

**Establishing A Guideline and Decision-Making Approach
for UAE Solar Assets Waste Management By Utilising
PVsyst**

وضع دليل ونهج لصنع القرار لإدارة نفايات الأصول الشمسية في دولة الإمارات
العربية المتحدة من خلال استخدام برنامج
PVsyst

by

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ABSTRACT

As the number of solar panel installations increases, the amount of discarded panels is also expected to escalate to an estimated 60 million tons by 2050, assuming a lifespan of 20-30 years for the panels. It is a newly declared global concern for the need to manage this new technology waste. End-of-life solar panels contain valuable components, but there currently needs to be globally documented guidelines in place to manage this type of waste efficiently.

This paper studies solar PV waste in relation to EOL end-of-life management of PV assets installed in a solar park in the United Arab Emirates. Given the specific research limitations in implementing the proposed methodologies, the researcher conducted a comparative analysis by studying four different climatic regions: the UAE, Canada, India, and Norway, to bridge the gap and reinforce the validity of the results.

The lack of comprehensive global guidelines and frameworks that guide decision-making regarding photovoltaic (PV) panel waste disposal and insufficient research on managing such waste are the driving forces behind this study. The study aims to address this gap by identifying the factors that affect the performance and efficiency of photovoltaic energy systems, specifically in the United Arab Emirates, a country known for its extremely hot and dry climate, and to develop assessment approaches and guidelines. PVsyst simulation software has been used for system performance analysis and to support decision-making by examining specially designed technical flow charts. The PV panels' basic performance-related parameters and meteorological information were identified as essential elements for evaluating the overall performance. The study also identified the primary tools for making end-of-life (EOL) decisions. The results revealed that the photovoltaic system in the UAE solar park completed its end-of-life with a PR ratio of 80% sooner than expected, with 22 years compared to the 25 years predicted by the manufacturer. This leads to the conclusion that installing PV panels in hot climate regions accelerates the deterioration of PV panels. India, a country with very hot and rainy weather, also backed up these assumptions by reaching an 80.8% PR in 22 years. The study provides a clear understanding of the factors that must be considered when deciding where to install solar panels due to their impact on the efficiency and health of the panels, and the conditions that cause PV systems to fail earlier than expected, thus introducing more waste to the environment.

ملخص البحث

مع ازدياد عدد تركيب واستخدام الألواح الشمسية، من المتوقع أن تزداد كمية الألواح المهملة إلى حوالي 60 مليون طن بحلول العام 2050. بافتراض أن عمر الألواح يتراوح بين 20 إلى 30 عاماً وبهذا فإن هنالك خوف عالمي جديد معن بضرورة إدارة هذا النوع الجديد من النفايات والمخلفات التكنولوجية. تحتوي الألواح الشمسية التي انتهت صلاحيتها وانتهى عمرها الافتراضي على مكونات قيمة، ولكن لا توجد حالياً إرشادات عالمية موثقة لإدارة هذا النوع من النفايات بكفاءة.

تهدف هذه الدراسة إلى دراسة نفايات الطاقة الشمسية الكهروضوئية فيما يتعلق بإدارة أصول الطاقة الشمسية التي وصلت إلى نهاية عمرها المتوقع، المثبتة في مزرعة للطاقة الشمسية في دولة الإمارات العربية المتحدة. نظراً للقيود على تطبيق طرق البحث المقترحة، قام الباحث بإجراء تحليل مقارنة من خلال دراسة أربع مناطق مناخية مختلفة: الإمارات العربية المتحدة وكندا والهند والنرويج، لتعزيز صحة النتائج وإثبات صلاحيتها وكفاءة البرنامج المستخدم.

القوى الدافعة لهذه الدراسة هي عدم وجود موجهات وأطر عالمية شاملة توجه عملية اتخاذ القرار بشأن التخلص من نفايات الألواح الكهروضوئية، وكذلك عدم وجود دراسات كافية لإدارة مثل هذه النفايات. تهدف الدراسة إلى معالجة هذه الفجوة من خلال تحديد العوامل التي تؤثر على أداء وكفاءة أنظمة الطاقة الشمسية الكهروضوئية، خصوصاً في دولة الإمارات العربية المتحدة - وهي دولة معروفة بمناخها الحار والجاف للغاية، وبالإضافة إلى تطوير أساليب التقييم والإرشاد. أستخدم برنامج المحاكاة بي في سيست PVsyst لأغراض تحليل أداء النظام وفعاليته، وتقديم الدعم في عملية اتخاذ القرار بشأن أصول الألواح الكهروضوئية من خلال عرض وشرح رسوم بيانية تقنية مصممة خصيصاً، حيث حددت المعلومات الأساسية المتعلقة بأداء وفعالية الوحدات الشمسية، جنباً إلى جنب مع معلومات الأرصاد الجوية، كعناصر مهمة لتقييم الأداء العام. حددت الدراسة أيضاً الأدوات الرئيسية المستخدمة لاتخاذ القرارات المتعلقة بنهاية العمر الافتراضي.

أظهرت نتائج البحث أن العمر الافتراضي للنظام الكهروضوئي في حديقة الطاقة الشمسية في الإمارات العربية المتحدة وصل إلى عمره النهائي في وقت أقرب مما هو متوقع بنسبة 80%، في خلال 22 عاماً وليس 25 عاماً كما متوقع من الشركة المصنعة. هذا يقود إلى استنتاج بأن تركيب الألواح الشمسية الكهروضوئية في مناطق ذات مناخ حار يسرع من تدهور صحة وأداء الألواح الشمسية. بالإضافة إلى ذلك، دعمت الهند، وهي دولة ذات طقس حار جداً وممطر، هذه الافتراضات حيث وصلت الألواح الشمسية التي تم اختبارها لنسبة أداء وكفاءة إلى 80.8%، أي 22 عاماً أيضاً. توفر هذه الدراسة فهماً واضحاً للعوامل التي يجب مراعاتها عند اتخاذ قرار بموقع تركيب الألواح الشمسية الكهروضوئية نظراً لتأثيرها على كفاءتها وصحتها. بالإضافة إلى ذلك، وضحت الدراسة الظروف التي تؤدي إلى فشل أنظمة الألواح الشمسية الكهروضوئية أبكر من المتوقع، وبالتالي يتسبب في زيادة كميات النفايات المطروحة في البيئة.

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Chapter 1 Introduction

1.1 Introduction

Electricity is an essential component of any country's infrastructure that contributes to its long-term development. Solar photovoltaic panels (PV) are frequently acknowledged as one of the world's top renewable energy sources (Papamichael et al., 2022). The United Arab Emirates and Dubai, in particular, are concentrating their investments in technology and initiatives related to renewable energy (RE), and by being chosen to house the International Renewable Energy Agency's headquarters (IRENA), the UAE has established itself as a global leader (Obaideen et al. 2021). In this context, Dubai set up policies and mechanisms to ensure the availability and reliability of power supply for current and future generations by implementing best practices to ensure effective operations while conserving the environment and ensuring resource sustainability.

One of the crucial initiatives of HH Sheikh Mohammed bin Rashid Al Maktoum's ambition to create a green economy in the United Arab Emirates and achieve sustainable development goals (SDGs) is the creation of Mohammed bin Rashid Al Maktoum Solar Park. The MBR Solar Park, the world's largest renewable energy project on a single site with a projected production capacity of 5,000 MW upon completion in 2030, is committed to meeting the UAE Energy Strategy 2050, the Dubai Clean Energy Strategy 2050, and the Dubai Net Zero Emissions Strategy 2050 by producing 100% of its energy from clean sources by 2050 (Obaideen et al. 2021 & DEWA 2019).

It is essential to understand the significance of end-of-life management in the context of sustainable development, mainly when dealing with PV assets. To address the gap in existing research works in the field and build on the need for further empirical investigation, this study explores the most significant variables that affect PV asset performance in four countries with four different climate characteristics and utilises a technical method and approach to provide a proper guide for End-of-life EOL decisions related to PV solar panels.

Although solar panels are designed to withstand environmental pressures and have a lifespan of around 20-30 years (Oteng et al. 2022; IRENA 2021, European-Ukrainian 2021, Parliament et

al. 2020 & Sharma et al. 2019), there is a lack of end-of-life management area in existing studies. Most countries need more regulations regarding the proper disposal of solar panels, resulting in the likelihood of many panels being discarded in landfills, which can have harmful environmental effects.

This research paper aims to provide a clear and systematic approach to evaluating the efficiency and performance of PV panels by utilising PV simulation software analysis tools (PVsyst) to investigate system performance which will support the decision-making process of PV asset waste at the mid-life or End-life cycle.

1.2 Problem Statement

The solar asset management sector is developing and maturing at a new level. Power utilities are looking to shift their assets from fossil fuels to cleaner and renewable energy assets to keep up with new chances and challenges. One of the concerns is how to manage solar PV waste after it has served its purpose. End-of-life PV panels are made of high-quality components and provide an excellent opportunity to develop a strategy or framework for managing a significant amount of its produced waste. There needs to be a globally documented framework, process, or mechanism for effectively handling such waste (Papamichael et al., 2022). EU is the only region that has proposed detailed legislation for the disposal and recycling of solar PV components.

1.3 Research Significance and Novelty

This research paper aims to outline the first guideline and decision-making process for the waste of solar assets at the level of Dubai, the UAE, the Arab Gulf, and the Middle East countries. Hence, its novelty by introducing a new approach and proposing a new pioneering solution in this field. The researcher's goal is to help, guide and encourage the stakeholders to set asset management plans in advance for the EOL End-of-life or Mid-of-life asset cycle of the solar panels considering a 25 to 30 years' timeframe. For example, if a PV panel fails in the middle of its lifespan, it could be disposed of or repaired earlier than predicted by the manufacturer. By identifying clear objectives and creating a comprehensive plan for solar

assets, the project's sustainability can be improved, and solar stakeholders can also prevent or avoid unexpected situations.

1.4 Research Questions:

The author aims to answer and achieve the following research questions and objectives.

1. What are the primary parameters of PV modules for evaluating performance?
2. What is the most effective approach to evaluating PV panel performance to inform end-of-life (EOL) decisions?

1.5 Research Objectives:

1. Maximize the production efficiency and performance of PV systems by adopting asset performance analysis software & tools to support decision-making and evaluate the impact of waste generated by PV assets.
2. Provide guidelines & decision-making procedures during and after solar assets' lifecycle.
3. Identify effective criteria and parameters for the decision-making process.

1.6 Research Outline Structure:

The following report will go through six chapters:

- Chapter 1: is the introductory chapter for the whole research paper, it will give holistic view of the entire study.
- Chapter 2: will review the literatures to satisfy the research objectives through looking into what others have already explored and studied about the same topic, it will help in understand what's already known and what researchers still need to discover.
- Chapter 3: is the methodology that the research will follow to obtain the final results.
- Chapter 4: which discusses the data analysis and results.
- Chapter 5: concludes the report and discusses the suggested recommendation to support decision making process and improve current practices.
- Chapter 6: references.

Chapter 2 Literature Review:

The following literature review discusses four main topics: Asset Management, Solar Waste Management, Performance Evaluation of Solar PV Systems, and Evaluation and Decision-Making standard tools. For further discussion and analysis, they were segregated into sub-topics. The first topic explores ISO 55001 series for asset management AM, its impact on managing asset performance, and its role in maximising energy generation plants' efficiency. The second topic provides an overview of waste management, including how decisions are made at the end-of-life of the assets, managing solar photovoltaic systems waste, and discussing the established policies and regulations to manage solar PV waste. The third topic then discusses four different PV systems performance evaluation methodologies. Finally, the fourth topic presents MCDM methods and Technical flow charts, two commonly used evaluation and Decision-Making tools.

The main goal of this literature review is to build a comprehensive understanding of the solar assets' situations at their end of life when it is converted to waste, the role of extending their lifespan through the ISO 55000 standards, and how to evaluate their performance after it served its purpose to make the proper decision regarding its waste as per earlier published studies.

2.1 Asset Management

Reference to (Alsyounf et al. 2021; Favar et al. 2022; Lima and Costa 2019; Pillot et al. 2021; Renan 2021), effective asset management systems qualify companies to efficiently manage their physical assets to accomplish the organisation's goals and objectives by properly utilising the available knowledge and resources to optimise the cost, risk, opportunity, and performance. As per studies conducted by (Alsyounf et al. 2021; Favar et al. 2022; Mirhosseini & Keynia 2021), asset management involve various stages of an asset's lifecycle, starting with investing in the right asset for performance enhancement, optimising the efficiency of operation and maintenance, and taking the most suitable decision at the end of asset's life amongst repair, disposal, or refurbishment. However, relying too much on physical assets highlights the need for solid and reliable asset management systems. Several studies, such as (Favar et al. 2022 & Konstantakos et al. 2019), have proved that effective asset management has a significant

influence on maximising companies' performance in the power and electricity sector, which makes it an essential factor for sustainability and improvement of organisations in the short and long term.

2.1.1 ISO 55000 Standards Impact on Managing Asset Performance

To review the impact of following ISO 55000 standards on the management and utilisation of asset performance, recent studies by (Alsyouf et al. 2021; Favar et al. 2022; Renan, 2021) presented the ISO 55000 chain of asset management standards that was announced in 2014. It has a great opportunity to improve maintenance performance. Managing the asset lifecycle maintenance phase properly can have many benefits, such as services and risk management improvement, increased efficiency and asset life, and improved organisational sustainability. Furthermore, all industries and asset types are eligible to apply the ISO 55000 series since it provides a methodical approach to asset management, and it is based on the commonly known Plan Do Check and Act cycle PDCA used to accomplish management system continuous improvement. ISO 55000 and ISO 55002 guide users to apply ISO 55001, the certified asset management system standard. Thus, compliance with ISO 55001 is necessary to obtain certification for a standardised asset management system.

As reported by (Renan 2021), asset management systems built with respect to ISO 55001 standards can effectively interact with other management systems, such as ISO 9001 and ISO 14001, because of their similar structures and components. Many studies investigated the impact of ISO 9001 and ISO 14001 on organisational performance. However, more research needs to be established on how ISO 55000 affects the overall performance of an organisation. This represents a hopeful and potential direction for future research in this field. Asset management is essential to all asset life cycle stages, from manufacturing to disposal. When compared with other management systems, it focuses so much on the operation and maintenance phases because they represent the major cost of the total asset life cycle. A well-structured approach is essential to perform asset disposal and end-of-life management, which highlights the importance of addressing asset management carefully during the life cycle of assets.

Moreover, (Silva & Souza 2020) studied how to relate the use of the ISO 55001 Asset Management System with Total Productive Maintenance (TPM). Traditional theories indicate

that asset maintenance activities are considered a cost that must be minimised. Oppositely, recent studies by (Mirhosseini & Keynia, 2021 and Silva & Souza, 2020) supported the maintenance activities' long-term planning to eliminate breakdowns and defects. The long-term planning includes identifying and addressing equipment causes & failures and assessing what factors are affecting production efficiency. On the other hand, (Lima & Costa, 2019), a Brazilian company that works in the electric power transmission sector, is applying an asset management model. The model focuses on following and complying with regulations for improving the asset management process in an organisation that operates with multiple assets.

2.1.2 ISO 55001 Standard's Role in Maximizing Efficiency in Energy Generation Plants

According to (Alsyounf et al. 2021), previous research papers discussed challenges related to the implementation of the ISO 55001 standards. Examples include establishing an asset management decision-making model that utilises the ISO 55001 general framework to optimise resource allocation and maximise the efficiency of the electric power grid. Another study focused on the utilisation of ISO 55001 and an extensive asset management approach to improve the performance of power systems while reducing operating and maintenance costs. In addition, a specific management framework for asset management in renewable energy was developed, which aims to identify and overcome challenges faced by renewable energy companies, such as limited knowledge sharing between equipment suppliers and users and a lack of guidelines for developing asset maintenance plans for renewable power plants that have multiple technologies. However, there needs to be more research that investigates the effect of mixing ISO 55000, ISO 9001 and ISO 14001 on the performance of plants generating renewable power before and after implementation, particularly in the UAE, which indicates a gap for future research. Further, (Brem et al. 2020; Pasvorarotkool & Mongkon 2020) agreed that ISO 50001 international standards and certifications have a role in improving quality, efficiency and performance in different types of industries. These standards ensure efficient operations and highlight key areas to enhance the development and function of the systems that affect their processes. Additionally, ISO 50001 standards are designed to provide a globally valuable framework that supports companies in the achievement of energy savings and emissions reduction. It aims to serve as a benchmark in the energy management area by supporting continuous improvement plans to enhance energy efficiency and performance.

Many organisations in UAE are certified in ISO 55001. According to the well-known Technical Committee (ISO), there are 279 organisations worldwide accredited to ISO 55001, 21 of them are in Middle Easter countries, and 12 of them are located in the UAE, which makes it one of the best ISO 55001 accredited countries. These certified companies include Al Ain Distribution Company, TRANSCO, Dubai Electricity and Water Authority (DEWA), Emaar Asset Management, Farnek, National Archives, and QuantGulf. Equipment and General Maintenance, RTA RTA, ADNOC LNG, ADNOC, Abu Dhabi Ports, BESIX Processor. Dubai Electricity and Water Authority (DEWA) is recognised as the first utility in the area to implement the RCM method (Reliability Centered Maintenance Method) and was given the ISO 55001 Asset Management certification in 2016. It was the first company worldwide to win this prestigious award. (Al-Sayouf et al. He, 2021) investigated the implementation of asset management standards (ISO 55001) effect on the performance of UAE organisations with ISO 55000 accreditation. The study revealed many benefits associated with the implementation of ISO 55001, such as improvement in financial performance, enhanced asset allocation and risk management, improved provided services and outputs, a very strong company reputation, and increased system efficiency.

2.2 Waste Management

Waste refers to any substance or item that is disposed of or expected to be disposed of by the user or owner, and it is either in a solid, liquid or gaseous shape. As per (Abenezer et al. 2019), this waste can come from various sources such as homes, industries, healthcare facilities, and more. As generated waste has increased dramatically in past years due to growth in population, development projects and technological advancements, efficient waste management becomes a must to maintain a sustainable environment successfully. In most countries, open waste dumping areas remain the classical method of waste management due to their lower costs. As agreed by (Oti et al. 2023; Çelik & Cansu 2022; Abenezer et al. 2019), different aspects shall be viewed once determining effective management of waste. It includes the administrative, environmental, financial, technical and social factors.

2.2.1 Waste Management Decision-Making

In a study by (Celik et al. 2022), the researchers highlight that the existing research on waste management shall incorporate statistics and MCDM methods which stand for multi-criteria decision-making methods. The study was conducted in Turkey using the MCDM approach to examine how medical waste management is done. Using MCDM, the evaluation criteria are defined depending on the previous studies and expert opinions findings. For decision-making improvement in undefined situations, the authors proposed a decision-making (DM) model that applies combining viewpoints and judgments through group decision-making (GDM). The study built on conducting an impact assessment to understand the effect of changing the weights of criteria on the other evaluations. The results found that the leading medical waste disposal method in Turkey is burning. The study is valuable to both researchers and practitioners as it provides a real-world guide for developing medical waste management procedures. However, researchers can consider integrating blockchain technology in their future research in addition to exploring different MCDM methods to improve waste management.

Another study supports the MCDM method conducted by (Selim et al. 2022). The study focuses on managing marine OSRW (oil spill response waste). The researchers developed a framework of six stages, which included product life cycle valuation, MCDM, and cost analysis—the framework aimed to assess the environmental footprint and costs of different OSRW management plans. The study ranked strategies based on their environmental impact and cost and identified other disposal options for combining filtration and landfilling. Besides regression models were also developed to forecast the effect on the environment. The study concluded that landfilling has considerable negative impacts on human health and the environment; however, adopting the proposed framework can help decision-makers in evaluating different scenarios of OSRW management strategies.

2.2.2 Asset Waste Management (EOL End of Life Management)

Asset waste management is not a well-known term in the area of waste control and management. Still, the interest in applying waste management theories and principles to asset management is increasing. According to (Silva & Souza 2020), asset management is essential to guarantee efficient operation and maintenance O&M of new equipment. Poor knowledge or

lack of equipment historical performance and maintenance events can lead to decreasing equipment lifetime. Therefore, building an integrated asset management and maintenance system is essential. One way to create such a system is to benchmark with existing systems and apply the required improvements. Additionally, the asset management system must meet the requirements of ISO 55001, considering the links between the asset management system and waste management system structure.

Many studies in the power system management field didn't take the asset end-of-life EOL into considerations while studying and analysing the systems. As an example, (Mirhosseini & Keynia 2021) conducted a study focusing on improving the cost-effectiveness of equipment during its lifetime. The study included various phases, such as network design, asset management, and asset commissioning, to confirm the safe and efficient operation. However, the study did not reflect asset management at the end of its life cycle EOL. Another recent study by (Wang & Wang 2022) focused on the electronic & electrical waste recycling sector located in China. The Fuzzy Delphi technique was utilised to identify the main challenges and the industry's cause-and-effect relationships. Researchers found that guidelines implementation and proper dismantling of electronics were the most critical challenges to achieving organisational development. As a result, the government shall improve the implementation of e-waste disposal regulations and tackle challenges such as ineffective laws and unofficial waste collectors.

2.2.3 Solar Asset Waste Management (Solar EOL)

2.2.3.1 Solar Photovoltaic Assets

As discussed by (Guo & Gong 2022; Pillot et al. 2021), there are major universal problems such as climate change, environmental risks, and lack of energy and resources, where countries and governments need to work together to find sustainable solutions for global energy development. Solar panels are widely known as a significant source of renewable energy production (Papamichael et al., 2022). According to (Stock, 2022), the Indian government is focusing on building large solar parks to fight climate change and commit to meeting Paris Agreement. The researcher also highlighted the huge impact of climate change on rural areas in South Asia, which stresses the importance of quickly switching to renewable energy sources to protect these areas. One of the Indian initiatives is ISA International Solar Alliance, which was

introduced to help and support other underdeveloped regions in building solar parks. Similarly, as presented by (Obaideen et al. 2021), the UAE, especially Dubai, is focusing its investment in renewable energy new technology and projects. One of Dubai's major investments is the Mohammed bin Rashid Al Maktoum Solar Park. This project advocated achieving the sustainable development goals of the UAE by 2030 by being the largest renewable energy project in one location in the world, with an expected power generation of 5,000 megawatts.

According to (Huxley et al. 2022), three main factors must be considered when predicting and evaluating the efficiency of PV panel energy generation. First: weather data, including temperature, solar irradiation, wind, and humidity. Second: electrical or technical measurements of energy output to evaluate the performance of the PV system. Third: technical specification of the system, such as the site location, age of commissioning, and capacity of PV modules. The Netherlands were pioneering in establishing a model that studies the significant factors affecting PV energy generation, such as dirt, shading, sunlight, system efficiency, panel surface reflectivity, and module temperature. Adopting these models and actual weather data help in estimating the performance and efficiency of the PV systems. However, when data are missing or not sufficient for accurate system configuration, a failure mode impacts analysis is frequently used to evaluate uncertainty in PV capacity. Following this method helps in maintaining PV assets and extending their lifetime before reaching the EOL end of their life.

2.2.3.2 Solar Asset Waste Management

As stated by (Fiandra et al. 2023), PV solar panels will become waste at the end of their service-useful life; then, they shall be treated as per the standard methods for electronic waste (WEEE). However, the difficulty in repairing, preserving, reusing and recycling their components is due to the module design that restricts the recovery of the valuable materials. Moreover, panels that reach end-of-life are classified as hazardous waste because they contain harmful elements besides the valuable components mentioned earlier. Proceeding with the recovery of these valuable materials is the main goal of PV waste treatment, and this requires placing appropriate management plans for improving the efficiency and quality of material recovery.

As highlighted by (Fiandra et al. 2023, IRINA 2021, Papamichael et al. 2022, and Sharma et al. 2019), with the increased adoption of PV systems for achieving sustainable development, taking action related to EOL management policies and regulations has become very important. Furthermore, the increase in the number of PV installations will reflect on the increased amount of expected decommissioned PV panels; hence, a significant amount of waste is coming by early 2030, and an estimation of 60 million tons of global waste by 2050 assuming panel life of 20-30 years. And as declared by (Farrell et al. 2020 and Oteng et al. 2022), a large volume of PV waste may end up in landfills, which could be more ecologically sustainable due to the existence of risky metals in the panels that can pollute the soil. Therefore, proper management measures are required. In addition, (Curtis et al. 2021, IRINA 2021, and Obaidin et al. 2021) agreed that to ensure the durability and sustainability of PV systems, assessing the economic, environmental, and social impacts of end-of-life management is necessary, even with the current lack of established technologies and guidelines for managing these PV waste.

2.2.3.3 Policy and Regulations Managing Solar PV Waste

The solar PV recycling industry is facing serious challenges in meeting waste collection and recycling goals as a result of insufficient regulations and policies, leading to the dumping of panels in landfills. Wide research is being conducted worldwide to understand the factors affecting solar efficiency to extend its life and, on the other hand, the management and recycling of PV waste once it reaches the end of its life. As per the studies by (Curtis et al. 2021; Fiandra et al. 2023; Oteng et al. 2022; Salim et al. 2021; Sharma et al. 2019; Parliament et al. 2020; Sandanayake et al. 2022), researchers highlighted the importance of exploring all current practices and established approaches for solar PV waste management. Moreover, governmental and private sector professionals need to evaluate the methods used to transport, treat and recycle PV waste.

In reference to (Oteng et al. 2022; Salim et al. 2021), recent studies highlight the need to prevent negative environmental and health impacts caused by hazardous PV materials, and countries are attempting to develop waste management guidelines and policies for solar PV to solve these concerns.

As discussed by (Daniela-Abigail et al. 2022; Nain and Kumar 2022; Oteng et al. 2022), China lacks regulations that tackle PV waste management. However, ongoing research is being conducted to discover safe disposal methods and recycling techniques. Furthermore, Japan and India also lack regulations for managing PV modules at EOL, and waste in India is treated as general waste under their waste law. Additionally, Australia listed the need to establish a PV waste regulation as a priority in the National Waste Policy Action Plan. (Oteng et al., 2022) highlighted that Australia lacks suitable management plans to deal with PV waste hazardous components and lacks recycling facilities for its valued components. The study aims to find the gap in PV waste management by using expert interviews and analysis. It provides a theoretical framework of present processes and benchmarks Australia's PV waste management practices with other countries. Besides, as pointed in (by Curtis et al. 2021, Oteng et al. 2022, Daniela-Abigail et al. 2022, Nain and Kumar 2022), in the US, each state is developing its policies since US federal law does not regulate the recycling of solar PV waste.

(Oteng et al. 2022, Majewski et al. 2021, Parliament et al. 2020) The European Union (EU) earned a leading role in regulating PV waste generation and management in Europe through the employment of the WEEE directive. EU is considered the only region with defined regulation for the disposal of solar PV components, established by the revised WEEE Regulation 2012/19/EU. This directive necessitates European countries establish plans to manage PV waste, coordinating with suppliers and manufacturers.

In a study conducted by (Curtis et al. 2021), conference calls and email were used in interviewing PV industry professionals, including manufacturers, PV asset stockholders, and recycling companies. The study aimed to identify the most important difficulties and gaps that prevent the effective management of PV asset waste. The results discovered that there are many challenges, such as a lack of test readings or data, insufficient recycling systems, lack of infrastructure facilities, and improper regulations. The study also highlighted areas that require further research and access to required data, such as the cost and value of used PV materials, anticipating the volume of upcoming PV modules that will reach the end of their life, evaluating technological development related to PV systems disposal, and assessing the required infrastructure. Some factors are considered essential for managing EOL PV panels, like establishing governmental-approved guidelines, practising creative and innovative business

plans, and enhancing the capabilities of local businesses and the PV recycling industry. Countries that are new to the challenges of PV systems recycling can learn from the EU's lessons learnt, knowledge, and in developing frameworks. Benchmarking the best practices with qualified PV manufacturers is important, too, in putting the right sustainable solutions for PV end-of-life management (Sharma et al. 2019).

2.3 PV Systems Performance Evaluation Methodologies:

Building on this approach, several methodologies and tools are commonly presented under the efficiency and performance evaluation of the solar asset that will support future decision-making at the EOL phase, such as I-V curve testing, Performance Ratio PR calculation, and PV laboratory flash tests.

2.3.1 The I-V Curve Testing:

The I-V curve test is an important testing tool for evaluating the electrical performance and healthiness of a PV system. The test helps understand and assess the efficiency and performance by providing valuable information on the panel's voltage, current (short & open circuit), and maximum power point, under different operational environments. Moreover, temperature and radiation are two main variables being measured during the test, as they can impact panel efficiency. The data collected in the site test is then normalised for precise evaluations between different PV panels. Overall, the I-V curve test is a crucial tool that helps make informed decisions about panel performance and maintenance requirements.

2.3.2 Performance Ratio (PR) Calculation:

One of the highly important measures of a PV system's efficiency is the Performance Ratio (PR). It indicates the ratio of the actual energy production of the system to its expected energy production under standardised test conditions STC (IEC 61724 standard). The PR is calculated in different ways, manually using mathematical equations or by using software such as PVsyst, based on significant identified parameters like location, panel technical specifications, and meteorological data. A high PR indicates an efficient and effective operative system, while a

low PR indicates functioning issues or inefficiencies. The PR allows efficient system operation and maintenance over time, providing valuable perceptions of its performance.

Performance Ratio (PR) equation:

PR = Actual Power Output / nominal Power Output (Cura et al. 2022)

$$PR = P_i \left(\frac{I_t}{1000} \right) \times P_n$$

Where P_i (W) is the Actual power output generated by the PV system, I_t (W/m²) Total solar radiation is the total amount of solar radiation received by the PV system and P_n (W) is the nominal power output of the PV system.

2.3.3 The Flash Test:

The flash test is a highly reliable method for accurately evaluating the performance of PV panels, usually when there is an indication of low-efficiency results from the I-V site test. During the test, the panel is exposed to a short burst of light to simulate an increase in solar irradiance to measure then how well it is producing electrical energy. The flash test is conducted in a laboratory under a controlled environment and testing conditions, and using specialised software, machines, & equipment for accurate and reliable results. Furthermore, this test is recognised globally by all PV panel manufacturers and used to validate the performance, quality, and warranty claims of PV panels.

2.3.4 PVsyst Simulation Software:

According to (, Agyekum et al. 2022), one of the commonly used simulation software in designing power plants optimisation projects and evaluating and investigating the performance and energy production of the plant to assist the site engineers and manufacturer in improving the system design or efficiency is the PVsyst simulation tool. This tool needs specific meteorological data, such as the effect of solar irradiation, temperature, and local environmental conditions, and the electrical specifications of the PV system components for the simulation. The use of PV technology and extensive knowledge is essential for the accurate prediction of system output. Various recent research papers supported the use of this tool (Ahmad & Ahmad

2019; Agyekum et al. 2022; Belmahdi & Al Bouardi 2020; Al-Zoubi et al. 2021; Ahmed et al. 2021).

2.4 Evaluation and Decision-Making Common Tools:

2.4.1 Multi-Criteria Decision-Making MCDM:

According to (Lima & Costa (2019), companies with multiple types of assets operating in strict and highly controlled sectors shall adopt a decision-making approach that considers various criteria and expert opinions. This approach helps companies in classifying and prioritising the most important things they need to do regarding following their industries' guidelines and regulations. Effective business management is important as it helps them utilise their assets while ensuring they are sustainable and can compete well, even with the restrictions and limitations forced by regulations.

It is important to consider various aspects when it comes to deciding the waste of PV solar assets, such as electrical, environmental, thermal, and economic. Popular tools utilised to make the best decision are called Multi-Criteria Decision-Making (MCDM) methods, which propose analytical tools for choosing the best option among alternatives. MCDM methods contain MODM, known as Multi-Objective Decision-Making, and MADM, which is recognised as Multi-Attribute Decision-Making. This research aims to serve as a decision-making tool for dealing with PV panels at the end of their lifetime. (Villacreses et al. 2022 and Topsis 2022).

According to (Li et al. 2022), previous studies on power sector planning utilised multi-criteria decision-making methods to provide a theoretical basis for energy planning. However, these studies didn't offer to consider preparing frameworks for effective capacity allocation of energy systems. In response, (Li et al. 2022) developed a framework for rural regions to plan renewable energy systems. The developed framework considered important factors like the economy, available resources, and environment. in the Multi-Criteria Decision-Making (MCDM) system and offered an optimisation model to evaluate the cost and system effectiveness. The MCDM system was applied in four Chinese cities to determine the most effective renewable energy type to be used for each city. The study evaluated the power output, cost, and efficiency of system energy during various seasons and mainly focused on two objectives: minimising cost and

maximising energy efficiency. The results discovered that the proposed framework provides an effective approach related to renewable energy planning by considering the unique features of each renewable energy source and area and seasonal weather differences.

Beside the MCDM methods, researchers utilised other suitable methods for the management of end-of-life (EoL) solar photovoltaic (PV) waste. According to (Bui et al. 2020; Oteng et al. 2022; Wang and Wang 2022), earlier studies of waste management utilised the Fuzzy Delphi method (FDM). As per (Oteng et al. 2022), researchers used a revised version of FDM to develop a theoretical framework for managing end-of-life solar PV waste in Australia through interviewing professionals and government members and analysing qualitative data using NVivo software. The study parameters included solar technology types, available regulations and policies, monitoring and logistics, suitable treatment processes, and infrastructure needed for PV waste management. The theoretical framework aims to help researchers and PV owners to understand the condition of PV waste now and in future to guide them in preparing management or recycling plans. Moreover, it aims to establish future research that focuses on the life cycle assessment and consumer expectations of PV life and waste management.

A study (Hocine & Samira 2019) investigated what factors influence the efficiency of PV panels in Algeria to improve their performance and expand their lifespan. One of the factors is age, where the ageing process is complex due to different factors that make each panel age differently. Harsh weather conditions can accelerate ageing, specifically in hot and dry desert areas, and the most optimal replacement timing for a PV is every 25 years. However, different climate impacts can increase the average ageing of panels by over 0.8%. The authors found that the average ageing of PV panels in highland, coastal, and desert areas was 0.8%, 1%, and 1.2%, respectively. In addition, waste of PV panels can still produce electricity for rural lighting or pumping in remote areas as an alternative to decommissioning.

2.4.2 Technical Evaluation Flowcharts:

(Jerome et al., 2022) stated that a common tool used to address the gaps in LCA life cycle assessment case studies is technical flowcharts. By developing a detailed flowchart, the researcher aims to help the reader in reviewing existing indicators by demonstrating clear processes and testing the resource flows, providing direction for recognising, selecting, and

developing evaluation indicators that will be compared with the LCA results and investigating the differences in the drawn conclusions of the two methods. (Dong et al., 2023) supported the use of flowcharts by establishing a product decision-making system that depends on the flowchart input and output parameters.

Moreover, studies showed that technical evaluation flowcharts are widely used for decision-making in the medical sector (Chao et al., 2022)—a medical study aimed to demonstrate a mutual decision-making process among diverse specialised doctors for high-risk patients. To help with decision-making, flowcharts were generated to employ various clinical techniques, where doctors collaborated and discussed with one another and proved the benefit of the adopted decision-making method. Another study (Chen & Bai 2023) revealed the value and positive sides of using flowcharts when making decisions. First, it allows a thorough evaluation of data and helps in forecasting the required results. This is preferable when depending on specialised judgment. Furthermore, it prevents confusion and reduces the workload on the professionals. Finally, the technique is easy to use, reliable and effective in completing its objectives.

To conclude, it was essential to conduct a comprehensive review of the existing research to understand better the challenges and opportunities related to solar PV. This literature review focuses on the current level of knowledge regarding waste management for solar PV assets, which covers the need for existing global guidelines or laws established for managing this waste. It also covered recent research on decision-making in the areas of Asset Management and waste management, with specific stress on topics such as the ISO 55000 series of asset management and its role in maintaining the efficiency of assets in power systems, certified organisations in UAE with asset management standards, an overview of Solar Asset Waste Management, and standard tools and methods used in earlier studies for waste management to investigate, assess the PV performance and efficiency to relate them to the decision-making procedure.

The researcher also discussed several methodologies and tools that are commonly used for the efficiency and performance evaluation of PV solar assets, such as the I-V test, flash test, performance ratio calculations, and utilising simulation software. In addition, for establishing a process or guideline related to waste management and end-of-life (EOL) photovoltaic (PV) waste, the multi-criteria decision-making methods and technical flowcharts were presented to

offer alternatives to the researcher and reader as accepted methods for evaluation and decision making. This review aims to provide awareness of which tool is most proper to be used in the following stages of the report and which methodology to adopt to verify and achieve the research objectives.

Chapter 3 Research methodology:

3.1 Research Design:

3.1.1 Research Approach: Qualitative.

3.1.2 Research Design: Descriptive and Correlational.

3.1.3 Motivation:

The study will utilise both descriptive and correlational designs to analyse the performance of PV panels and identify connections between various variables such as power output, voltage, current, panel age, degradation rate, and performance indicators with respect to the weather parameters, which are the primary influence on the PV panels health and efficiency. This mixed methods approach will provide a comprehensive understanding of the lifetime performance of PV panels, which is essential for making informed decisions about their end-of-life.

3.2 Participants and Data Collection:

The research methodology will consist of several phases to explore the topic novelty broadly and agree on the proper methodologies and tools that will be adopted in the performance evaluation and decision-making process regarding solar assets. As represented in the earlier chapter of the literature review, the below-listed tools are considered the most effective and trusted in recent studies and as experts' opinion:

- 1- I-V curve tracing
- 2- Flash Test
- 3- Performance Ratio PR calculation
- 4- PVsyst simulation software

First, a review of recent studies will be represented to inspect the most used techniques and methods in PV systems performance evaluation. Then, to examine the research objectives and to ensure the accuracy and comprehensiveness of the evaluation, the study will employ a commonly used simulation software tool (PVsyst) to build a convenient research conclusion,

support the evaluation process further and offer a reliable framework for assessing the efficiency of PV panels, with the possibility to implement the same in other contexts under the renewable energy industry.

Due to the limitations confronted in this research paper, the researcher contacted four different organisations, three in UAE and one in France, through different communication channels such as physical meetings, online Zoom meetings, phone calls, and emails to obtain the I-V curve tracing data (Actual data from site testing) to calculate the performance of PV panel. All these efforts failed since all utilities consider these data highly confidential. Moreover, the Flash Test suggestion was disregarded since this test requires special laboratories and qualified experts to execute the test and obtain the results. Furthermore, it is possible to implement Performance Ratio (PR) calculation through any of the three above methodologies; therefore, the researcher has no choice but to use the PVsyst simulation software, which is a highly reliable and effective tool to indicate plant performance.

3.2.1 Comparing Methodologies for Evaluating Photovoltaic Performance: A Review of Recent Studies

Table 1: Comparison of Methodologies for Evaluating PV Performance

Regions	Authors	Year	Methodology	Parameters	Result/Discussion	Identified GAP
Hungary	István Bodnár, Dávid Matusz- Kalász , Rafael Ruben Boros and Róbert Lipták	2021	Flash Test	Max Power Max Volt Max Current Voc – Isc	Evaluate PV performance by using the Flash test that gives a comprehensive view of the real state of the modules in the LAB by finding PR and I-V curves.	This study relies solely on flash tests to evaluate performance and does not address low efficiency or end-of-life (EOL) waste decision-making.
Egypt	Nancy Mahmoud Badawy, Hosam Salah El Samaty, & Ahmed Abd Elaziz Waseef	2022	PVsol software	Geographical and weather data and electrical parameters (Max Power Max Volt Max Current	The study aims to select the most appropriate PV type for application in certain locations through simulation using PVsol. The results showed which type is inadequate under similar weather conditions in terms of	This study relies exclusively on PVsol software for decision-making in selecting the best technology in certain regions and does not address decision-making related to low efficiency or end-of-life (EOL) waste.

				Voc – Isc)	their (PR), output power, and annual yield and indicated the module that provides the highest PR and annual yield.	
Morocco	Brahim Belmahdi & Abdelmajid Al Bouardi	2020	PVsyst Software	Geographical and weather data and electrical parameters (Max Power Max Volt Max Current Voc – Isc)	Modelling & simulation for PV plant & evaluate its performance. PR and Power losses are calculated in 3 different Cities to decide on the feasibility of installing PV in one of them. PVsyst used the mathematical model (Perez model) to calculate the amount of solar radiation that is expected to be incident on the surface.	This study relies solely on PVsyst to evaluate performance and does not address low efficiency or end-of-life (EOL) waste decision-making.
Jordan	Habis Al-Zoubi, Yaqoub Khasawneh, & Waid Omar	2021	PVGIS software & software (PVsyst). Geographical and weather Data,	Geographical and weather data and electrical parameters (Max Power Max Volt Max Current Voc – Isc)	technical and economic feasibility study of utilising an on-grid photovoltaic (PV) system through simulation using Photovoltaic Geographical Information System software (PVGIS) and photovoltaic software (PVsyst). PR, energy production & losses calculated, and degradation rate. Results confirm that the on-grid PV system is beneficial and suitable to implement.	The study used PVGIS & PVsyst software for performance evaluation. However, No decision-making was discussed regarding EOL PV waste.
Pakistan	Naseer Ahmed, Atif Naveed Khan Naveed Ahmed, Adnan Aslam, Kashif Imran	2021	PVsyst Software	Geographical and weather data and electrical parameters (Max Power	The study aims to evaluate the feasibility of PV plants by analysing technical, economic, and environmental factors using PVsyst software. Validation shows that the	This study relies solely on PVsyst to evaluate performance and does not address low efficiency or end-of-life (EOL) waste decision-making.

	Muhammad Bilal Sajid, & Adeel Waqas			Max Volt Max Current Voc – Isc)	plant's actual energy production matches the predicted energy production.	
China	WANG Hong, WANG Zhijie2, & FU Xiaolin	2019	PVsyst Software	Weather data, parameters for the selected modules in the software	Used PVsyst software to simulate and calculate project first-year power generation and degradation. The simulation aims to carry out reliable references which help in financial evaluation.	This study relies solely on PVsyst to evaluate performance and does not address decision-making related to using PR or I-V curves and low efficiency or end-of-life (EOL) waste.
Morocco	Salima Sarikha, Mustapha Raoufia, Amin Bennounaa, Ahmed Benlarabib, Badr Ikkenb	2020	I-V curve tracer	Geographical and weather data and electrical parameters (Max Power Max Volt Max Current Voc – Isc)	This paper examined how the degradation of PV modules, & cell cracks affect the I-V curve in PV technology, and compared them to reference modules using simulation.	This study relies solely on an I-V curve tracer to evaluate PV degradation and does not address using any software or take decisions related to low efficiency or end-of-life (EOL) waste.
China	Zhixiang Zhang, Mingyao Ma, Wenting Ma, Rui Zhang, Jun Wang	2022	I-V curve	electrical parameters (Max Power Max Volt Max Current Voc – Isc)	PV string current fault was diagnosed through the I-V curve. The method involves utilising the I-V curve data to create a detection line for the rapid and straightforward identification of current faults.	This study relies solely on the I-V curve to evaluate PV performance and does not address using any software or making decisions related to low efficiency or end-of-life (EOL) waste.
Italy	Fabrizio Leonforte, Claudio Del Pero, Niccolò Aste, Alessandro Miglioli, Lorenzo Croci, Giorgio	2020	Flash Test	Geographical and weather data and electrical parameters (Max Power Max Volt Max Current	The objective of the study was to evaluate and monitor the energy of a novel photovoltaic-thermal system, to enhance its thermal efficiency without compromising its electrical performance, thereby maximising the	This study relies solely on the Flash test to evaluate PV thermal performance and does not address using any software or making decisions related to low efficiency or end-of-life (EOL) waste.

	Besagni			Voc – Isc)	overall performance of the PV system.	
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The above table-1 displays a sample of nine studies that were conducted in nine different countries around the world to evaluate the performance of photovoltaic systems. The main objective of this analysis is to identify previous practices and the most commonly used methodologies for evaluating PV systems performance, which will be taken into consideration in this research paper. By reviewing these studies, the key parameters and methods that were implemented in previous research will be documented and will be useful in determining the most efficient and trustworthy methods for evaluating PV performance.

3.2.2 PV Systems Performance Parameters:

Performance parameters for PV assets are identified through a comprehensive review of the literature and expert knowledge. The parameters are explained in detail further, along with the equations used for calculating the performance ratio by the software. The parameters are classified into two categories: electrical and meteorological. The inclusion of these parameters is crucial for the analysis, as they have a significant impact on the overall performance of each system.

PVsyst simulation software requires specific data (Site Location, Meteorological data, Module Technical Specifications), which are gathered from several sources and used as the input variables:

1. **Site Location & Meteorological data:** The data include average Temperature, Humidity, Wind Speed, and Solar Radiation in specific locations. To compare the effect of different weather conditions on the efficiency and performance of the PV panel, it was significant to perform a comprehensive investigation of the actual energy performance and losses in numerous climatic conditions. Hence four different climate regions were purposely selected in this study, aiming to get a variety of locations with a variety of meteorological data:
 - 1- Very Hot & dry (UAE)
 - 2- Very Cold & Snowy (Norway)

- 3- Very Hot & Rainy (India)
- 4- Very Cold & Rainy (Canada)

In UAE, the main case is to study and investigate a Solar Park in UAE, and data were obtained from the National Center of Meteorology (NCM) website as it is the latest updated source compared with other global sources used in many different research papers. However, NCM covers UAE zones only and has constraints in providing worldwide data. As an alternative, the NASA Meteorological database (Nasa.gov, 2023) was used for the other regions. However, to have consistent data for all regions, data are acquired for the duration from Jan 2000 – Dec 2021 (22 years).

2. PV Module Technical Specifications (Mechanical Characteristics and Electrical Specification) are gathered directly from the actual site of a solar park located in UAE and from the Technical Specifications datasheet provided by the PV module Manufacturer. The same PV module was used in the four regions to ensure an identical comparison.

Below table-2 and table-3 list the most essential PV model technical and mechanical parameters required to evaluate PV panel efficiency and performance as commonly stated by (Ma et al. 2021, Yaichi et al. 2023, Ramanan et al. 2019, Zhang et al. 2022, Seddik et al. 2022).

3.2.2.1 PV Module Mechanical Parameters:

Table 2: PV Module Mechanical Specifications

Parameter	Values
Asset Make	JinkoSolar
Asset Type	Photovoltaic panel JKM410M-72H-TV
Power rating	410W
Cell Type and No. of cells	Half Cell - Mono PERC 72 Cell
Temperature coefficient	of Isc: 0.048%/°C
Dimension	2031x1008x40 mm

Weight	23.3 kg
Warranty	12 Year Product Warranty and 30 Year Performance Power Warranty

(Source: www.jinkosolar.com)

3.2.2.2 PV Module Electrical Parameters:

Table 3: PV Module Electrical Parameters

Parameter	Values
Open circuit voltage (V_{oc})	48.56 V
Short circuit current (I_{sc})	10.51 A
Peak power current (I_{pmax})	10.16 A
Peak power voltage (V_{pmax})	40.38 V
Peak power (P_{max})	410 Wp
Module Efficiency STC (%)	20.03%
Normal operating temperature T_c	45 ± 2 °C
Temperature coefficients of (P_{max})	-0.36%/°C
Temperature coefficients of (V_{oc})	-0.29%/°C
Temperature coefficients of (I_{sc})	0.048%/°C

(Source: www.jinkosolar.com)

3.2.2.3 PV Module Meteorological Parameters:

Table 4, 5, 6, & 7 below includes the weather data of UAE, Canada, India, and Norway for the period (Jan 2000 – Dec 2021) obtained from NASA. In UAE, average temperatures during the

22 years ranged between 20.2 - 35.77 °C, in Canada from -10.56 to 20.94°C, in India between 23.25 - 31.09 °C, and in Norway from -10.8 and 14.37 °C.

Table 4: UAE Average Meteorological and Solar Data (January 2000 - December 2021)

	Temperature °C	Humidity (%)	Wind speed 2 meters (m/s)	Irradiance (kW- hr/m ² /day)
JAN	20.2	60.94	3.06	3.98
FEB	21.18	59.56	3.21	4.77
MA R	23.73	57.23	3.38	5.64
APR	27.64	52.45	3.2	6.39
MA Y	31.57	49.99	3.2	7.19
JUN	34.15	51.41	3.07	7.27
JUL	35.77	50.36	3.05	6.76
AU G	35.68	48.56	2.99	6.52
SEP	33.68	51.63	2.64	6.13
OCT	30.78	53.14	2.47	5.36
NO V	26.42	54.69	2.71	4.33
DEC	22.44	59.17	2.77	3.77
AN N	28.64	54.06	2.98	5.68

(Source: power.larc.nasa.gov)

Table 5: Canada Average Meteorological and Solar data (January 2000 - December 2021)

	Temperature °C	Humidity (%)	Wind speed 2 meters (m/s)	Irradiance (kW- hr/m ² /day)
JAN	-10.56	91.8	3.18	1.5
FEB	-9.16	90.2	3.43	2.45
MAR	-2.8	86.3	3.44	3.64
APR	5.18	81.2	3.13	4.47
MAY	12.81	79.9	2.61	5.29
JUN	18.1	80.4	2.32	5.78
JUL	20.94	79.7	2.12	5.75
AUG	20.37	78.2	2.07	5.08
SEP	16.13	78.3	2.26	4
OCT	8.72	82.3	2.53	2.39
NOV	1.55	86.2	2.68	1.49
DEC	-6.19	91.1	2.86	1.09
ANN	6.33	83.8	2.72	3.58

(Source: power.larc.nasa.gov)

Table 6: India Average Meteorological and Solar Data (January 2000 - December 2021)

	Temperature °C	Humidity (%)	Wind speed 2 meters (m/s)	Irradiance (kW- hr/m ² /day)
JAN	23.25	51.09	2.01	4.88
FEB	25.63	44.44	2.11	5.72
MA R	28.71	44.92	2.21	6.54
APR	30.76	52.52	2.28	6.98
MA Y	31.09	60.16	2.86	6.91
JUN	28.57	79.59	3.63	4.91
JUL	26.6	89.57	4	3.8
AU G	26.05	90.37	3.42	4.03
SEP	26.19	88.53	2.3	4.74
OCT	26.21	77.5	1.75	5.23
NO V	24.67	68.87	1.94	4.84
DEC	23.27	59.79	1.97	4.51
AN N	26.75	67.4	2.54	5.25

(Source: power.larc.nasa.gov)

Table 7: Norway Average Meteorological and Solar Data (January 2000-December 2021)

	Temperature °C	Humidity (%)	Wind speed 2 meters (m/s)	Irradiance (kW- hr/m ² /day)
JAN	-10.8	99.58	0.46	0.11
FEB	-10.05	99.45	0.47	0.64
MA R	-6.51	98.64	0.51	2.01
APR	-0.54	91.98	0.48	3.76
MA Y	6.07	80.8	0.38	4.68
JUN	11.27	77.79	0.23	5.28
JUL	14.37	81.14	0.19	4.81
AU G	12.23	85.59	0.2	3.61
SEP	7.22	90.24	0.2	2.05
OCT	0.73	95.61	0.18	0.81
NO V	-5.38	98.94	0.25	0.19
DEC	-8.9	99.67	0.39	0.03
AN N	0.87	91.58	0.33	2.34

(Source: power.larc.nasa.gov)

Chapter 4 Results and Discussion:

As represented in the previous methodology part, several methodologies and tools are suggested in the performance evaluation and decision-making process regarding the solar asset, such as:

2. I-V curve tracing
3. Flash Test
4. Performance Ratio PR calculation
5. PVsyst simulation software

However, due to the limitations confronted in this research paper, the researcher contacted four different organisations, three in UAE and one in France, through different communication channels such as physical meetings, online Zoom meetings, phone calls, and emails to obtain the I-V curve tracing data (Actual data from site testing) to calculate the performance of PV panels. All these efforts failed since all utilities consider these data highly confidential. Moreover, the Flash Test suggestion was disregarded since this test requires special laboratories and qualified experts to execute the test and obtain the results. Furthermore, it is possible to implement Performance Ratio (PR) calculation through any of the three above methodologies; therefore, the researcher has no choice but to use the PVsyst simulation software, which is a highly reliable and effective tool to indicate plant performance.

PVsyst simulation software requires specific data (Site Location, Meteorological data, Module Technical Specifications), which are gathered from several sources and used as the input variables:

1. Site Location & Meteorological Data:

The data include average Temperature, Humidity, Wind Speed, and Solar Radiation in specific locations. To compare the effect of different weather conditions on the efficiency and performance of the PV panel, it was significant to perform a comprehensive investigation of the actual energy performance and losses in numerous climatic conditions; hence four different climate regions were purposely selected in this study aiming to get a variety of locations with a variety of meteorological data:

1. Very Hot & dry (UAE)

2. Very Cold & Snowy (Norway)
3. Very Hot & Rainy (India)
4. Very Cold & Rainy (Canada)

In UAE, the main case is to study and investigate a Solar Park in UAE, and data were obtained from the National Center of Meteorology (NCM) website as it is the latest updated source compared with other global sources used in many different research papers. However, NCM covers UAE zones only and has constraints in providing worldwide data. As an alternative, the NASA Meteorological database (Nasa.gov, 2023) was used for the other regions. However, to have uniformity for all regions that are acquired for the duration from Jan 2000 – Dec 2021 (22 years).

2. PV Module Technical Specifications:

Mechanical Characteristics and Electrical Specifications are gathered directly from the actual site of a solar park located in UAE and from the Technical Specifications datasheet provided by the PV module Manufacturer. The same PV module was used in the four regions to ensure identical comparisons.

4.1 Dubai – UAE

4.1.1 Data Input Variables:

The first site location is Dubai – UAE. Weather data from (2000-2021) and panel technical specifications were identified in the methodology chapter. The system's energy production, consumption, performance, and losses over time calculations were obtained from PVsyst simulation.

4.1.2 Data Output Variables & Analysis:

The software provided several charts and tables to reflect the main performance indicators and metrics.

4.1.2.1 Grid-connected PV system production and performance analysis (Dubai-UAE)

Main results			
System Production	6476 kWh/yr	Normalized prod.	4.81 kWh/kWp/day
Specific prod.	1755 kWh/kWp/yr	Array losses	0.95 kWh/kWp/day
Performance Ratio	0.800	System losses	0.25 kWh/kWp/day

Figure 1: System Production in Grid-Connected System (Dubai-UAE)

Figure-1 shows system production in the grid-connected system per year equal to **6476 kWh/yr** with Performance Ratio (PR) = **80%** and System losses= **0.25 kWh/kWp/day**. This will be discussed further in the upcoming losses diagram.

In the PV industry, PR is a significant measure that is frequently used for warranty claims of PV systems and the validation of the guaranteed power performance provided by the manufacturer/contractor. It is specified in the norm IEC EN 61724 (Pvsyst, 2022). As defined by Pvsyst software, performance ratio PR is the overall efficiency of the system when it is measured compared to the nominal commissioned power (at STC as given by the manufacturer of the PV module) and the incident energy. STC (Pvsyst, 2022) is a standardised set of conditions used in the solar industry to assess and evaluate the performance of solar photovoltaic systems. Typically, it identifies three specific groups of parameters that serve as a reference point for testing and rating PV modules as follows:

1. Irradiance: The irradiance level is set to 1,000 watts per square meter (W/m^2) that the panels are exposed to consistently.
2. Temperature: The module temperature is set to be tested at 25 degrees Celsius.
3. Air Mass: The air mass factor is set to AM 1.5. When the sun is at a specific angle of 48.2 degrees from the zenith, the sunlight passing through the Earth's atmosphere is modified to match the spectral content and path length.

PV panel manufacturers and testing laboratories can confirm reliable and consistent measurements of module performance using STC, which allows for fair evaluations between different solar modules or systems, providing a common reference point for assessing and evaluating their electrical production.

Table 8: Produced Energy and Performance Ratio PR (Dubai-UAE)

Energy use and User's needs		
	E_Grid	PR
	kWh	ratio
January	509.4	0.838
February	494.8	0.833
March	538.2	0.820
April	566.9	0.797
May	576.3	0.779
June	546.6	0.777
July	537.5	0.775
August	537.1	0.775
September	556.6	0.780
October	570.8	0.792
November	542.6	0.818
December	499.0	0.839
Year	6475.7	0.800

Table-8 illustrates how well the specified solar panel system performed in generating energy over the year (E_Grid) and reflects the performance ratio (PR), which is how efficiently the system converted the solar irradiation into energy in the grid. These PR values range from **77.5% to 83.9%**. This indicates that the system reached the cut-off in 22 years which is earlier than anticipated. The manufacturers guarantee a power performance of up to **80.2%** until reaching **25** years (Figure-2). Hence, the researcher can conclude that the panels reached the time for decommissioning and shall be removed from the power system. Furthermore, it is noticeable that the performance ratio was higher in winter rather than the summer, with less shade and more sunlight; this may be credited to the high temperatures observed and experienced during those months, which have an opposing impact on the efficiency of the solar cells. A drop below **78%** in June, July, & August, indicating that there might be issues with

system components overheating or it could be due to extreme weather conditions such as a rise in temperature or sand storms and dust (Ahmad & Ahmad 2019, Agyekum et al. 2022, Conde et al. 2023). According to (Satya et al. 2021), there is a direct relationship between temperature and solar PV module cell efficiency, where the PV cell's performance tends to decrease when temperature rise (Conde et al.,2023). This happens because of disrupted internal transmission of PV cells leading to problems with the energy movement within the panel which make it work and function less efficiently. Hence, the temperature is a crucial factor in the power-generating process affecting the overall performance. Figure-3 is an illustration of the PR of the given PV system, which is equal to = 80% in a Uniform shape.

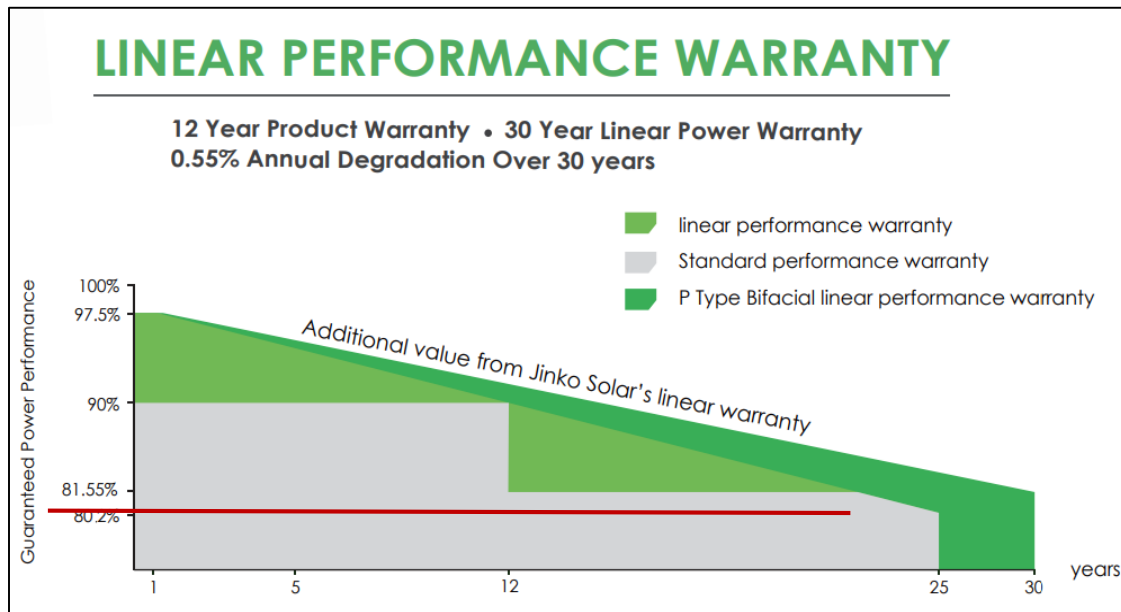


Figure 2: Guaranteed Power Performance by manufacturer

(Source: www.jinkosolar.com)

As shown, table-9 represents the normalised performance coefficients which are equal to the daily energy of the system (Y_f) over the daily output produced energy of the array plane (Y_r) = $4.81/6.01 = 80\%$.

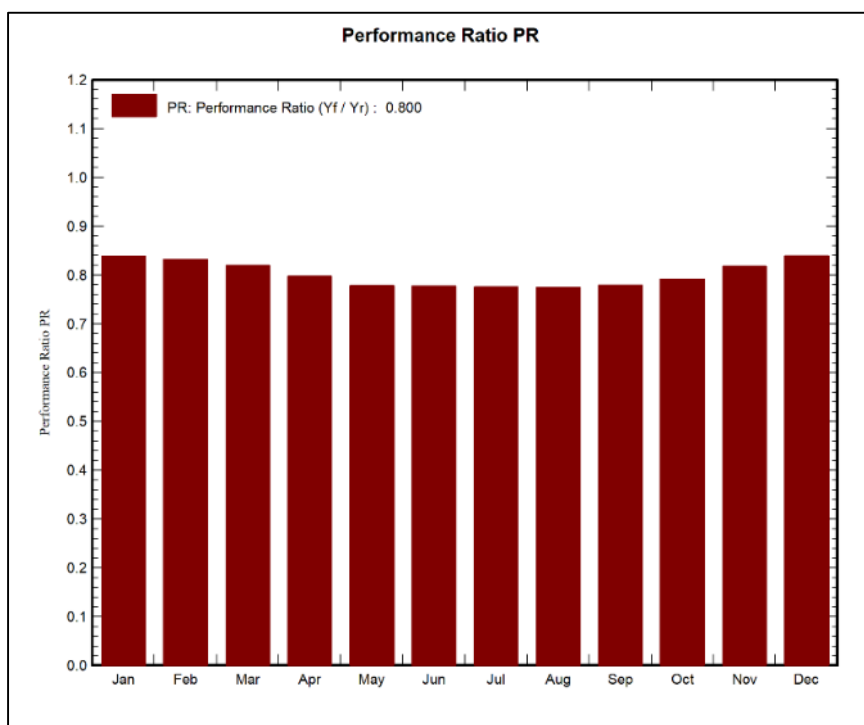


Figure 3: Months Vs Performance Ratio PR (Dubai-UAE)

Table 9: Normalized Performance Coefficients (Dubai-UAE)

Normalized Performance Coefficients								
	Yr	Lc	Ya	Ls	Yf	Lcr	Lsr	PR
	kWh/m ² /day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio	ratio	ratio
January	5.31	0.63	4.68	0.23	4.45	0.118	0.043	0.838
February	5.75	0.72	5.03	0.24	4.79	0.125	0.042	0.833
March	5.74	0.80	4.94	0.24	4.71	0.139	0.041	0.820
April	6.42	1.04	5.39	0.26	5.12	0.161	0.041	0.797
May	6.47	1.17	5.30	0.26	5.04	0.181	0.040	0.779
June	6.35	1.16	5.19	0.25	4.94	0.183	0.040	0.777
July	6.06	1.12	4.94	0.24	4.70	0.184	0.040	0.775
August	6.06	1.12	4.94	0.24	4.70	0.185	0.040	0.775
September	6.45	1.16	5.29	0.26	5.03	0.180	0.041	0.780
October	6.30	1.05	5.25	0.26	4.99	0.167	0.041	0.792
November	5.99	0.85	5.15	0.24	4.90	0.142	0.041	0.818
December	5.20	0.62	4.58	0.22	4.36	0.119	0.042	0.839
Year	6.01	0.95	5.05	0.25	4.81	0.159	0.041	0.800

4.1.2.2 Performance Analysis & Energy Losses in (Dubai-UAE) PV System Simulation

The loss diagram shown in Figure (4) is a key output of all simulations performed by PVsyst software. The figure provides a thorough overview of the energy flow during which the energy is produced and lost at different stages until it is connected to the grid (Ahmad & Ahmad 2019 and Agyekum et al. 2022). The energy flow starts at the stage of global horizontal irradiation; in this stage, it is equal to $= 2042\text{kWh/m}^2$ for the region of Dubai (UAE). At the beginning of the energy flow, there is an increase in the energy equal to $(+7.4\%)$, which can be caused by the PV array being tilted southward and thus collecting a more significant amount of energy than being horizontal. An important point to make regarding panel orientation is that according to (Tsoukp et al., 2022), the best and most efficient angle to position a solar panel is to rotate it in accordance with the latitude angle of the specific site location to collect the most sunlight and produce the most energy throughout the entire year. For locations with north latitude, the solar panel plate shall be facing south, while for locations with south latitude, it shall be facing south, toward and away from the equator, respectively.

After this rise, the (-1.8%) arrow shows a loss concerning the energy that remained present and active at the previous stage (Agyekum et al. 2022). Following that, the effective irradiation on the collector is determined and calculated by multiplying the final irradiation on the collector by the total collector area $= 2145\text{kWh/m}^2 * 18\text{ m}^2\text{ coll}$. This tells the total luminous energy available on the collector. Multiplying this value by the nominal efficiency of the PV module at STC $= 20.06\%$ to attain the nominal PV electrical energy $= 7759.37\text{ kWh}$, rounding it up to the nearest whole number will give 7960 kWh . This value will be developed every time the PV modules function at their nominal efficiency.

The following losses $(-0.4\% \text{ \& } -12.0\%)$ are due to the fact that PV modules don't operate under STC at their maximum efficiency. In sunny weather conditions, the PV loss due to irradiance level may be lower, whereas, in very hot environments with poor airflow (like Dubai-UAE), the PV loss due to high temperature might be increased. Subsequently, there are losses on the inverter level (a device that converts DC to AC to be injected in the grid), as shown in the diagram; the inverter has operational losses, which are indicated as efficiency loss $= -4.9\%$. Other losses are null. Since there are no further losses considered, the output of the inverter is

equal to the generated power, which is shown at the bottom of the diagram. The output energy is equivalent to = 6476 kWh, which is the electrical energy injected into the grid.

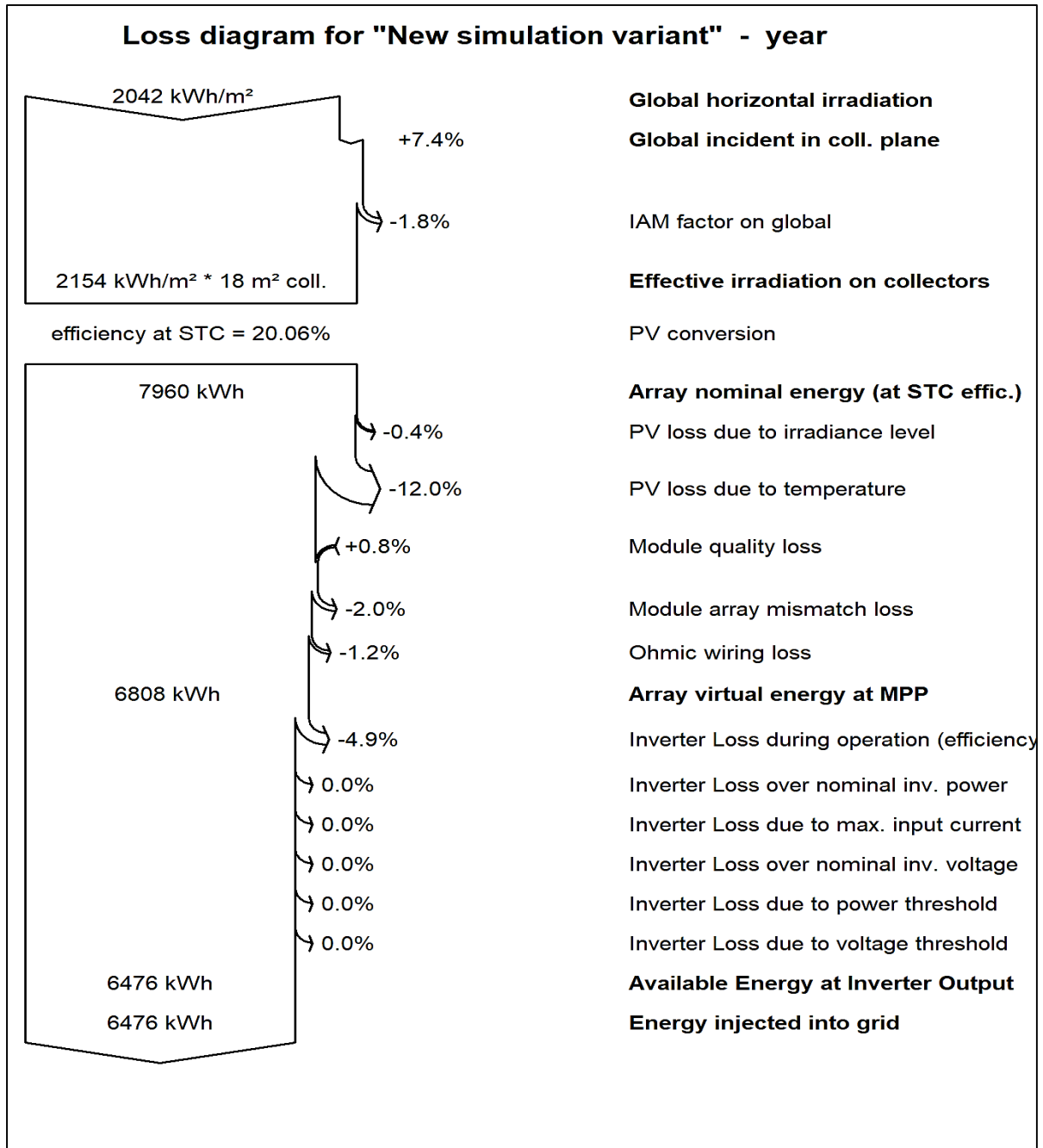


Figure 4: Loss diagram (Dubai-UAE)

4.1.2.3 Energy Production and system output assessment (Dubai-UAE)

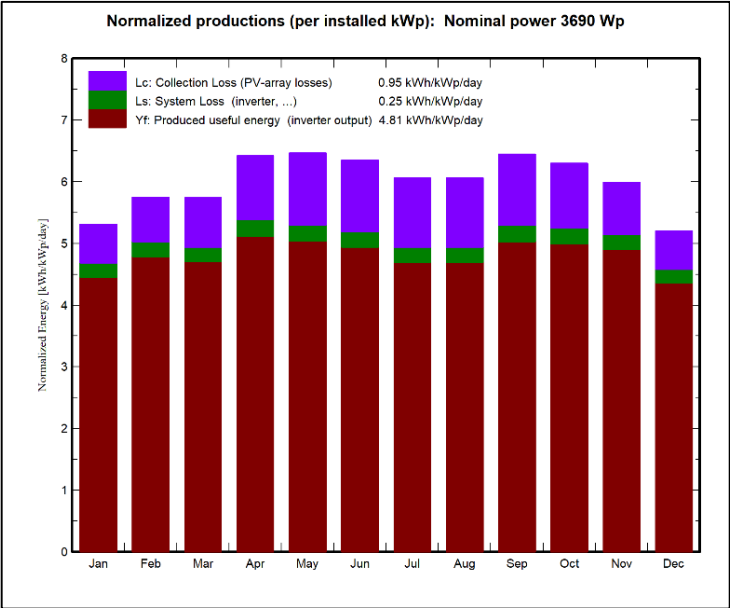


Figure 5: Months Vs Normalized Energy (Dubai-UAE)

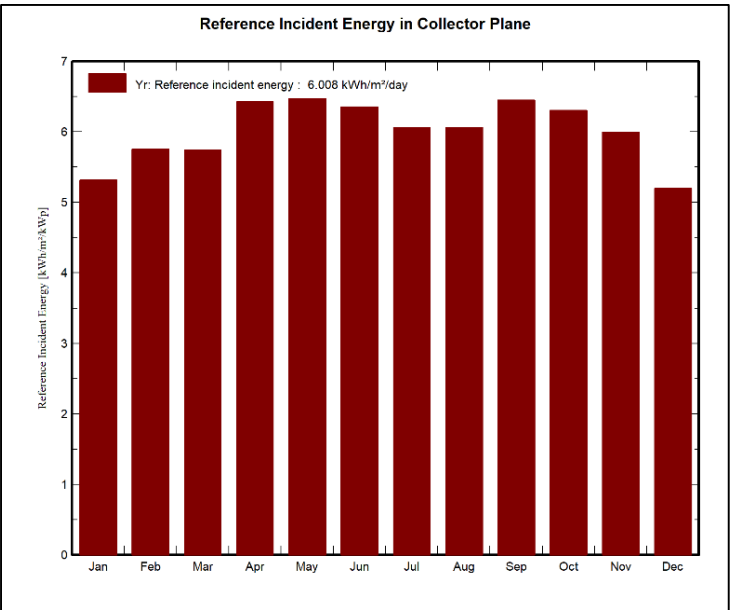


Figure 6: Months Vs Reference Incident Energy (Dubai-UAE)

The above two figures are significant in assessing the performance of the PV module. Figure-5 indicates the normalised energy production and losses generated annually in the PV system and helps evaluate the system's efficiency. Normalised power, collection loss (PV-array losses), and System loss values = are equal to 4.81, 0.95, and 0.25 kWh/kWp/day, respectively. Figure-6 expresses the amount of sunlight reaching the collector, which is relatively stable over the year. Analysing and assessing the reference incident energy in the collector plane support the site engineers and operators in optimising the PV system position and configuration and then maximising the system performance (Agyekum et al., 2022 Tsoukpoe, 2022).

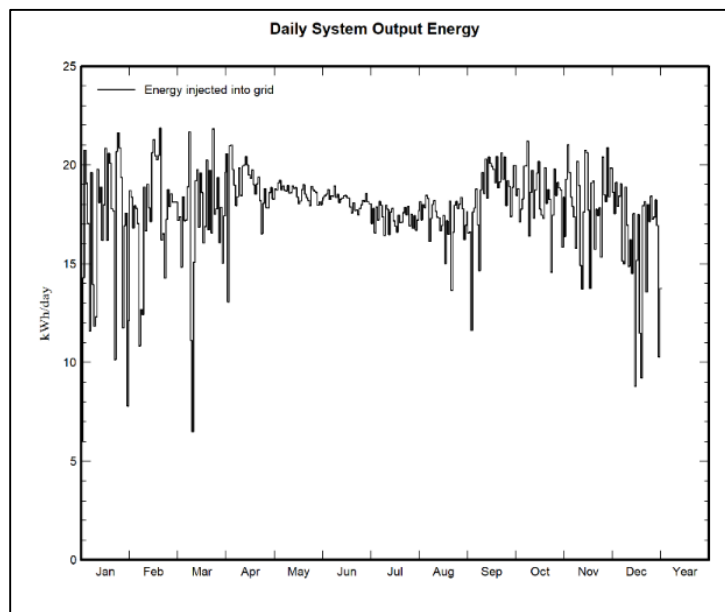


Figure 7 Months Vs Energy injected into grid (Dubai-UAE)

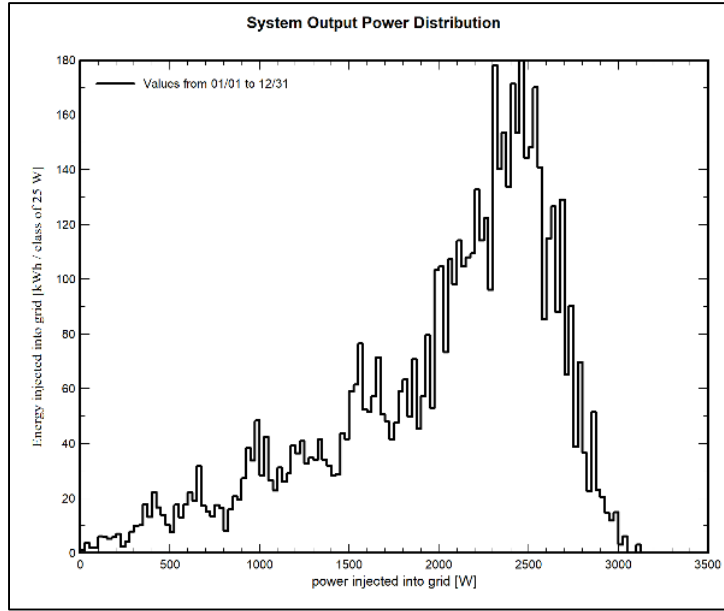


Figure 8: Power injected into grid Vs Energy injected into grid (Dubai-UAE)

The above two figures discuss the energy generation and injection into the grid by the PV system. The daily system produced energy injected into the grid from the PV system is displayed in Figure-7. It is noticed that values are less fluctuating between April-August and virtually inconsistent in winter (December- March), which proves that during summer, the grid is getting the greatest energy injection due to the extended time & greater intensity of solar radiation during summertime (Agyekum et al. 2022). However, there is a significant drop in March that requires further investigation. It might be due to inaccurate weather data values that affected the simulation or due to the overload on the inverter during this time (Agyekum et al.,2022). Figure-8 draw the distribution of the produced power injected into the grid concerning the energy injected into the grid over the year. It is negatively skewed to the left, which means most of the power output takes values between 1500 – 2500 (W). Figures highlight the seasonal variations and issues the grid exposed, and analysing them asses in improving system performance.

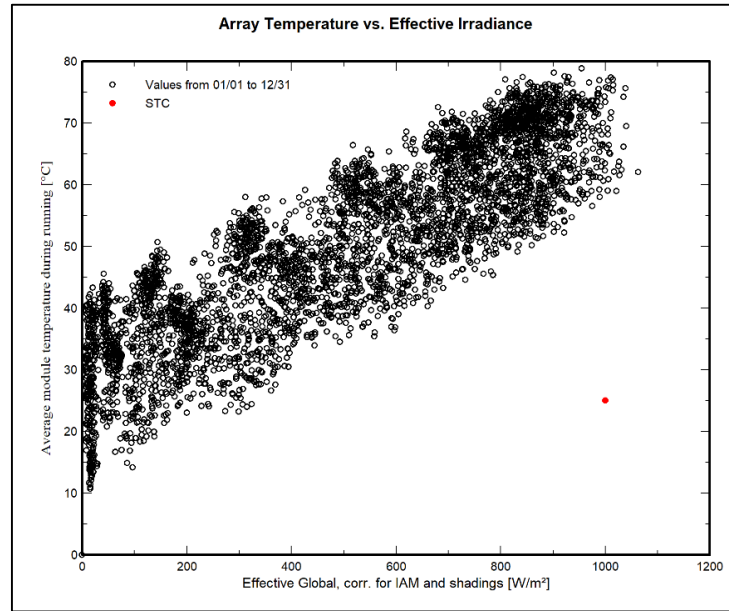


Figure 9: Effective Global corr. For IAM and shadings vs Average module temperature during running (Dubai-UAE)

Figure-9 shows how the array's temperature is changing with varying effective irradiance. The temperature of the collection fluctuated from as low as 11 °C throughout the winter to as high as near 79 °C in the summer, which is too far from STC values (25 °C at 1000 W/m²).

4.2 Varennes – CANADA

4.2.1 Data input variables:

For a very cold & rainy region, Canada was selected as the second site. The software identifies all the technical (electrical) and physical (geometric) input parameters of the PV panel. In addition to the input parameters such as Model technology & specifications, Manufacturer name, manufacturer electrical specifications and measurements, model size and dimensions, etc., were identified in the previous chapter. In addition, the monthly average and annual weather data obtained from NASA (2000-2021) were introduced to the system too.

4.2.2 Data output variables & Analysis:

The system's energy production, consumption, performance, and losses over time calculations were obtained from the PVsyst simulation, and the software created several charts and tables to reflect the main performance indicators and metrics.

4.2.2.1 Grid-connected PV system production and performance analysis (Varennnes - CANADA)

Main results			
System Production	5006 kWh/yr	Normalized prod.	3.72 kWh/kWp/day
Specific prod.	1357 kWh/kWp/yr	Array losses	0.35 kWh/kWp/day
Performance Ratio	0.872	System losses	0.20 kWh/kWp/day

Figure 10: System production in the grid-connected system (Varennnes – CANADA)

Figure-10 shows system production in the grid-connected system per year equal to **5006 kWh/yr** with Performance Ration (PR) = **80.72%** and System loses= **0.20 kWh/kWp/day**. This will be discussed further in the upcoming performance and losses diagram.

Table-10 demonstrates the healthiness of the PV system in generating energy over the year and how capably the system transformed the solar irradiation into energy injected into the grid. These PR values range from 82.8.5% to 95.2%. This indicates that the system is performing exceptionally well and above expectations compared to the manufacturer's guarantee of power performance (Figure-2). However, it is observed that the PR was at the highest in November, December, & Jan, but the generated energy was significantly less compared to the rest of the months (243.3, 200.6, and 302.5 kWh). This lower Solar energy production is expected due to the low sunny days during those winter periods, which negatively affect the amount of solar irradiation that the panel collects or the elevated electrical resistance in the panel's cells due to cold and rainy weather that usually causes a decrease in the current flow.

Table 10: Produced Energy and Performance Ratio PR (Varennnes –CANADA)

Energy use and User's needs		
	E_Grid	PR
	kWh	ratio
January	302.5	0.952
February	372.3	0.944
March	495.9	0.911
April	488.1	0.881
May	520.1	0.851
June	523.9	0.837
July	538.2	0.828
August	517.2	0.832
September	460.7	0.844
October	343.1	0.878
November	243.3	0.908
December	200.6	0.936
Year	5005.9	0.872

According to (Pero et al. 2021), on cloudy, rainy days, PV panels tend to produce less than their maximum capacity since the thick cloud shade performs as a shield and shifts the sunlight away from the collector, which then negatively impacts the conversion efficiency. However, after the storm, it will help the solar panels to operate efficiently because rainwater washes all dust or dirt.

Figure-11 is an illustration of a PR Uniform shape of the given PV system, which is equal to = (80.72%). The minor variations in the values of the PR can be assigned to the circumstances and variables that impact the function of the PV system, such as limited sunlight and cloudy or rainy days. In Canada, the weather is unpredictably rainy from April to June. According to (Pero et al. 2021), the experimental and theoretical results showed that during the fall and winter seasons, rain is not helpful and does not have a beneficial effect on the solar panels. The air temperature is already low even during the limited sunny hours, forbidding the PV cells from getting too hot; thus, the cooling effect is either minimal or neglected. Besides, rainy periods are often associated with low levels of solar irradiation, which in turn reduces energy generation, and the panel is not producing its optimal capacity.

Overall, (Pero et al. 2021) concluded that when there are clouds and rains, solar panels perform 5% lower than clear sky timings. This is because there is a shortage in sunlight availability, mainly in winter, and low levels of solar radiation during rainy winter hours lead to further losses for solar panels. These factors beat any possibility of getting benefits from the reduced sunlight reflections resulting from rainwater on the panel's surface.

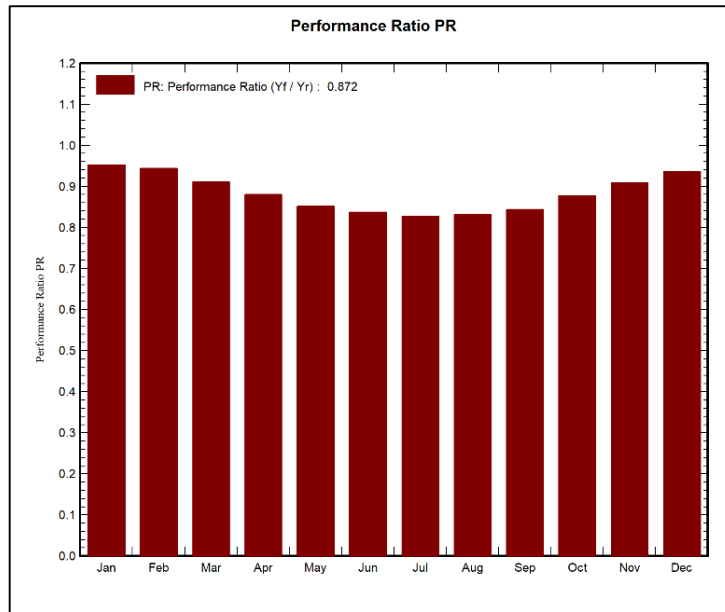


Figure 11: Months Vs Performance Ratio (Varennes - CANADA)

Table 11: Normalized Performance Coefficients (Varennes - CANADA)

Normalized Performance Coefficients								
	Yr	Lc	Ya	Ls	Yf	Lcr	Lsr	PR
	kWh/m ² /day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio	ratio	ratio
January	2.78	-0.01	2.79	0.14	2.64	-0.003	0.051	0.952
February	3.82	0.03	3.79	0.19	3.60	0.007	0.049	0.944
March	4.76	0.20	4.56	0.23	4.34	0.041	0.048	0.911
April	5.01	0.37	4.64	0.23	4.41	0.073	0.046	0.881
May	5.34	0.55	4.79	0.24	4.55	0.104	0.045	0.851
June	5.66	0.67	4.98	0.25	4.73	0.119	0.044	0.837
July	5.68	0.73	4.95	0.25	4.71	0.129	0.043	0.828
August	5.43	0.68	4.76	0.24	4.52	0.124	0.043	0.832
September	4.93	0.56	4.38	0.22	4.16	0.113	0.044	0.844
October	3.42	0.26	3.16	0.16	3.00	0.075	0.047	0.878
November	2.42	0.10	2.32	0.12	2.20	0.042	0.050	0.908
December	1.87	0.02	1.85	0.10	1.75	0.011	0.052	0.936
Year	4.26	0.35	3.91	0.20	3.72	0.082	0.046	0.872

As displayed in Table-11, PR is equal to the daily energy of the system (Yf) over the daily output produced energy of the array plane (Yr) = $3.72/4.26 = 80.72\%$.

4.2.2.2 Performance Analysis & Energy Losses in (Varennnes - CANADA) PV System Simulation

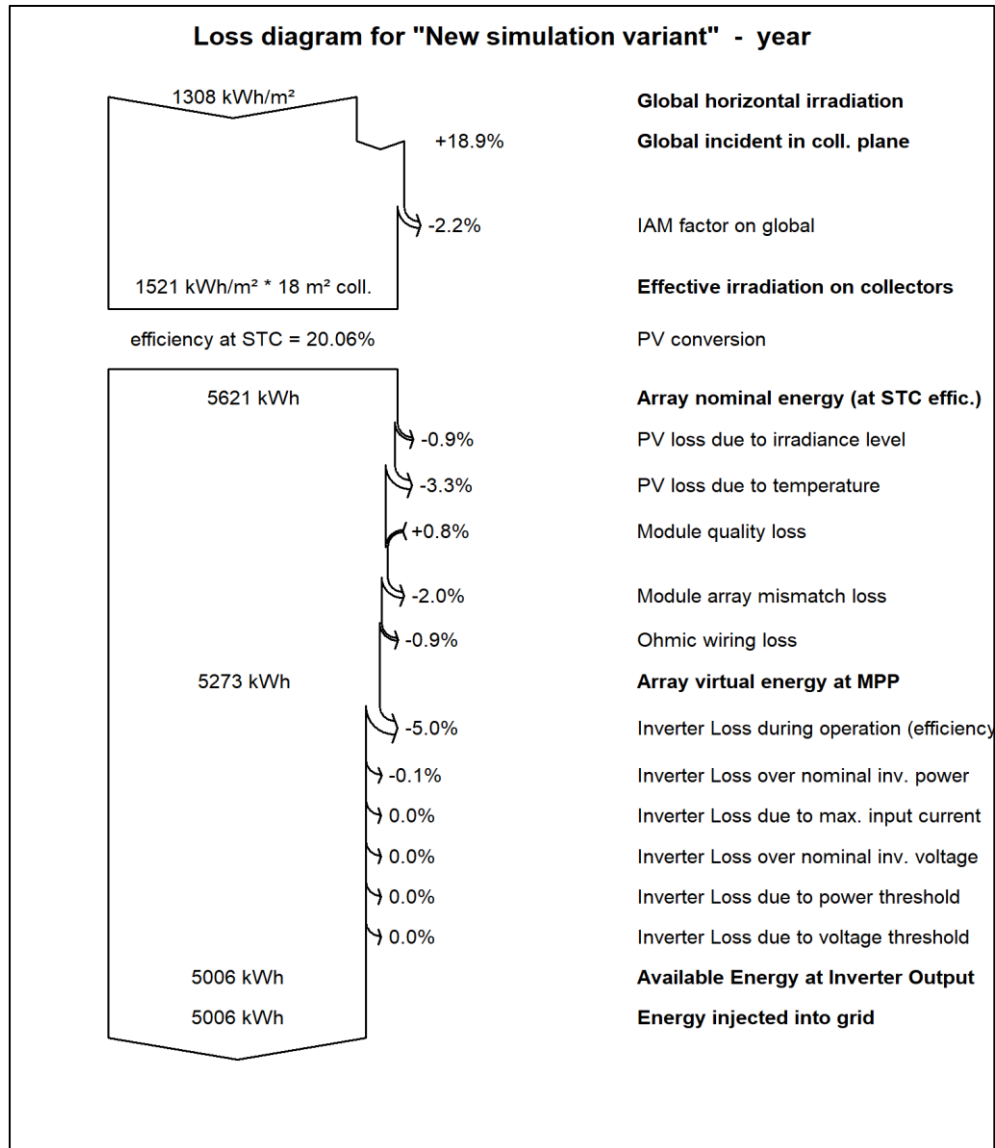


Figure 12: Loss diagram (Varennnes - CANADA)

In the loss diagram shown in Figure-12, the energy flow starts at the stage of global horizontal irradiation; in this stage, it is equal to = 1308 kWh/m² for the region of Varennnes (Canada). At the beginning of the energy flow, the energy increased by (+18.9%), which can be caused by

the PV array being tilted southward and thus accumulating a more significant amount of energy than being horizontal. Following, the (-2.2%) arrow suggests a relative loss for the energy that continued to be active at the previous stage. Next, when functioning at STC efficiency, the nominal array energy is calculated = 5621 kWh. The following losses (-0.9% & -3.3%) are due to the fact that PV modules don't operate at STC. PV loss due to irradiance level is not controlled with cold, cloudy, and rainy weather conditions; similarly, PV loss due to temperature is generally very low in cold environments with rich rain, as in CANADA. Subsequently, there is the inverter operational efficiency loss = -5%, and since other losses are null, the output of the inverter is equal to the generated power injected into the grid = 5006 kWh.

4.2.2.3 Energy production and system output assessment (Varennnes - CANADA)

Figure-13 indicates the annual normalised energy production and losses generated by the PV system. At the same time, Figure-14 shows a systematic bell-shaped visualisation of the energy production over the year. The daily system-produced energy injected into the grid from the PV system is displayed in Figure-15. It is noticed that energy values started decreasing between (Nov-Jan), and were most stable the rest of the year (Feb-Sep), which is evidence that during cold, cloudy, rainy days, the grid is getting the most negligible energy injection due to the shortened time & lower intensity of solar radiation. Figure-16 draws a negatively skewed to the left distribution, which means most of the power output values range between 1500 – 3000 (W).

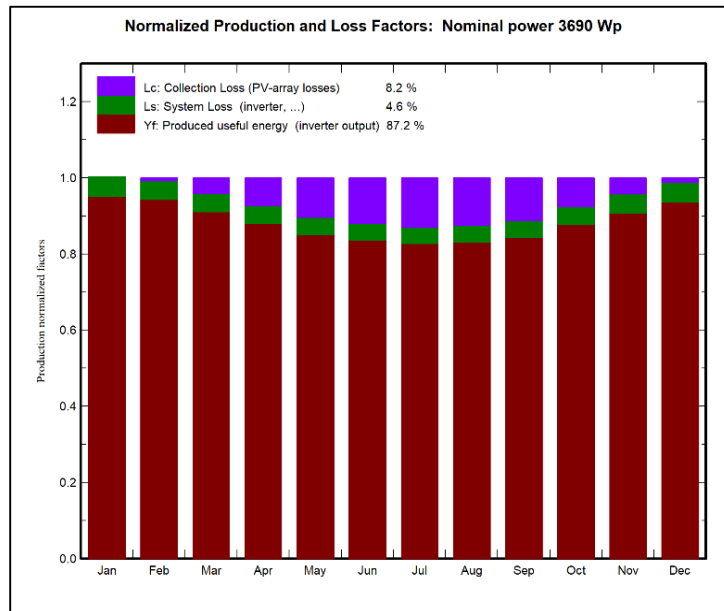


Figure 13: Months vs Production Normalized Factors (Varennnes – Canada)

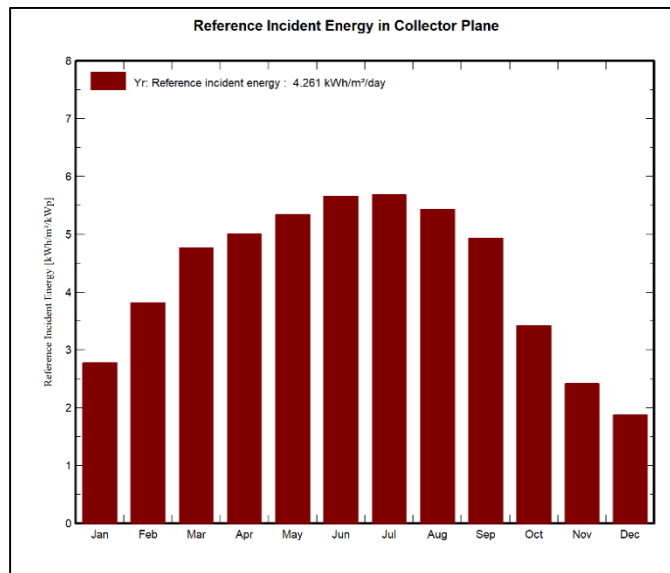


Figure 14: Months vs Reference Incident Energy (Varennnes – Canada)

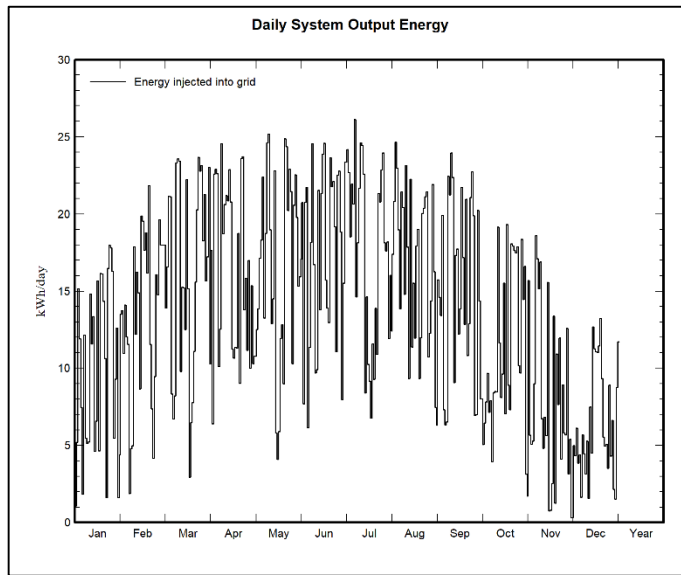


Figure 15: Months vs Energy injected into grid (Varennnes – Canada)

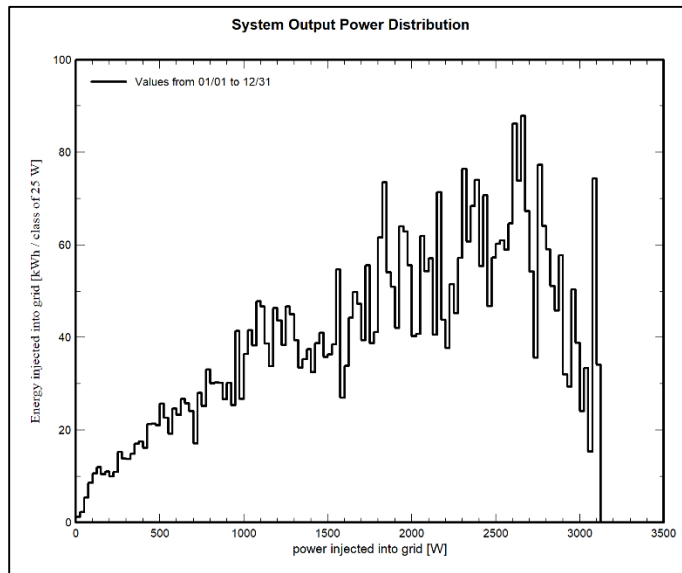


Figure 16: Power injected into grid vs Energy injected into grid (Varennnes – Canada)

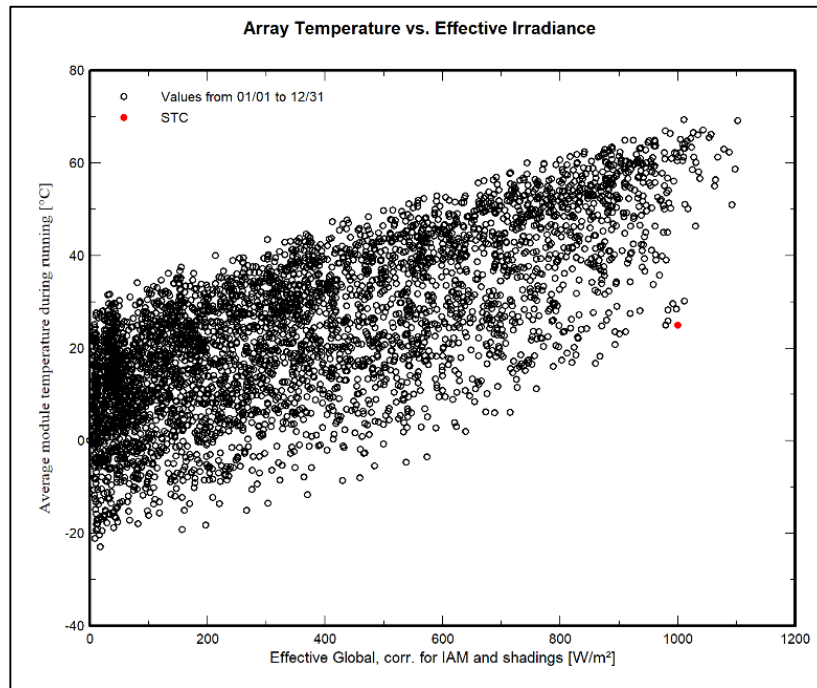


Figure 17: Effective Global corr. for IAM vs Average module temperature during running (Varennnes – Canada)

The temperature characteristics of the arrays versus effective irradiance are indicated in Figure-17. The average temperature of the module was functioning at STC at some points; however, it mostly varied from as low as -19°C throughout the winter to barely as high as nearly 70°C in the summer.

4.3 Mumbai – India

Main results			
System Production	6373 kWh/yr	Normalized prod.	4.26 kWh/kWp/day
Specific prod.	1554 kWh/kWp/yr	Array losses	0.81 kWh/kWp/day
Performance Ratio	0.808	System losses	0.20 kWh/kWp/day

Figure 18: System production in the grid-connected system (Mumbai – India)

4.3.1 Data input variables:

Mumbai- India, was selected as the third site for a very hot & rainy region. Similar input parameters of the PV panel were identified to the software, technical specifications and measurements, plus the weather data from (2000-2021).

4.3.2 Data output variables & Analysis:

Figure-18 shows system production in the grid-connected system by simulation equal to = **6373 kWh/yr** with Performance Ration (PR) equal to = **80.8%** and System loss equal to = **0.20 kWh/kWp/day**. This will be discussed further in the upcoming performance and loss diagrams.

4.3.2.1 Grid-connected PV system production and performance analysis (Mumbai-India)

Table 12: Produced Energy and Performance Ratio PR (Mumbai - India)

Energy use and User's needs		
	E_Grid	PR
	kWh	ratio
January	654.1	0.809
February	637.0	0.794
March	685.0	0.797
April	633.3	0.802
May	589.7	0.804
June	384.9	0.821
July	277.4	0.822
August	345.4	0.827
September	439.1	0.825
October	541.1	0.810
November	599.9	0.805
December	586.3	0.812
Year	6373.2	0.808

Table-12 reveals that the PR values range from **79.4%** to **82.7%**, indicating that the system is performing well and within expectations, as noted in the manufacturer's power performance guarantee (Figure-2). Furthermore, it is observed that from June to September, the power output was at its lowest compared to the rest of the months; this may be due to the continuous rainfall with heavy dark clouds as this is the famous season in India which witness constant rainfall, mostly in July and August (Singh et al. 2022). However, the performance was at its highest simultaneously, proving the studies that revealed that rain could be really good and useful for solar panels. It has an exceptionally positive effect on their performance during the spring and summer seasons. This positive impact is observed in many forms, as stated by (Pero et al. 2021): Initially, rain cools the panel surface, reducing the high summer temperature and then the amount of lost energy. Secondly, when there is water on the panels, minimal radiation moves off; accordingly, more of it is converted into electricity. Further, rain cleans the panel's surface from dirt and dust, allowing it to maximise the amount of sunlight collection. Therefore, rain is beneficial for solar panels to work better in specific seasons and situations.

Figure-19 illustrates the PR performance ratio of the PV system (80.8%) in a symmetrical uniform shape. As displayed in table-13, it is also calculated that PR is equal to the daily energy of the system (Yf) over the daily output produced energy of the array plane (Yr), which equals $= 4.26/5.27 = 80.8\%$.

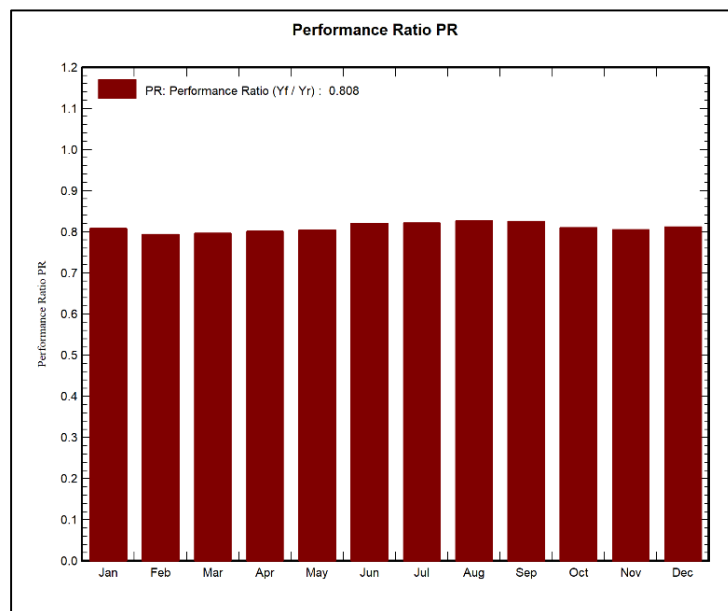


Figure 19: Months vs Performance Ratio PR (Mumbai-India)

Table 13: Normalized Performance Coefficients (Mumbai-India)

Normalized Performance Coefficients								
	Yr	Lc	Ya	Ls	Yf	Lcr	Lsr	PR
	kWh/m ² /day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio	ratio	ratio
January	6.36	0.98	5.39	0.24	5.15	0.154	0.038	0.809
February	6.99	1.18	5.81	0.26	5.55	0.169	0.037	0.794
March	6.76	1.12	5.64	0.25	5.39	0.166	0.037	0.797
April	6.42	1.03	5.39	0.24	5.15	0.161	0.038	0.802
May	5.77	0.91	4.86	0.22	4.64	0.158	0.038	0.804
June	3.81	0.53	3.28	0.15	3.13	0.139	0.040	0.821
July	2.66	0.36	2.30	0.12	2.18	0.134	0.044	0.822
August	3.29	0.43	2.85	0.14	2.72	0.132	0.041	0.827
September	4.33	0.59	3.74	0.17	3.57	0.136	0.038	0.825
October	5.26	0.81	4.45	0.20	4.26	0.153	0.037	0.810
November	6.06	0.96	5.10	0.23	4.88	0.158	0.037	0.805
December	5.68	0.85	4.83	0.22	4.61	0.150	0.038	0.812
Year	5.27	0.81	4.46	0.20	4.26	0.153	0.038	0.808

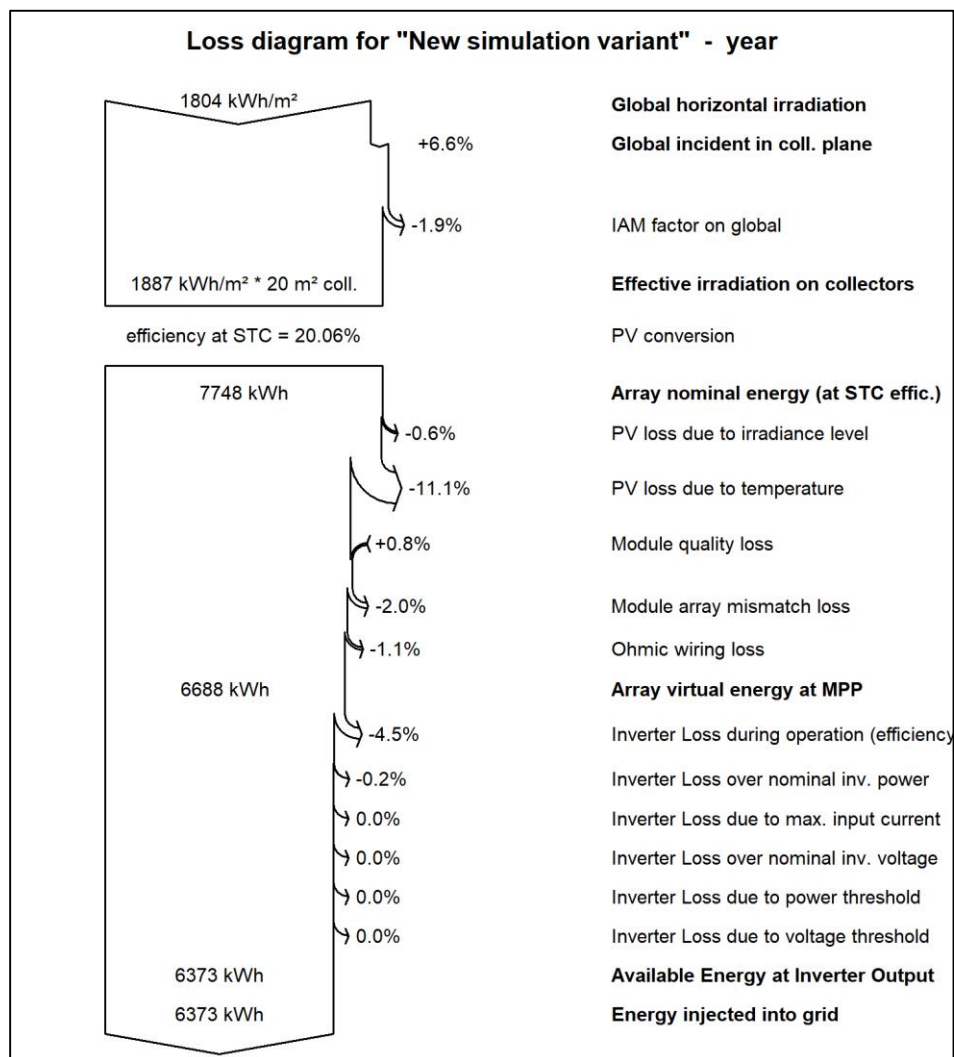


Figure 20: Loss diagram (Mumbai-India)

4.3.2.2 Performance Analysis & Energy Losses in (Mumbai - India) PV System Simulation

Similar to the previous discussions, the loss diagram shown in Figure-20 is a key output for the entire simulation period. The energy flow starts at the stage of global horizontal irradiation; in this stage, it is equal to = 1804 kWh/m² for the region of Mumbai (India). At the beginning of the energy flow, the energy increased by (+6.6%), which can be caused by the PV array being titled southward and thus accumulating more tremendous energy than the horizontal. Following, loss for the energy that continued to be active at the previous stage indicated, and the PV module energy functioning at nominal STC efficiency was calculated, which is equal to = 7748 kWh.

The following losses (-0.6% & -11.1%) are due to the fact that PV modules don't operate at STC, and there is the inverter operational efficiency and nominal losses are equal to = -4.5%, -0.2 correspondingly. Other losses are null. Since there are no further losses, the output of the inverter is equal to the generated power = 6373 kWh which is the electrical energy injected into the grid.

4.3.2.3 Energy Production and System Output Assessment (Mumbai-India)

Figure-21 shows a U- shaped visualisation of the energy production over the year. At the same time, Figure-21 indicates the annual normalised energy production and losses generated by the PV system. Furthermore, the daily system-produced energy injected into the grid from the PV system is displayed in Figure-23. Energy production is not stable and fluctuates all over the year, and output values started decreasing in summer between (Mid-May – Mid-August). This might lead to an assumption that during hot summer days, the produced energy is reduced due to the effect of high temperature on panel cells or the effect of cloudy, rainy days that shorten the time & decrease the intensity of solar radiation reaching the cells. Therefore, the grid is getting less energy injection. The distribution in Figure-24 is negatively sharply skewed to the left, and an abnormality in power output took values over 3000 (W) with an undetermined injected energy amount; this requires further investigation; however, it might be due to inaccurate weather data values during this month that affected the simulation.

Figure 25 illustrates that the temperature of the array varies from as low as 15°C throughout the winter to as high as nearly 75 °C in the summer, which is overly far from operating at STC values.

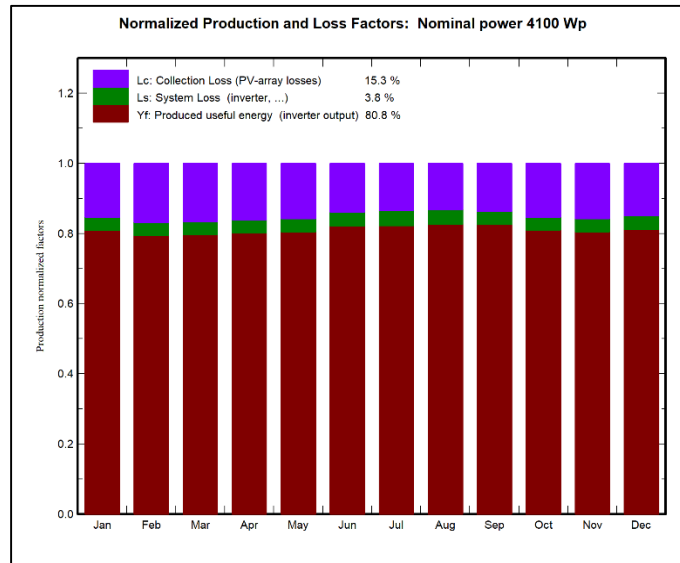


Figure 21: Months vs Production Normalized Factors (Mumbai-India)

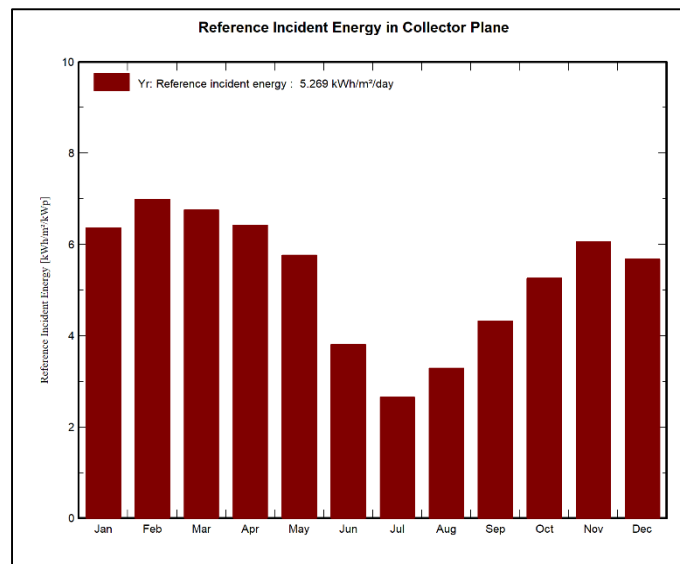


Figure 22: Months. Vs Reference Incident Energy (Mumbai-India)

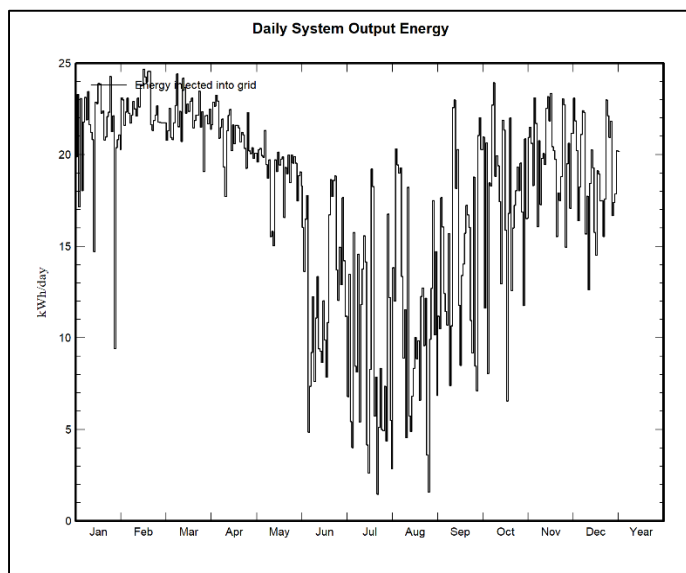


Figure 23: Months vs Energy injected into grid (Mumbai-India)

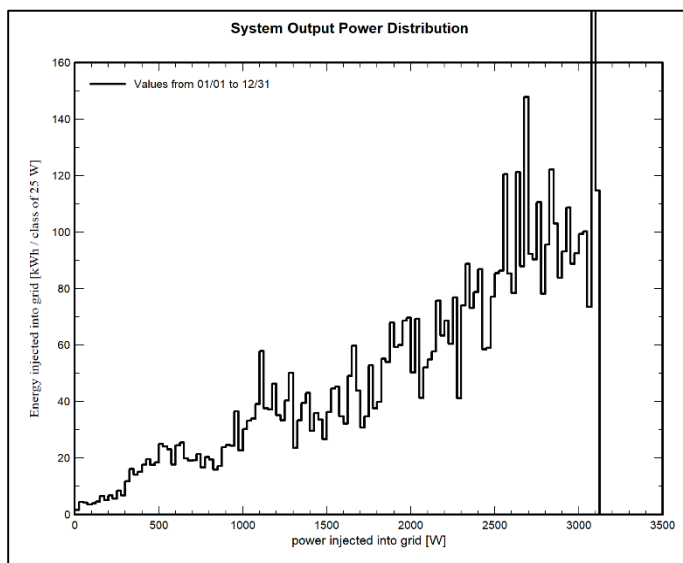


Figure 24: Power injected into grid vs Energy injected into grid (Mumbai-India)

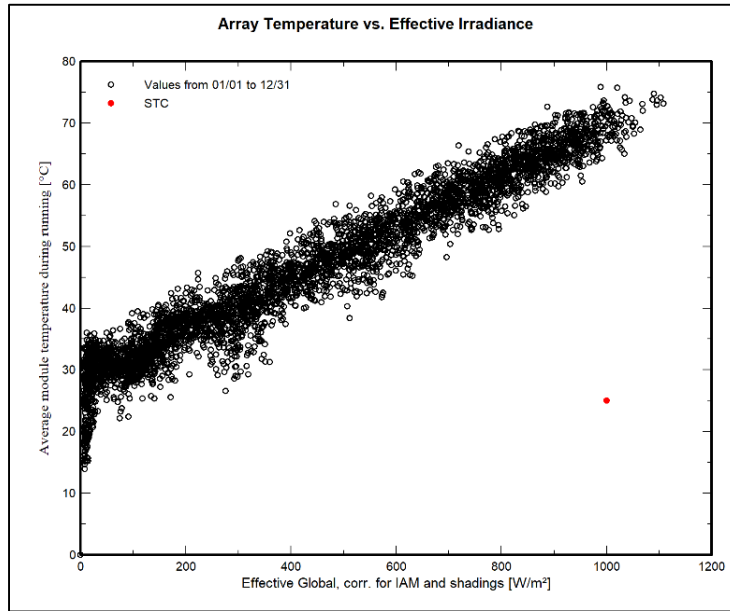


Figure 25: Effective Global corr. for IAM vs Average module temperature during running (Mumbai-India)

4.4 Norway

4.4.1 Data input variables:

For a very cold & snowy region, Norway was selected as the fourth site. Similar input parameters of the PV panel were identified in the simulation software. In addition to the 22 years of weather data.

4.4.2 Data output variables & Analysis:

Main results			
System Production	3714 kWh/yr	Normalized prod.	2.76 kWh/kWp/day
Specific prod.	1006 kWh/kWp/yr	Array losses	0.22 kWh/kWp/day
Performance Ratio	0.885	System losses	0.14 kWh/kWp/day

Figure 26: System production in the grid-connected system (Gunnarn – Norway)

4.4.2.1 Grid-connected PV system production and performance analysis (Gunnarn – Norway)

The system's energy production, consumption, performance, and losses over time calculations were obtained from PVsyst simulation. And the main performance indicators and metrics are represented in the upcoming tables and charts. Figure-26 shows system production in the grid-connected system per year equal to **3714 kWh/yr** with Performance Ratio (PR) equal to = **88.5%** and System losses equal to = **0.14 kWh/kWp/day**.

Table 14: Produced Energy and Performance Ratio PR (Gunnarn – Norway)

Energy use and User's needs		
	E_Grid kWh	PR ratio
January	43.5	0.944
February	149.9	0.954
March	381.1	0.935
April	492.6	0.908
May	555.9	0.879
June	557.7	0.865
July	538.9	0.850
August	465.2	0.865
September	327.6	0.885
October	152.5	0.908
November	48.9	0.907
December	0.0	0.000
Year	3713.7	0.885

Table-14 demonstrates the healthiness of the Norway solar panel system in generating energy over the year and how efficiently the energy is injected into the grid. These PR values range from **85.0%** to **95.4%**, indicating the system is operating perfectly and exceeding expectations compared to the manufacturer certification (Figure-2). Furthermore, a very important and significant note is that in December, the energy injected into the grid equals **zero**; therefore, the PR is **zero** too, which leads to validating this incident by verifying the irradiance data in that month = **0.03 kW-hr/m²/day**. Also, it is observed that from October to February, very little energy is being injected into the grid, this is possibly due to the extremely low temperatures and heavy snowfall during those winter months, which negatively affect the amount of solar

irradiation that panel collects since snow blocks sunlight from reaching the cells, or it raises the electrical resistance in the panel's cells that usually causes a decrease in the flow of electrical current. This provides a conclusion that low temperatures affect the PV panel's energy generation but doesn't affect the performance of the PV module itself since it doesn't damage the cell components.

Figure-27 displays the performance ratio of the given PV system as 88.5% in a Uniform shape, with zero PR value in December. The same is also calculated in table-15, equal to the daily energy of the system (Yf) over the daily output produced energy of the array plane (Yr) = (2.76/3.11).

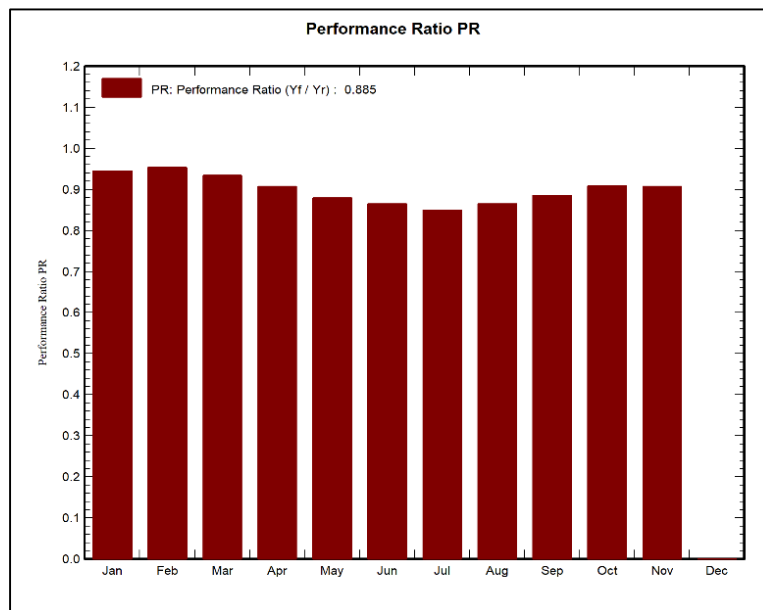


Figure 27: Months vs Performance Ratio PR (Gunnarn – Norway)

Table 15: Normalized Performance Coefficients (Gunnarn – Norway)

Normalized Performance Coefficients								
	Yr	Lc	Ya	Ls	Yf	Lcr	Lsr	PR
	kWh/m ² /day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio	ratio	ratio
January	0.40	0.00	0.40	0.02	0.38	0.000	0.056	0.944
February	1.52	-0.01	1.53	0.08	1.45	-0.003	0.050	0.954
March	3.56	0.07	3.49	0.16	3.33	0.021	0.044	0.935
April	4.90	0.24	4.67	0.22	4.45	0.048	0.044	0.908
May	5.53	0.42	5.11	0.25	4.86	0.076	0.045	0.879
June	5.83	0.53	5.30	0.26	5.04	0.091	0.045	0.865
July	5.54	0.59	4.95	0.24	4.71	0.107	0.044	0.850
August	4.70	0.43	4.27	0.20	4.07	0.092	0.043	0.865
September	3.34	0.23	3.11	0.15	2.96	0.070	0.045	0.885
October	1.47	0.06	1.41	0.08	1.33	0.039	0.053	0.908
November	0.49	0.01	0.48	0.03	0.44	0.023	0.069	0.907
December	0.00	0.00	0.00	0.00	0.00	1.000	1.000	0.000
Year	3.11	0.22	2.90	0.14	2.76	0.069	0.045	0.885

4.4.2.2 Performance Analysis & Energy Losses in (Gunnarn – Norway) PV System

Simulation

Similar to the previous discussions, Figure-28 shows the loss diagram of the Norway simulation. The system input energy = **895 kWh/m²**. However, at the beginning of the loss diagram, the energy increased by (+27%), which can be caused by the array tilted southward and thus building up a greater amount of energy than the horizontal. Following, 4085 **kWh** is the value of PV modules functioning at their nominal STC efficiency. The following losses (**-1.3%**, **-1.1%**, **-2.0% & -0.8%**) are due to the fact that PV modules don't operate at STC. The inverter operational efficiency losses = **-4.8%**, and other losses are zero. Hence, the output of the inverter is equal to the generated electrical power injected into the grid = **3714 kWh**.

Figure-30 shows a symmetrical bell-shaped visualisation of the energy production over the year. In contrast, Figure-29 indicates the normalised energy production and losses generated annually.

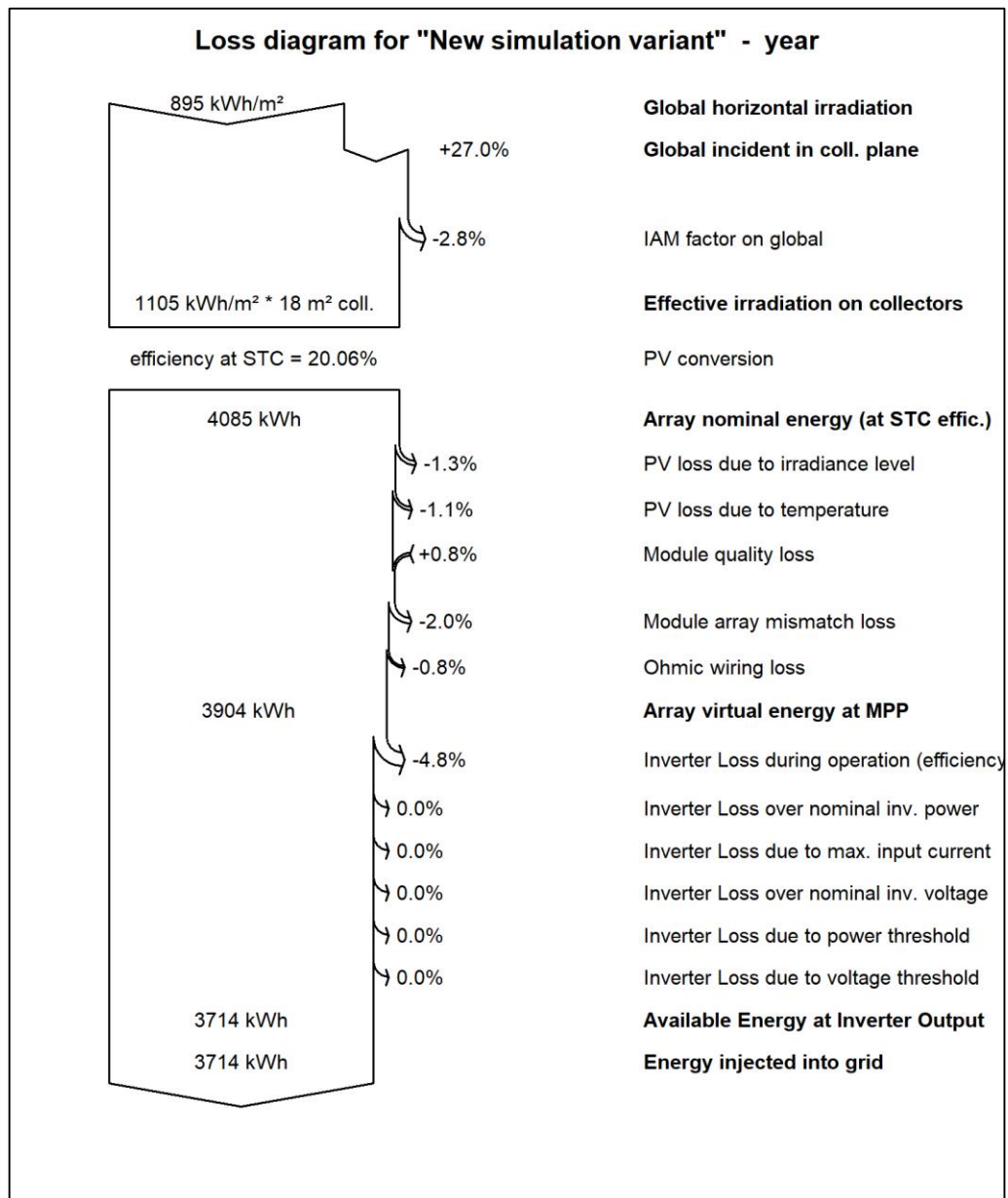


Figure 28: Loss diagram (Gunnarn – Norway)

4.4.2.3 Energy Production and system output assessment (Gunnarn – Norway)

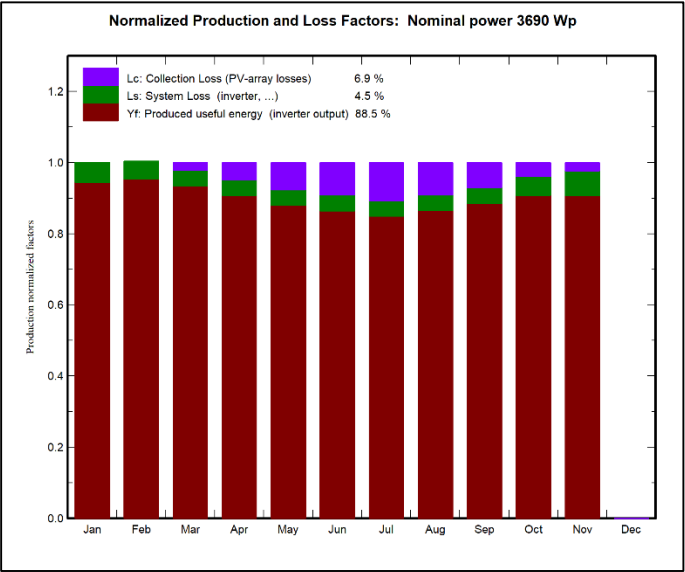


Figure 29: Months vs Production Normalized Factors (Gunnarn – Norway)

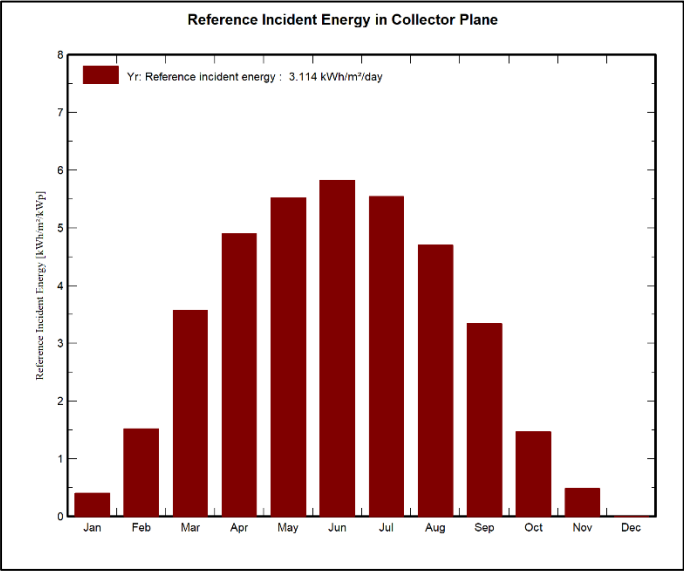


Figure 30: Months. Vs Reference Incident Energy (Gunnarn – Norway)

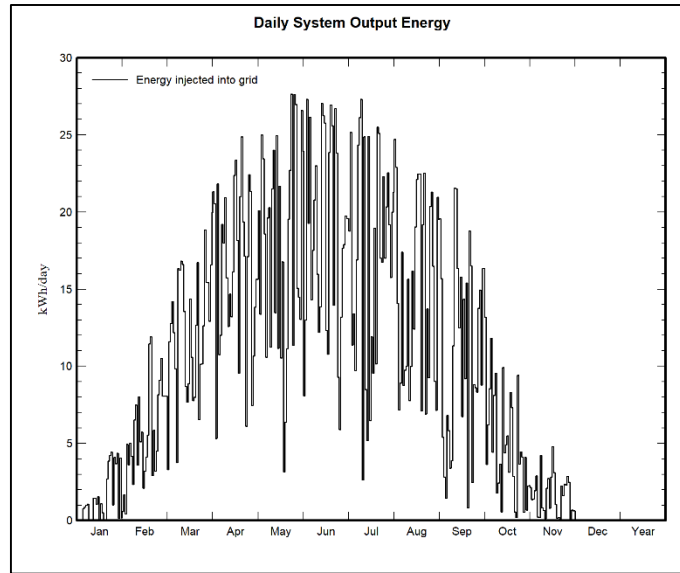


Figure 31: Months vs Energy injected into grid (Gunnarn-Norway)

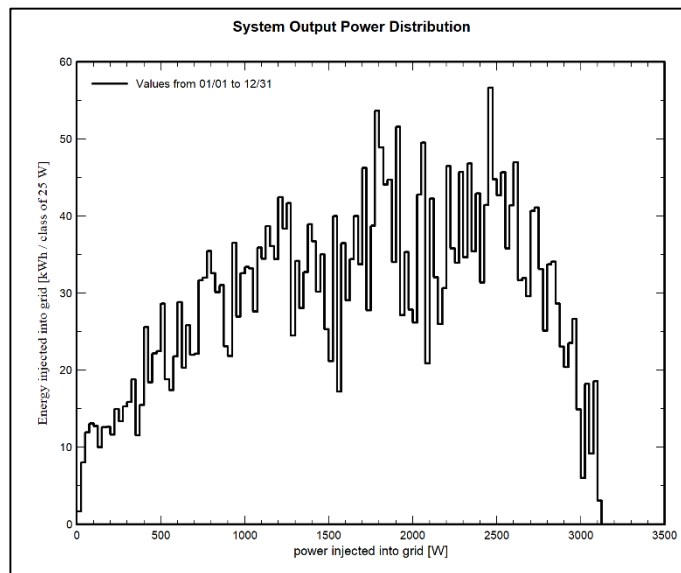


Figure 32: Power injected into grid vs Energy injected into grid (Gunnarn-Norway)

Figure-31 draws the distribution of the produced power injected into the grid for the energy injected into the grid over the year. The daily system-produced energy injected into the grid from the PV system is displayed in Figure-32. It is noticed that energy values form a symmetrical bell-shaped at the beginning and end of the year. Energy injected into the grid fell to the lowest in winter from October to February and reached its maximum between April to August. In Norway, energy production is not considered high or extreme over the year, which is an indication that during very cold and snowy days, the grid is getting the minor energy injection due to the shortened time & lower intensity of solar radiation due to the heavy snow that blocks the sunlight from reaching the PV cells. It is remarkable to mention that low temperature doesn't affect the efficiency of PV panels since it generates electricity from sunlight, not sun heat. A study conducted by (Jackson & Gunda, 2021) showed that the performance of a solar PV plant is strongly affected by snow among all other weather conditions, as it decreased by approximately 55%. This indicates that the solar power plant works less efficiently on snowy days compared to days without snow.

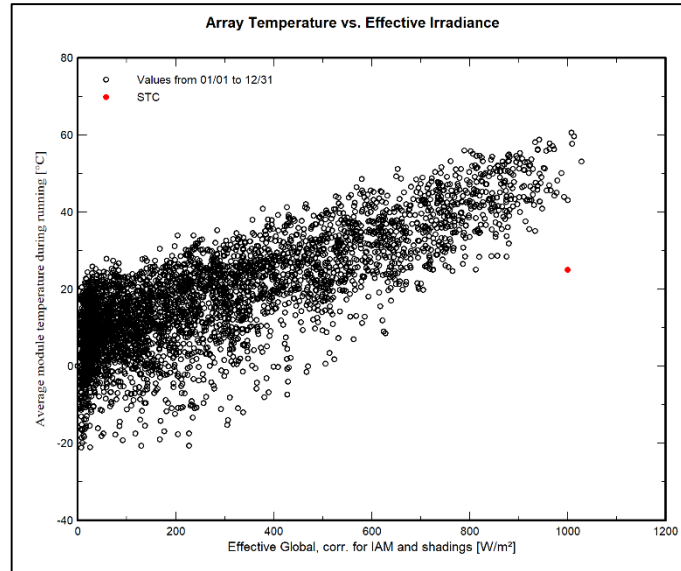


Figure 33: Effective Global corr. for IAM vs Average module temperature during running (Norway)

Figure 33 shows that the module is operating identically at STC values. The temperature of the array varied from as low as -20°C throughout the winter to as high as nearly 55 °C in the summer.

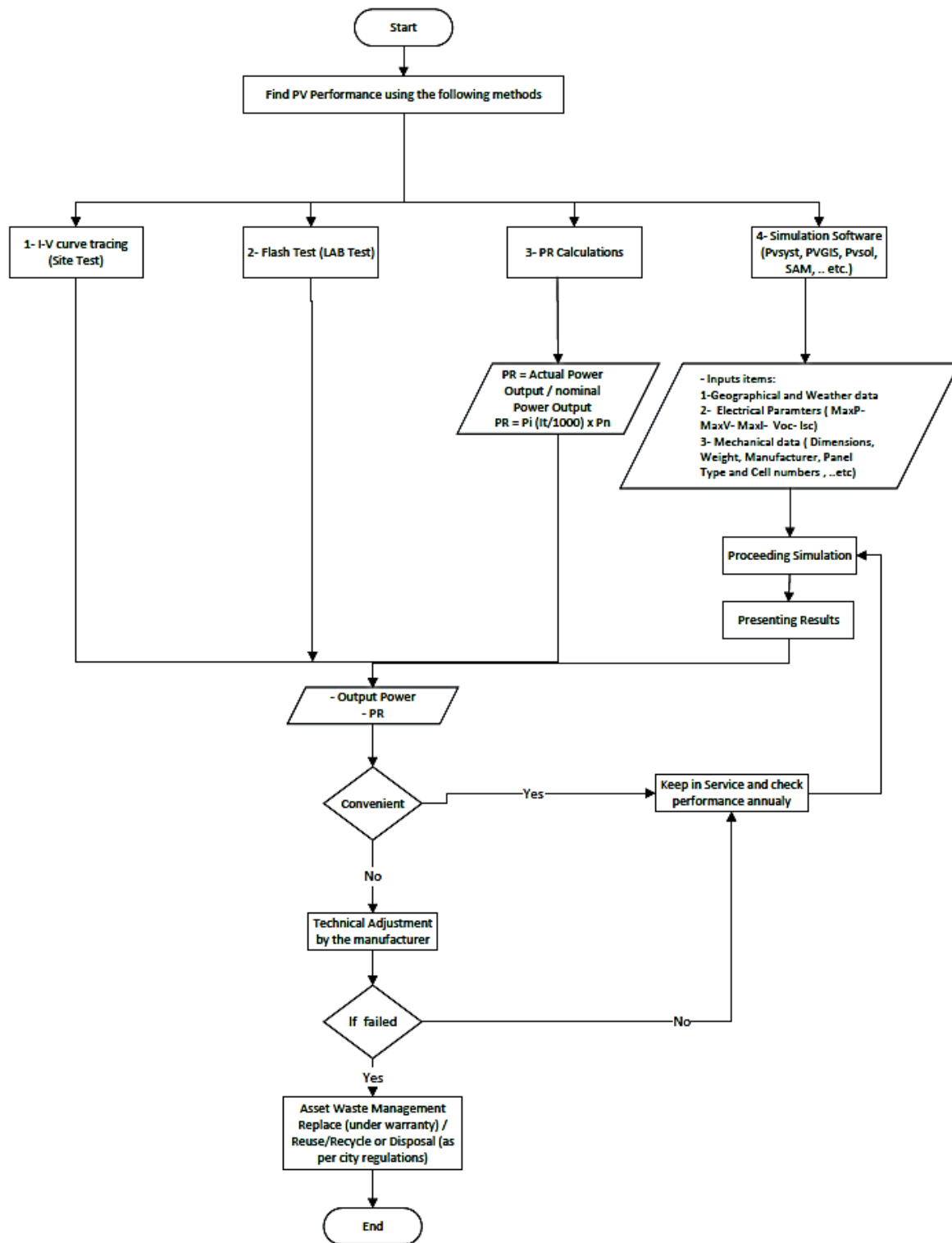


Figure 34: Proposed process flowchart for PV performance Evaluation at EOL

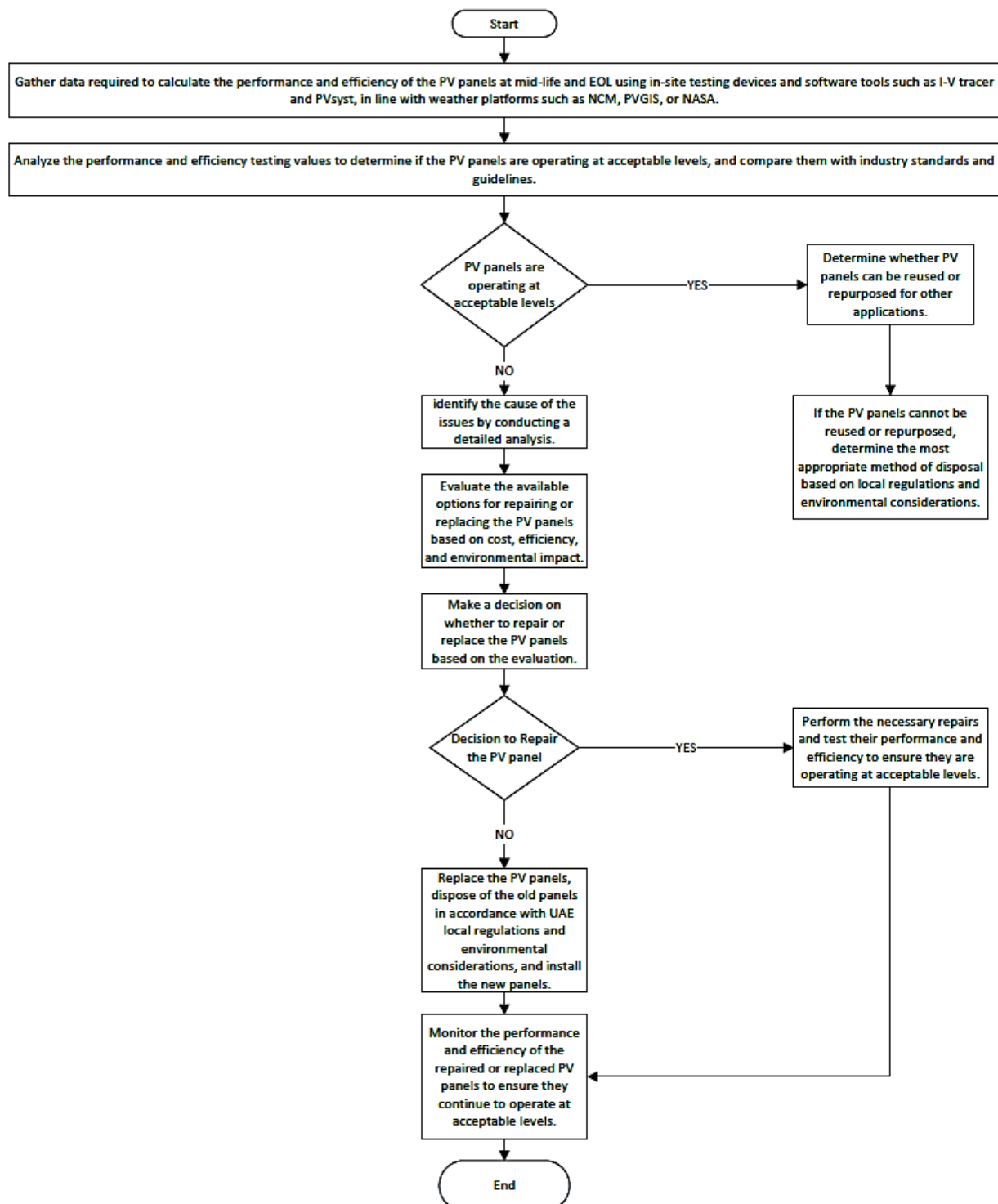


Figure 35: Proposed process flowchart for PV Decision-Making at EOL

Chapter 5 Conclusion and Recommendations:

This study examined the energy production efficiency, system performance, and losses of PV systems in four different climate regions: UAE, Canada, India, and Norway. The researcher presented through the discussion the most common and effective methodologies used for evaluating PV panel performance to support decisions related to panels reaching the end-of-life (EOL). However, due to limitations, PVsyst software & technical flowcharts were utilised. It was decided to investigate the four different climate regions once the limitations and constraints in implementing the proposed methodologies were recognised. This comparative analysis aimed to fill this gap by exploring and evaluating the different impacts on efficiency and strengthening the findings' validity. The findings and analysis allowed for broader assumptions about the system conditions and variations observed and indicated by the researcher. The research objectives were achieved successfully as the critical parameters of the PV module were identified and utilised using the simulation software and were supported by the flowcharts Figure 34 & Figure-35 for evaluating the performance and reinforcing the final decision.

In summary, the operating temperature plays a vital role in the energy production process using photovoltaic solar panels. The four countries diver in their weather & location characteristics and hence affect the same experienced PV system performance differently. High temperatures, rain, and snow directed to different assumptions as follows:

It was witnessed that solar panels generally work effectively when operating in cold environment temperatures, with clear skies and cool sunny days, free from heavy dark clouds or snow. The effect of rain in cold environments varies from rain in hot climates. In hot regions, rain has a positive impact on the overall performance of PV systems. Continuous rainfall, especially falling during sunny timing, is useful for solar panels to work better by cooling the heat of PV cells, and cleaning or washing the panel from dust, soil, or dirt, hence managing improved efficiency. While in cold regions, the thick dark rain clouds have a negative effect on the efficiency of the system during rainfall time, where the dark clouds act as a cover that blocks the sunlight from reaching the cells. Consequently, lower collection and less production than their optimal capacity.

On the other hand, there is no problem with cold weather as the low temperature doesn't affect the efficiency of PV panels since it generates electricity from sunlight, not sun heat; however, in cold regions, the snow is the factor influencing the efficiency undesirably. It acts as a shield covering the panel and prevents sunlight from reaching the cells, which stops energy generation. Alternatively, high temperatures do affect the efficiency and physical conditions of PV panels. High-temperature weather leads to an increase in the cell's heat that ruin or burns the cell's components, reducing its expected lifetime and lowering its performance while operating.

This assumption is proved by the result of the UAE solar park simulation that indicated the system reached the cut-off in 22 years with a performance of 80.0%, which is earlier than anticipated. The manufacturers guarantee a power performance of up to 80.2% until reaching 25 years. India is almost reaching the cut-off with a performance of 80.8% in 22 years, which also support the high-temperature effect assumption.

Accordingly, it is preferred that Solar panels that are less sensitive to temperature are installed in areas with hot climates, as considered in UAE and India earlier, and PV solar panels that are more reactive or sensitive to temperature changes will operate much better in colder environments (like Canada and Norway). These factors are to be considered when deciding where to install the solar panels due to their impact on the efficiency and healthiness of the panels.

To summarise the findings:

- Efficiency of solar panels operating in hot environments is lower due to the heat effect on destroying or burning the internal PV cells components, making it function less efficiently.
- Efficiency of solar panels operating in cold environments, free from heavy dark clouds or snow, is higher.
- Efficiency of solar panels in hot, rainy regions is higher due to rain benefits in cooling the heat of PV cells and cleaning the panel from dirt. While it is lower in cold regions due to the thick cloud shade.
- Efficiency in cold, snowy regions is decreased due to the snow-cover act, which lowers the amount of sunlight that the panel collects or raises the resistance to energy conversion.

After evaluating the PV system's efficiency in generating energy and power performance, and using the manufacturer's performance warranty as the benchmark, 80.2% PR after 25 years, for condition monitoring and evaluation, it is suggested to use the provided technical flowcharts (Figure 34 & 35) to make an adequately evaluated decision for UAE solar park PV system, which might recommend decommissioning the panels since their validity or usefulness reached its end earlier than anticipated. These two tools are significant to support the site engineers, system operators, and manufacturers in optimising the PV system's healthiness and configuration to maximise the system performance and extend the lifespan, to delay reaching the End-of-life stage.

The following recommendations are proposed to be incorporated into future studies:

- Manufacturers, clean energy companies, and PV asset owners are encouraged to participate in real data collection through I-V site testing, which will provide an accurate indication of PV system performance and behaviour under real-world conditions. Furthermore, performing laboratory tests can strongly validate and reinforce the results. Overall, it will be a win-win situation for the participating companies to develop and enhance their assets.
- Economic assessment of PV panels waste management:
To assess the health of PV assets and determine the optimal point at which maintenance is no longer cost-effective, future researchers to consider specific criteria like tracking the decrease in performance ratio (PR) and decrease in energy yield in accordance with the cost assessment of operation and maintenance (O&M). Hence, making better decisions about when it is economically reasonable to decommission the assets by evaluating these criteria over time.
- Future research can include the assessment of carbon footprint and CO₂ emissions reduction of the in-service PV panels.

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