portfolio, instead of covering all installations. Although selected sites give us good insights and information into different operational and geographical conditions, they may not fully represent the whole portfolio. There could be differences in type of installations, varying tilt angles, installation capacity, local regulations as well as operational practices at other sites that may lead to different performance patterns.

Another important limitation related to the use of assumptions and literature-based data used during analysis. As mentioned before, due to the limited data, the performance losses due to soiling, snow accumulation, and inverter downtime were estimated using benchmarking values reported in existing study literature. While this approach is quite common in the field of photovoltaic performance studies, it can only provide a rough approximation, and it may not fully capture site-specific conditions. Additionally, some scenario-based assumptions were made while carrying out analysis with respect to curtailment impacts and operational strategies. As such assumptions were based on existing research, they do not show an element of uncertainty with regard to the outcomes. Furthermore, based on initial analysis results, the Belgium site was expected to act as a benchmarking case for assessing possible improvements opportunities at underperforming sites. But, due to limited access to detailed operational data including high-resolution production data, maintenance data, and load profiles, it restricted its use as a fully quantitative reference model. Consequently, the Belgium site could only be used as a general example of good operational performance, while several improvement suggestions based on research literature and site-based estimates.

The results are mostly applicable to the company's logistics operations at the chosen case sites. Factors like warehouse energy usage pattern, power grid limitations, and contractual conditions are closely related to the operational context of the organization. For this reason, although this framework and approach can be generalized to other companies, the conclusions drawn may not directly apply to other sectors or PV systems without adjustment. So, future work could focus on testing this framework in other sectors to access its broader applicability.

Even with these limitations, this study provides useful indicative findings and a logical decision-making process to improve PV systems effectiveness and support to enhance sustainability goals of the organization. Importantly, it is worth mentioning that addressing these limitations by improving data availability, reducing reliance on assumptions, and expanding the scope of research as in future studies would allow us to conduct more robust and detailed analysis.

7.5. Future Research

Now, considering the future research scope for this study should focus on improving the availability and quality of operational data that is used for performance assessment. Currently, there are limitations in availability of data such as lack of detailed hourly production data, site-level load profile, and system downtimes. It is restricted from achieving the level of precision in conducting a performance analysis. In a simpler way, if higher quality of data was available, then performance analysis could have been more effective and loss identification could have been made more efficiently. Also, future work is needed to develop advanced modelling approaches, especially in regard to curtailment and energy management systems (EMS). As current literature already revealed, forecasting and data-driven models can improve coordination between photovoltaic (PV) systems, energy storage, and grid integration (Lalbiakhlua,2025). Such work is important especially in locations like Sweden and the Netherlands, where curtailment is an essential factor that actually limits a PV system's performance. So, in future research work with more accurate modelling could help simulate different operational scenarios and help to identify optimal solutions for reducing losses.

Another important area for future research is use of longitudinal and validation studies. This present study is only an analysis conducted based on a limited time period, which may not fully cover changes that could occur during different seasons or the effects of long-term usage. Basically, this multi-year analysis approach will help us to understand and learn about the issues such as soiling, snow accumulation, and systems downtime. For instance, sites like Belgium and Sweden are affected by seasonal factors (dust / snow accumulation) which can only be properly assessed over longer time periods. Moreover, future studies should include comparison between before and after results (E.g. Cleaning, Maintenance) in order to measure the success of the improvement made. Furthermore, such initiatives also support enhancing monitoring systems or optimized maintenance strategies. This could be more relevant for sites like the UK and Belgium where operational improvements such as better monitoring and cleaning processes are expected to have measurable impacts on PV systems performance. Overall, this would allow validation of the proposed recommendations and provide strong quantitative evidence of their effectiveness.

Lastly, future research is required to assess the scalability of the proposed decision-making model across larger and more diverse PV portfolios. Although this study concentrates on specific chosen sites, including Sweden, the Netherlands, Thailand, the UK and Belgium, assessing the validity of the proposed model in wider scope of logistics facilities would help test its robustness under different climatic, regulatory, and operational conditions. A scalable model would also support benchmarking across sites and also help with the identification of best practices at a portfolio level. This is particularly relevant for global logistics companies where energy management strategies need to be standardized in order to enhance operational efficiency and sustainability goals. One latest research work shows that the positive impact of digital and data-driven systems approaches can help to improve better coordination and decision-making among PV systems (Pan, 2023). Therefore, the expansion of framework in this direction will definitely be useful in the transition from optimization at individual sites to the strategic management of PV systems in the entire value chain.

8. REFERENCES

Abdallah, R., Juaidi, A., Abdel-fattah,S., Qadi,M., Shadid, M., Albatayneh,A., Camur,H., Garcia-Cruz, A., and Manzano-Agugliaro, F. (2022), “ The effect of soiling and frequency of optimal cleaning of PV panels in Palestine.” Energies, Vol.15, 4232, https://doi.org/10.3390/en15124232.

Asirin et al. (2023) “Cost-benefit analysis framework for utility-scale solar energy development: a life cycle approach,” IOP Conference Series: Earth and Environmental Science, 1220(1), p. 012040. Available at: https://doi.org/10.1088/1755-1315/1220/1/012040.

Aydin, B., Holt,R., and Almassalkhi ,M.R., (2025), “Fairness-aware dynamic hosting capacity and the impact of strategic solar PV solar curtailment.” Sustainable Energy, Grids and Network, Vol.43, 101869, https://doi.org/10.1016/j.segan.2025.101869.

Baranyai, N.H., Esses, N.,Vincze, A. and Zsiboracs, H.(2025), “The effect of orientation and tilt angle on Pv system energy production in Hungary: regional comparison and optimization possibilities. Discover Sustainability, https://doi.org/10.1007/s43621-025-02082-z.

Brahma, H., Pant, S., Micheli, L., Smestad, G.P., and Sarmah, N.(2023), “Effect of environmental factors on photovoltaic spilling :Experimental and statistical analysis”, Enegies, 16(1), P.45. https://doi.org/10.3390/en16010045

Cannava,L., Dadras Javan, F., Najafi,B., and Perotti, S.,(2024), “Green warehousing practices: assessing the impact of PV self-consumption enhancement strategies in a logistics warehouse.” Renewable Energy, pp.1-14, https://doi.org/10.1016/j.seta.2024.104054.

Çevik, B.S., and Tırmıkçı, C.A., (2025). “Performance analysis of solar panels: Effects of panel tilt, surface cleanliness, and weather conditions.

Chen, S. A., Vishwanath, A., Sathe, S., and Kalyanaraman, S. (2016), “Shedding light on the performance of solar panels: A data driven view”. ACM SIGKDD Explorations Newsletter, pp.24-36, available at: https://dl.acm.org/doi/abs/10.1145/2897350.2897354.

CHROSIS (2019), Whitepaper on PR vs CUF, On performance Ratio (PR) and Capacity Utilization Paper (CUF).

Cooremans, C., (2012). Investment in energy efficiency: do the characteristics of investments matter?. Springer Science, pp. 497-518.

CSIRO (2021), Solar Photovoltaics: Optimizing Performance. Building Technology Resources, Available at: https://research.csiro.au/infratech/wp-content/uploads/sites/38/2024/12/4393_SolarPhotovoltaicsoptimisingperformance_WCAG.pdf

Datta, U., Kalam, A. and Shi, J. (2020) "The economic prospect of rooftop photovoltaic (PV) systems in the commercial buildings in Bangladesh: a case study," Clean Technologies and Environmental Policy, 22(10). Available at: https://doi.org/10.1007/s10098-020-01963-3.

Dawood,T.A., Barwari, R.R.I., and Arkoot, A., (2023), "Solar Energy and Factors Affecting the Efficiency and Performance of Panels in Erbil/Kurdistan", International Journal of Heat and Technology, Vol. 41 No.2, pp.304-312.

Dellaly, M., Skander-Mustapha,S., and Slama-Belkhodja, I.,(2023), "Optimization of a residential community' curtailed PV power to meet distribution grid load profile requirements." Renewable Energy, Vol. 218, 119342.

DSV(2024), " DSV launches first renewable energy assets in Sweden. Available at: https://www.dsv.com/en/about-dsv/press/news/com/2024/12/dsv-launches-first-renewable-energy-assets-in-sweden.

ELEXON (2022). System Prices Analysis Report: February 2025. [online] Elexon BSC. Available at: https://www.elexon.co.uk/bsc/data/system-prices-analysis-report/.

EPPO (2026). CO2 Statistic. [online] www.eppo.go.th. Available at: https://www.eppo.go.th/index.php/en/en-energystatistics/co2-statistic

Eze, V.H.U., Richard, K., Ukagwu, K.J., Okafor, W. (2024), " Factors influencing the efficiency of solar energy systems", Journals of Engineering, Technology and Applied Science, Vol.6 No.3, pp. 119-131.

Faccio, M., Persona, A., and Zanin, G. (2013), Sustainable Warehouse Design: A Literature Review", International Journal of Production Economics, Vol. 141(1), pp. 190-201.

FfE (2025). European day-ahead electricity prices in 2024 - FfE. [online] FfE. Available at: https://www.ffe.de/en/publications/european-day-ahead-electricity-prices-in-2024/.

Gov.UK (2025). Welcome to GOV.UK. [online] GOV.UK. Available at: https://www.gov.uk/.

Haydaroglu, C., Kılıç, H., Gümüş, B., (2024), " Performance analysis and comparison of performance ratio of solar plant ", Turkish Journal of Electrical Power and Energy Systems.

Heidari, N., Gwamuri, J., Townsend, T. and Pearce, J.M. (2015). Impact of Snow and Ground Interference on Photovoltaic Electric System Performance. IEEE Journal of Photovoltaics, [online] 5(6), pp.1680–1685. doi:https://doi.org/10.1109/jphotov.2015.2466448.

Ilse,K., Micheli, L., Figgis,B.W., Lange, K., DaBler, D., Hanifi, H., Wolfertstetter, F., Naumann, V., Hagendorf, C., Gottschalg, R., and Bagdahn, J. (2019), "Techno-economic assessment of soiling losses and mitigation strategies for solar power generation." Joule, Vol.3, pp.2303-2321.

International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), (2022), "Soiling losses: Impact on the performance of photovoltaic power plants, IEA PVPS Task 13 report". Available at: https://iea-pvps.org/key-topics/soiling-losses-impact-on-the-performance-of-photovoltaic-power-plants/

International Energy Agency PVPS(2022), "Operational and Maintenance of PV systems: Data and Guidelines." Available at: https://iea-pvps.org/wp-content/uploads/2022/11/IEA-PVPS-Report-T13-25-2022-OandM-Guidelines.pdf

Joint Research Centre (2023). Clean Energy Technology Observatory, Photovoltaics in the European Union - Publications Office of the EU. [online] Publications Office of the EU. Available at: https://op.europa.eu/en/publication-detail/-/publication/3e0f0a74-722a-11ee-9220-01aa75ed71a1/language-en.

Khalid, A.M. et al. (2016) "Performance ratio – Crucial parameter for grid connected PV plants," Renewable and Sustainable Energy Reviews, 65. Available at: https://doi.org/10.1016/j.rser.2016.07.066.

Köntges, M., Kurtz, S., Packard, C., Jahn, U., Berger, K.A., Friesen, T., Liu, H., and Van Iseghem, M.,(2017), "Review of failures of photovoltaic modules. IEA PVPS Task 13 Report T13-01."

Kougias, I., Taylor, N., Kakoulaki, G., and Jager-Waldau, A., (2021), " The role of photovoltaics for the European Green Deal and the recovery plan". Renewable and Sustainable Energy Review, Vol.144.

Kull, K., Asad, B., Khan, M.A., Naseer, M.U., Kallaste, A., and Vaimann, T., (2025), "Faults, failures, reliability , and predictive maintenance of grid-connected solar systems: a comprehensive review". Applied Sciences, 15(21), 11461, DOI: https://doi.org/10.3390/app152111461

Lalbiakhlua,K., Deb, S., Singh, K.R., Datta,S., Shuaibu, H.A., and Ustun, T.S.,(2025), "Deep learning based solar forecasting for optimal PV BESS sizing in ultra fast charging stations." Scientific Reports, Vol. 15, 32392, https://doi.org/10.1038/s41598-025-17408-0.

Lee, B., Trucka, M., Hensen, J. L. M., (2012). Rooftop photovoltaic (PV) systems for industrial halls: Achieving economic benefit via lowering energy demand, SciVerse ScienceDirect, pp. 326- 333.

Li, J., Wang, C., and Wang,H. (2024). “Attentive convolutional deep reinforcement learning for optimizing solar-storage systems in real-time electricity markets.” IEEE Transactions on Industrial Informatics.

Mackenzie, W. (2020). Wood Mackenzie. [online] Woodmac.com. Available at: https://www.woodmac.com/press-releases/annual-solar-repairs-and-maintenance-spend-to-grow-to-%249-billion-by-2025/

Marion,B., Schaefer, R., Caine, H., and Sanchez,G. (2013), “Measured and molded photovoltaic system energy losses from snow for Colorado and Wisconsin locations.” Solar Energy, Vol.97, pp.112-121.

National Renewable Energy Laboratory (NREL), (2022), "Photovoltaic soling loss and soiling ratio (IWSR) method. Available at: https://www.nlr.gov/pv/soiling.

Nord Pool (2026). Nord Pool | Data Portal. [online] Nordpoolgroup.com. Available at: https://data.nordpoolgroup.com/auction/day-ahead/prices?deliveryDate=latest¤cy=EUR&aggregation=PriceTrend&deliveryAreas=AT.

Pan, H., Bayanati,M., Vaseei, M., and Chobar, A.P., (2023), “Empowering solar photovoltaic logistic operations through cloud-enabled blockchain technology: a sustainable approach”. Frontiers in Enegry Research, Vol.11, pp.1-10, 1293449, https://doi.org/10.3389/fenrg.2023.1293449.

Peter,U., Mulati,D., Kamau, J., and Soitah, T.(2025), “The optimal tilt angle for maximizing energy production from bifacial solar panels under varying height in tropical regions.” Journal of Sustainable Development of Energy, Water, and Environment System,Vol.13, 1130628.

Reich, N.H. et al. (2012) “Performance ratio revisited: is PR > 90% realistic?,” Progress in Photovoltaics: Research and Applications, 20(6). Available at: https://doi.org/10.1002/pip.1219.

Ren, Z. and Chen, Y. (2023) “Economic analysis of rooftop photovoltaic systems under different shading conditions for 20 cities in China,” in Building Simulation Conference Proceedings. IBPSA. Available at: https://doi.org/10.26868/25222708.2023.1243.

Ruan, T., Wang, F., Topel, M., Laumert, B. and Wang, W. (2024). A new optimal PV installation angle model in high-latitude cold regions based on historical weather big data. Applied Energy, [online] 359, p.122690. doi:https://doi.org/10.1016/j.apenergy.2024.122690.

Sarmah, P., Das, D., Saikia, M., Kumar,V., Yadav, S.K., Paramasivam, P., and Dhanasekaran, S. (2023). “Comprehensive analysis of solar panel performance and correlations with metrological parameters”, ACS Omega.

Schardt, J., te Heesen, H., (2021), “ Performance of roof-top PV systems in selected EU countries from 2012-2019”, Solar Energy, pp. 235-244.

Sharma, M.K., Kumar, D., Dhundhara, S., Gaur, D., and Verma, Y.P.(2020), “Optimal tilt angle determination for PV panels using real-time data acquisition.” Global Challenges, Vol. 4,1900109, https://doi.org/10.1002/gch2.201900109.

Shravan Chunduri (2025). High-Power Modules In TOP SOLAR MODULES Analysis. [online] TaiyangNews - All About Solar Power. Available at: https://taiyangnews.info/technology/high-power-modules-in-top-solar-modules-analysis

Skoplaki, E., and Palyvos, J.A. (2009), “On the temperature dependence of photovoltaic module electrical performance: A review of efficiency / power correlations”, Solar Energy, Vol. 83, pp. 614-624.

SMA Solar Technology AG (2011), Performance Ratio: Quality Factor for the PV Plant Technical Information, Version 1.1.

Smith,H.K.,(2024), “Renewable energy integration in sustainable transportation and logistics”. Available at: https://www.researchgate.net/publication/382116674_Renewable_energy_integration_in_sustainable_transportation_and_logistics

Solarco (2025). *Solarco*. [online] Solarco. Available at: https://solar-co.be/en/solar-panel-cleaning-price/

UKWA (2022), Investment case for rooftop solar solar power in warehousing.

van Noord, M., Landelius, T. and Andersson, S. (2021). Snow-Induced PV Loss Modeling Using Production-Data Inferred PV System Models. Energies, [online] 14(6), p.1574. doi:https://doi.org/10.3390/en14061574.

Veiga, A. (2022), “RatedPower: Ultimate guide to utility-scale PV system losses”. Available at: https://ratedpower.com/blog/utility-scale-pv-losses/

Wang, D.D., and Sueyoshi, T., (2017), Assessment of large commercial rooftop photovoltaic system installations: Evidence from California. Applied Energy, Vol.188, pp.45-55.

Woyte, A, Richter, M, Moser, D, Mau, S, Reich, N. et al. In: Proceedings of the 28th European solar PV conference and exhibition, 30 September–4 October, Paris, France; 2013

Zhou, H. et al. (2025) “Techno-economic analysis of solar photovoltaic systems integrated with battery energy storage for university campuses,” Journal of Energy Storage, 129, p. 117360. Available at: https://doi.org/10.1016/j.est.2025.117360.

Zuñiga-Cortes, F., Garcia-Racines, J.D., Caicedo-Bravo, E. and Hernan Moncada-Vega (2023). Minimization of Economic Losses in Photovoltaic System Cleaning Schedules Based on a Novel Methodological Framework for Performance Ratio Forecast and Cost Analysis. Energies, 16(16), pp.6091–6091. doi:https://doi.org/10.3390/en16166091.

APPENDIX 1: SOLAR PV SITE PERFORMANCE ASSESSMENT QUESTIONNAIRE

Section A – Site Characteristics:

1. Site ID:
2. Country and Site Name:
3. Enter the year when the system became fully operational
4. Is the facility where the photovoltaic (PV) system is installed owned or leased by your organization?
5. What type of mounting system is used for the photovoltaic (PV) panels at your facility? ☐ Rooftop ☐ Ground-mounted ☐ Other (please specify): _______
6. Is the PV system is roof-mounted, what type of rooftop installation is used?
7. ☐ Flat / flush-mounted ☐ Tilted structure ☐ Both
8. Installed Solar capacity (MWp) for your Site:
9. What is the approximate annual electricity demand of the site?
10. PV Solar module type:
    ☐ Mono-crystalline ☐ Poly-crystalline ☐ Thin film ☐ Other (please specify):

Section B –Technical Configuration:

11. Do you know the approximate tilt angle of the installed solar panels (photovoltaic modules) at the facility?
    ☐ Less than 10° ☐ 10°–20° ☐ 20°–30° ☐ More than 30° ☐ Other (please specify):
12. Has any inverter within the PV system been replaced during the past 3 years?
    ☐ Yes (please specify): ☐ No
13. If a battery system is installed, what is the approximate storage capacity(kWh)?
14. Is the battery charged only by PV, or also from the grid?
15. Have the site experienced grid export restrictions or curtailment events that may have affected energy production during the analysis period (2023–2025)? If yes then, kindly Specify.

Section C – Operation & Maintenance:

16. How frequently is scheduled preventive maintenance performed at this PV site?
    ☐ Weekly ☐ Monthly ☐ Quarterly ☐ Twice A Year ☐ Other (please specify): _______
17. Who is responsible for maintenance of the PV system?
    ☐ Site Teams ☐ External Contractor ☐ Landlord ☐ Other (please specify): _______
18. What is the overall maintenance cost level of photovoltaic (PV) systems?
    ☐ Low ☐ Moderate ☐ High ☐ Managed by Landlord ☐ Not known / Not sure

19. In your opinion, is the current maintenance practice sufficient to ensure optimal system performance?

    ☐ Yes ☐ Partially ☐ No ☐ Not sure If partially or no, please briefly explain.
20. Please indicate the frequency of solar panel cleaning at this site. If cleaning is performed only, when necessary, please specify that as well and indicate approximately how many hours are spent on cleaning.

    ☐ Weekly ☐ Monthly ☐ Quarterly ☐ Twice A Year ☐ Other (please specify): _______
21. Has the solar system experienced any downtime in the past 3 years? If yes, please specify the duration and main reason?
22. Who performs the cleaning at your site?

    ☐ Site Teams ☐ External Contractor ☐ Landlord ☐ Other (please specify): _______
23. Does company have operational control over the facilities and systems used to generate solar energy at the site, or are they managed by the landlord? Please indicate the ownership structure of the photovoltaic (PV) system.

    ☐ Company-owned ☐ Third-party owned (Power Purchase Agreement – PPA / lease) ☐ Landlord-owned ☐ Other (please specify): _______
24. Has the battery system experienced any operational issues or downtime that affected solar energy utilization? If yes, please briefly specify the issue.

Section D – Environmental Factors:

25. Are there any nearby constructions or physical obstructions (e.g., buildings, trees, or equipment), as shown in the reference image, that cause partial or full shading of the photovoltaic (PV) system? If yes, how significant is their impact on system performance? ☐ No shading issues ☐ Minor shading (limited impact on performance) ☐ Moderate shading ☐ Major/Severe shading affecting performance ☐ Not sure
26. Has your site experienced any of the following issues? (You may select multiple options if applicable.)

    ☐ Snow accumulation issues ☐ Dust accumulation / Soiling ☐ Bird droppings ☐ Extreme weather damage ☐ Other (please specify): _______

Section E – Monitoring, Data Quality, & Certifications:

27. Does the site utilize a real-time monitoring system for tracking photovoltaic (PV) system performance? If yes, please specify the system name.
28. Does the PV monitoring system automatically generate performance alerts in the event of underperformance or system faults?

☐ Yes ☐ No ☐ Maybe

29. Is the Performance Ratio (PR) automatically monitored in your system? Whereas PR = Actual solar energy output / Theoretical energy output. If yes, please specify the calculation methodology used (e.g., how actual solar output and theoretical output are defined and measured)
30. In your opinion, what are the primary factors contributing to the deviation between the actual and expected performance of the photovoltaic (PV) system? (Select all that apply.) If the reason is not listed, please specify under "Other."

    ☐ Soiling ☐ Shading ☐ Inverter malfunction ☐ Grid limitation ☐ Monitoring/data issue ☐ Battery issue ☐ Unclear / need further investigation ☐ Other (please specify): _______
31. Are there any recurring technical issues affecting the PV system? If yes, please elaborate.
32. If applicable, please provide any additional comments, observations, or recommendations that could contribute to improving the performance, efficiency, or management of the photovoltaic (PV) system at your facility.

Section G - Solar Production, Self Consumption/ Utilization & Grid Export:

33. Approximately what proportion of the electricity generated by the photovoltaic (PV) system is consumed on-site versus exported to the grid? If available, please provide an estimate or describe the current utilization pattern.
34. When solar electricity generation exceeds the on-site electricity demand, what typically happens to the surplus energy? (Please select the option that best applies)

    ☐ Exported to the grid ☐ Stored in batteries ☐ Generation is limited / curtailed

    ☐ Not sure ☐ Other (please specify): _______

    If you selected "Partially" or "No," please briefly explain the main reason(s) (e.g., low daytime electricity demand, grid export restrictions, lack of battery storage, or mismatch with operational schedules):
35. If your site is in Europe, does the facility generate renewable energy certificates, such as Guarantees of Origin (GOs), for the electricity produced by the photovoltaic (PV) system? If applicable, please briefly describe how the process is managed and indicate who is responsible for applying for or managing these certificates (e.g., the company, landlord, energy provider, or a third-party service provider).
36. If the surplus electricity is exported to the grid, please specify whether there is a feed-in tariff or any selling arrangement in place (if known):
37. Do you see any opportunities to improve the utilization of solar electricity at this site? For example, this may include installing battery storage, adjusting operational schedules, exporting electricity to the grid, or increasing electricity demand during solar generation hours. Please briefly describe.

APPENDIX 2: INTERVIEW QUESTIONS

Belgium Site:

Site Characteristics

1. Was the tilt angle (20°–30°) selected based on optimization analysis (e.g., PVGIS), or was it determined by roof structure constraints? What is the orientation (azimuth) of the panels -are they primarily south-facing or installed in multiple directions across the roof?

Cleaning & Soiling Management

2. How did you decide on the current cleaning approach (twice a year using an external contractor), and what factors might lead you to change it in the future?
3. Do you have any way to quantify soiling loss (even roughly)? For example, do you have data showing the performance gain after each cleaning cycle?

Performance monitoring & issue detection

4. How do you currently track system performance? for example, through monthly invoices or reports from the landlord or documents from PPA provider?
5. When performance starts to decline slightly, how do you usually notice it in practice? Is there a formal process in place to escalate issues when performance deviates from expected levels?

Self-Consumption & Grid Export

6. The questionnaire response shows 61% of the solar energy is exported to the grid. Is this level mainly due to operational factors, or is it influenced by technical or contractual limitations?
7. You mentioned installing battery storage as an opportunity. Have you explored adjusting operational schedules to increase self-consumption? Also, what factors would make battery storage economically viable in the future, such as energy price changes, incentives, or load

patterns? Finally, what are the main technical or economic barriers currently preventing its adoption at this site?

8. Do you have any set KPIs for monitoring system performance? If so, what are they and how often are they reviewed?

9. Since there is no real-time monitoring system, what factors do you think are contributing to the site's strong performance?

Ownership Structure & Operational Control

10. Does the PPA include any performance incentives or penalties? If yes, how are these enforced through the external contractor? If not, is there a separate SLA in place with defined KPIs or performance targets?

Improvement options & cost-effectiveness

11. If you could share any approximate cost figures (e.g., annual O&M, cleaning cost, inverter replacement cost if applicable), that would help us build realistic business cases for other sites. And how do you evaluate if it is worth it?

12. As we are considering this site as a benchmarking reference, do you have any additional recommendations for improving solar PV performance?

UK Site:

Performance Gap Diagnosis

1. You indicated that "weather" is the primary factor contributing to the performance gap. Can you be more specific, for example, is it lower solar irradiation, cloud cover, or weather-related damage (e.g., hail, storms)?

2. What was the reasoning behind choosing the tilt angle (10°–20°)? Was any optimization analysis (e.g., using PVGIS or other simulation tools) conducted to decide the optimal angle for this location? what is the orientation of the panels—are they south-facing? If not,

was this orientation considered in the design phase, and what impact on expected generation was anticipated?

3. Since the expected performance already considers local weather conditions (using tools like PVGIS), what do you think causes the gap between expected and actual performance?

Maintenance & Cleaning Practices

4. As mentioned, Cleaning is done quarterly. Do you have any data showing performance improvement after cleaning? How was this frequency determined?

5. Are there any recurring issues with bird droppings or dust that cleaning doesn't fully resolve? Have you considered more frequent cleaning or anti-soiling coatings?

Monitoring & Performance Detection

6. Without real-time monitoring, how do you currently track system performance? Do you receive monthly generation reports from the site teams or the inverter system?

7. Do you have any set KPIs for monitoring system performance? If so, what are they and how often are they reviewed?

8. How do you find out when system performance is declining? Is it based on visual inspections, documented reports or checklists, electricity consumption data, or any other monitoring systems?

9. Do you see limited monitoring as a major issue, or something that can be managed with better processes like regular tracking and analysis?

Inspection Report

10. We reviewed an inspection report from another UK site (Tamworth) which revealed significant electrical non-compliances and safety issues. Has this site undergone a similar detailed inspection? If yes, were any issues found (similar to the inspection report of Unit 6, such as cabling problems, undersized fuses, or lack of proper bonding)? Have they been resolved? If not, why?

Ownership Structure & Operational Control

11. Currently, cleaning is handled by an external contractor, while routine maintenance is performed by site teams. Some sites (e.g., Belgium) use external contractors for all maintenance with costs managed by the landlord. Do you think shifting to a fully outsourced maintenance model would benefit this site? What would be the main barriers?

Improvement options & cost-effectiveness

12. Are there any plans to invest in improvements (e.g., better monitoring, repairs, or cleaning optimization) to address the underperformance? If so, what is the timeline?

13. Could you share approximate cost figures for PV system maintenance, such as annual O&M costs, site team involvement, cleaning cost per cycle, and any recent repairs or inverter replacements? Additionally, how do you assess whether these maintenance costs are justified in relation to system performance?

Thailand Site:

Technical Configuration

1. What factors were considered when deciding the panel tilt angle (<10°)? Was it optimized based on location or simulations, or mainly constrained by the roof? Also You also mentioned a potential 10 – 20% increase in production—how much of that is linked to the current tilt angle (<10°)? If so, what are the main barriers (e.g., structural, cost, or operational) to optimizing it?

2. What is the orientation of the panels—are they south-facing? If not, was this considered during the design phase, and what impact was expected on energy generation?

Maintenance & Cleaning Practices

3. As mentioned, Cleaning is done quarterly by the landlord. Do you have data showing performance improvement after cleaning? Is there any estimation of soiling loss (%)?

4. Is the cleaning frequency defined in the lease or contract, or is it decided by the landlord? Have you ever requested more frequent cleaning?

Monitoring & Performance Detection

5. You use FusionSolar for monitoring. Does it automatically calculate Performance Ratio (PR)? If not, how do you estimate expected generation?
6. Does the system generate automatic performance alerts? If not, how are issues currently detected and communicated to the landlord. Also, are there any plans to upgrade the monitoring system to improve visibility and performance tracking?

Utilization and Curtailment

7. You reported "generation is limited / curtailed." Why does curtailment occur (grid limit, inverter setting, contractual constraint)? How often does it happen, and what percentage of potential energy is lost?
8. Since the system is landlord-owned, who controls the curtailment decision? Is there any compensation or agreement about lost generation?

Ownership Structure & Operational Control

9. Since the system is landlord-owned, how are maintenance responsibilities and operational decisions handled in the real practice? Is there any formal agreement (e.g., SLA) covering response time, cleaning, or performance?
10. In cases of system underperformance, how does company typically respond? Is organization able to request corrective actions from the landlord, and are there any contractual provisions for compensation?

Improvement options & cost-effectiveness

11. Is there any flexibility in the warehouse's operating hours? For example, could some high-energy activities—such as forklift charging, air conditioning, or automation systems—be shifted to daytime hours to better match solar generation?

12. Are there any plans to introduce new electrical loads in the future, such as electric trucks (e-trucks) charging, additional cooling systems, or other equipment that could increase daytime electricity demand?
13. Could you share approximate cost figures (if available) for O&M, cleaning, or any planned upgrades? Since costs are managed by the landlord, do you have visibility into these figures?
14. How does company evaluate whether the current arrangement with the landlord is delivering value? Are there any performance benchmarks or KPIs in place?

Sweden Site:

Site Characteristics

1. The system is 14 MWp , but annual demand is 6,500 MWh. Was this capacity sized based on future expectations (e.g., e-trucks, increased demand) rather than current load?
2. Was the panel tilt angle chosen based on optimization (like using PVGIS or similar tools), or was it mainly due to roof constraints? If it was optimized, what improvement was expected compared to other angles? Also, what is the panel orientation, and if it's not south-facing, was that considered in the design and how does it affect performance?

Environmental Factors

3. You reported snow accumulation as an issue. How long do panels typically remain covered with snow annually? Is there any snow removal strategy, or do you rely on natural melting?

Inverter Issues & Service Response

4. You mentioned recurring inverter issues and challenges with the installer's service. Could you explain what kind of failures occur and how long this has been an issue? Also, what impact has it had on energy generation? Also, who is responsible for fixing it - are the inverters still under warranty? And are there any plans to repair or replace them?

Maintenance & Cleaning Practices

5. You clean only when production drops (trigger-based). How do you detect a performance drop—through your real-time monitoring system? Do you have data showing the performance gain after cleaning? Do you track performance before vs after cleaning?
6. Since bird droppings are an issue, have you considered more frequent cleaning or any anti-bird solutions? Also, what is the approximate cost per cleaning cycle?

Monitoring & Performance tracking

7. You mentioned using real-time monitoring through the Control Tower and comparing production with irradiance data. What key performance indicators (KPIs) do you track to evaluate system performance? How often are they reviewed?
8. Does the current monitoring system provide automatic alerts for underperformance? If not, what are the limitations, and are there any plans or options to upgrade the system to improve monitoring capabilities.

Grid Curtailment & System Design

9. You mentioned that grid export is limited to 7 MW due to the connection limit. How often does curtailment occur, and roughly how much energy generation is lost because of it?
10. Is curtailment handled automatically by the EMS, or does it require manual intervention? And is there any opportunity to use that curtailed energy for other purposes, such as heating or cooling?

Battery Storage & Operational Strategy

11. You mentioned the battery is charged from both the grid and PV, without control dependencies. How is it currently used—for example, is it mainly for storing solar energy, reducing peak demand, or responding to electricity prices? And is it controlled automatically by an EMS or manually?

Improvement options & cost-effectiveness

12. Could you share approximate cost figures (annual O&M, cleaning cost, inverter replacement, BESS capital and operational costs)? How do you evaluate whether investments are justified?
13. Lastly, As we are considering this site, do you have any additional recommendations for improving solar PV performance?

Netherlands Site:

Site Characteristics (Design Gaps)

1. Could you clarify the panel orientation (azimuth)—for example, are the panels primarily south-facing? Since the tilt angle is not documented in the questionnaire, was the system design optimized using tools or was it mainly constrained by roof structure? Also, to what extent do design factors (e.g., tilt, orientation, installation constraints) limit system performance, and is there any realistic potential for improvement through retrofitting or operational adjustments?

Performance Gap Diagnosis

2. You identified heat in summer as the primary factor contributing to underperformance, could you explain how heat impacts the system? For example, does it affect inverter efficiency or panel output? Also, do you have any estimate of how much energy is lost due to heat? And, have you taken any steps to reduce these losses, like improving ventilation, shading, or using other solutions?
3. Based on your experience, is the underperformance mainly caused by internal system issues like temperature, or by external factors such as grid limitations?

Grid Restrictions & Curtailment

4. Could you please explain a bit more about the “energy return fees” and “the 50% injection limit” you mentioned? Are these due to regulations or part of a contract?

5. How often does curtailment happen at your site, and roughly how much energy is lost each year because of it?

Maintenance & Cleaning Practices

6. Do you have any data demonstrating performance improvement after panel cleaning, and if so, how is this used to evaluate cleaning effectiveness? Additionally, the questionnaire response indicates that maintenance and cleaning frequencies are ‘unknown’—is this due to a lack of documentation, or because the site team is not directly involved in scheduling these activities?

7. In practice, how are maintenance and cleaning activities triggered, for example, are they scheduled by the external contractor based on a fixed plan, or are they performed only when issues are noticed? Could you clarify whether your site or the landlord is responsible for scheduling.

Monitoring & Performance Tracking

8. You mentioned using Scholt Energy and Fudura for monitoring— do they send automatic alerts when performance decreases? and if so, what triggers them (e.g., generation drops below a threshold)? Additionally, are there any plans to upgrade the monitoring system to improve visibility and performance tracking?

9. Performance Ratio (PR) is not automatically monitored. How do you currently assess whether the system meets expectations? Do you manually calculate PR or compare historical data?

Guarantees of Origin (GOs)

10. You mentioned GOs are managed through the Verticer platform by the Sustainability Manager. Does the revenue from GOs influence the economic performance of the PV system? Does it affect maintenance or investment decisions?

Ownership Structure & Operational Control

11. Do you have a formal service agreement (SLA) with your contractor that includes performance targets or KPIs? If not, do you think such an agreement would help improve performance? And do you currently track response times for maintenance issues?

Improvement options & cost-effectiveness

12. You mentioned BESS and EMS as potential solutions, have these been concretely evaluated or planned? To what extent would they help mitigate curtailment at your site? Before considering higher-cost solutions like BESS, have lower-cost measures (e.g., operational adjustments or maintenance optimization) been explored?

13. To help us build realistic business cases, could you share approximate cost figures where available for example, annual O&M, cleaning per cycle, recent repairs or inverter replacements, and any planned or completed improvement projects？