A Novel and Holistic Framework For The Selection of Performance Indicators To Appraise Photovoltaic Systems

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Abstract

Most of the countries have targeted to increase the share of renewable energy projects to mitigate the adverse effects of climate change. Among all renewables, the photovoltaic (PV) technology has seen the most remarkable increase in the previous years with a global installed capacity of 1.63 TW in 2022. While expanding the installed capacity of PV technology is commendable, it is also essential to ensure that the PV systems are operating optimally. Such appraisal process not only warrants that the PV systems generation forecasts are met, but also ensures that the ratio of production to investment is as its peak. In this context, a novel and holistic framework for the selection of key performance indicators (KPIs) to assess PV systems is proposed in this study. The approach utilised in this research includes the identification and categorisation of KPIs. The latter were categorised into five groups namely: Intermittent Demand, Performance Assessment, IEC 61724 Standards KPIs, Financial Aspect and Environmental Benefits. In order to conduct a comprehensive evaluation of the financial viability and performance of PV systems, the selected list of KPIs can be computed and evaluated. This process will yield benchmark values that can be used to compare and assess the performance of PV systems to a given extent. In this optic a list of suggestions to guide stakeholders on the utilisation of the selected KPIs is also presented.

Keywords: Photovoltaics, Key performance indicators, Performance assessment

1. Introduction

As per REN 21 (2022), by the end of 2021, 166 countries have committed to increase their share of renewables and are massively investing to achieve the set targets with an aim to mitigate the impacts of climate change. Photovoltaic (PV) is now at the epicentre of the global ecological transition and it is the preferred choice of renewables to meet the renewable energy targets in all countries. The PV sector is expanding at an incredible rate with the global installed capacity increasing from 942 GW_p in 2021 (REN21, 2022) to 1.63 TW_p in 2022 (IRENA, 2023). Installation of photovoltaic energy systems is a commendable initiative, however more important is to ascertain that they are performing to the expected level such that the interest of all parties is not jeopardised. Several guidelines on how to maintain renewable energy and especially photovoltaic systems have been reported and even international standards have been developed by the International Electrotechnical Commission (IEC) for the performance monitoring, measuring, and analysing power and energy production from a PV system. However, there is no reported framework on how to select the key performance indicators (KPIs) and how to interpret the KPIs for assessing the reliability of PV systems. Several authors have used performance appraisal indicators to assess the effectiveness of PV installations in recent literature.

For instance, Seme *et al.* (2019) performed a review of the state-of-the-art PV systems in Slovenia and their performance analysis, which was then compared to other countries worldwide. In their review, the performance ratio was defined as the final yield and reference yield which depends mainly on the intensity of solar radiation and module temperature. These results showed that the performance of the PV systems primarily depended on the proper inclination and azimuth angles of the photovoltaic modules. The reported values for final yield, performance ratio and capacity utilisation factor were 1038 kWh $k^{-1}W_p^{-1}$, 68.84 % and 11.85 % respectively.On the other hand, Klise *et al.* (2017) implemented the standards described in IEC 61724 by means of software to quantify long term performance of PV systems in different climates. The methodology involved data processing, quality control, and the computation of performance metrics as well as the identification of system performance issues found through the analysis. During the investigation, the open-source software packages Pecos and PVLIB were utilised to analyse data collected from the Regional Test Center (RTC) program managed by Sandia National Laboratories (SNL) – a program that collects data across several sites in the United States. The system performance was evaluated at the sites using methods outlined in IEC 61724-4.

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Additionally, Ameur *et al.* (2020) conducted an evaluation of the performance of PV systems by comparing the different PV technologies including monocrystalline, polycrystalline, and amorphous silicon (Si) systems. System efficiency, performance ratio, energy output, and capacity factor were computed using data over a period of 5 years. Their analysis revealed that polycrystalline-Si technologies perform better than both monocrystalline-Si and amorphous-Si technologies. The polycrystalline-Si technologies yielded the lowest levelized cost of energy (LCOE) of 0.10 USD $k^{-1}W^{-1}h^{-1}$. Moreover, a software simulated model of the system was developed and the simulated results were measured against the real values. The accuracy of the simulation was validated by means of statistical measures such as root mean square error and mean absolute percentage error. They also analysed and compared the performance of similar PV systems across Morocco using performance indicators including performance ratio (PR), system efficiency (η), and capacity factor (CF). The results showed that monocrystalline-Si has the highest annual average production followed by polycrystalline-Si and amorphous-Si. In 2016, Allouhi *et al.* conducted a performance, economic and environmental assessment of two grid-connected PV systems in Morocco. Reference yield, final yield, performance ratio, energy losses, capacity factor, overall system efficiency, levelized cost of electricity (LCOE) and payback period (PB) and annual avoided CO2 emissions were analysed. They reported that for similar rated systems, polycrystalline-Si modules had a better monthly yield than monocrystalline-Si modules. LCOE and payback period were found to be in the ranges of 0.073-0.082 USD $k^{-1}W^{-1}h^{-1}$ and 11.10-12.7 years, respectively. It was also reported that the installed PV systems could reduce around 5.01 tons of CO_2 emissions per year. Sharma and Goel (2017) monitored the results of a grid-tied 11.2 kW_p PV system between September 2014 and August 2015. PV module efficiency, array yield, final yield, inverter efficiency, performance ratio, capacity utilisation factor and energy losses including capture losses, thermal capture losses and miscellaneous capture losses of the systems were investigated.

In 2021, Anang *et al.* carried out the performance monitoring of a 7.8 kW_p grid-connected rooftop PV system under the feed-in-tariff system. Several performance parameters were assessed using the two-year production data for the period 2018-2019. PVSyst was used to find the optimal orientation and tilt angle of the system. The derating factor of the system was calculated from a two-day data collection which was then used to obtain economic indicators for the estimated system life cycle of 21 years. Performance indicators used included final yield, total energy losses, performance ratio, annual capacity factor and overall system efficiency. LCOE, capital recovery factor, and payback time were used as the economic indicators while the avoided CO_2 emission defined the environmental benefits. The overall system was found to have a payback time of 5-7 years, with a good long-term profit of RM 3,000 per year, while saving 136.5-156.5 tons of CO_2 over the project lifetime. In 2019, Ameur *et al.* performed a comparative analysis of key performance indicators for different photovoltaic technologies namely monocrystalline, polycrystalline, and amorphous silicon (Si) systems. Software solutions like Propre.ma was used in MATLAB to conduct this study. Parameters monitored included AC energy output, performance ratio, system efficiency and capacity factor. An economic analysis was also carried out to evaluate the LCOE of the three technologies. Results show that polycrystalline technology is the most cost-effective technology for the Ifrane region.

Taken together, a holistic PV system performance appraisal comprises several areas such as technical, financial, and environmental characteristics. The synthesis of existing literature revealed that the most used indicators in performance appraisal are efficiency, capacity factor, performance ratio, LCOE, payback time and avoided CO_2 emissions. However, the impact of certain key factors, such as temperature, are often overlooked. This suggests that this field is to be further explored and thus the need for further research. More so, it was also observed that the selection of the KPIs for the assessment of a given PV system mostly stood guided by common practice, rather than a systematic rationale or framework to follow. As such this study endeavours to propose PV stakeholders with a novel and holistic framework which will guide the selection and interpretation of KPIs for the appraisal of PV systems. Identification and categorization of key performance indicators (KPIs) was meticulously undertaken, leading to the development of a concise shortlist of KPIs specifically tailored to comprehensively assess the performance of solar PV systems. These selected KPIs encompass a spectrum of critical factors such as energy production efficiency, system reliability, financial viability, and environmental impact, offering a holistic framework to evaluate and benchmark PV system performance while simultaneously addressing sustainability concerns. This refined set of KPIs serves as a valuable tool for stakeholders in the PV industry, enabling them to make informed decisions, optimize system efficiency, and enhance the bankability of PV projects, thus advancing the adoption of renewable energy solutions. The paper organisation is as follows: Section 2 described the methodology employed, Section 3 presents and discusses the results obtained, and Section 4 provides a conclusion.

2. Methodology

The research has been conducted through a structured methodology encompassing several phases. In the initial phase, the research discusses the different types of PV systems, then focused on identification of KPIs pertinent to the appraisal of solar PV systems. Following this identification process, the KPIs were systematically categorized into five distinct groups. Subsequently, a set of guidelines was developed to aid in the selection of these KPIs. In order to conduct a comprehensive assessment of the overall effectiveness and the bankability of solar PV systems, it is necessary to computationally evaluate the following selected KPIs. In light of this perspective, a compilation of recommendations for the application of the guidelines was produced. This encompassed the identification of relevant PV datasets, along with the utilization of tools and methodologies to facilitate the modelling of solar PV systems. Consequently, the computed KPIs will therefore provide benchmark values which are able to facilitate a comparative analysis and assessment of the performance of PV systems.

2.1 Identification of KPIs

The research methodology for identifying the KPIs related to solar PV systems involved an extensive review of existing literature. This literature review encompassed a comprehensive exploration of scholarly articles, industry reports, international standards and relevant publications to compile a comprehensive list of PV system KPIs. This literature-based approach ensured a well-informed and comprehensive selection of KPIs, laying the foundation for a robust framework for assessing the performance and the bankability of solar PV systems.

2.2 Categorisation of identified KPIs

The identified KPIs were systematically categorized into five distinct groups, including Intermittent Demand, Performance Assessment, IEC 61724 Standards KPIs, Financial KPIs, and Environmental KPIs. This categorisation enhances the clarity and organization of the developed set of guidelines. These categories were established with the purpose of addressing the different aspects of solar PV systems. The Intermittent Demand category focused on metrics related to the variable nature of energy generation from PV systems, addressing issues such as energy demand fluctuations. Performance Assessment explored the KPIs that evaluated the overall efficiency and effectiveness of PV installations, including metrics related to energy production and system reliability. The inclusion of IEC 61724 Standards KPIs ensured adherence to industry standards and regulations, emphasizing the importance of compliance and quality assurance. The financial KPI category delved into metrics associated with the economic viability of PV systems, covering indicators like return on investment and cost analysis. Lastly, the Environmental KPI category considered indicators related to the environmental impact and sustainability of PV systems, acknowledging their role in reducing carbon emissions and promoting renewable energy adoption. This categorization facilitated a comprehensive evaluation of PV systems from various dimensions, enabling a more holistic assessment of their performance and significance.

2.3 Development of a set of guidelines for the selection of KPIs

The list of guidelines for the KPI selection was then developed, taking into account the unique characteristics and considerations of each category. These guidelines aimed to provide a framework for researchers and stakeholders to systematically select and apply KPIs that align with specific objectives and contexts within the realm of solar PV systems, ensuring a comprehensive and standardized approach to performance appraisal.

2.4 Utilisation of the selected KPIs

To effectively utilise the developed set of KPIs for assessing solar PV systems' performance, it is crucial to incorporate relevant solar PV system datasets. These datasets serve as the foundational source of information for evaluating overall system efficiency and productivity. They are essential for understanding how external factors influence solar PV output. The incorporation of performance metrics with actual meteorological data allows for a more precise evaluation of PV system performance under varying conditions. Furthermore, the use of PV system modelling techniques and tools enhances the assessment process by predicting performance, conducting financial analysis, and optimizing system design. A list of suggestions on the types of datasets which can be used along with modelling techniques is provided in the subsequent section.

3. Results and Discussions

3.1 Types of PV Systems

A PV system is a set of electrically interconnected equipment which may reliably convert solar power into electrical power and safely transfer the power to an electrical load in the most efficient and cost-effective manner. PV systems may be broadly categorised into grid connected and off grid systems. The grid connected systems may be further categorised into power optimiser-based systems, micro-inverter based systems, string inverter-based systems and central inverter-based systems. Furthermore, PV systems may be classified into small scale, medium scale and large scale projects. In the context of Mauritius, small scale systems are those with a capacity of less than 50 kW. Medium scale projects range between 50 kW to 2 MW. Large scale projects are those which are above 2 MW. For the sake of this several PV systems were identified in order to assess whether the proposed framework for performance appraisal may be applied to them based on their existing equipment. The performance of a PV systems is impacted by a number of factors such weather conditions, the environment surrounding the PV systems, the way the system has been physically deployed, the type of equipment used, the condition and age of the equipment and also on the way the system is maintained. It must be highlighted that the proposed framework for performance assessment of PV systems is not type specific and may be applicable to any type of PV systems.

3.2 Identification and Categorisation of KPIs

A performance assessment framework consists of detecting low performance in PV systems, investigating the causing factors and help in the setup of maintenance plans to minimise operational costs. The performance assessment of PV power systems is usually carried out by using different types of performance indicators that benchmark the output of these systems against the PV panel output at hypothetical operating conditions. The performance test condition or commonly known the Standard Testing Condition (STC) for the Solar PV systems refers to the reference values of the in-plane irradiance (G_{ref}) of 1000 Wm^{-2}, PV cell junction temperature, T_c of 25°C and air mass (AM) of 1.5 value to be used during the quality testing of any PV device (Ya'acob *et al.* 2014). Additionally, once PV systems are deployed, several other factors impact the expected solar PV performance, the production. Some of these factors include solar irradiance, temperature, and degradation rate (Vidyanandan, 2017). As described by the DOE (2021), PV module output decreases with temperature according to a temperature coefficient, δ, which is the percent reduction in power per degree Celsius above a reference temperature. PV module efficiency unavoidably degrades with age at a rate, of about 0.5% per year. Electrical losses will also occur throughout the balance of the system, which can be estimated. Failure rates are also higher in later years as the equipment ages, increasing downtime. Events such as severe weather can also impact PV system performance in unpredictable ways. A comparison of the system's actual output with the expected output can be used to quantify underperformance.

In this research, the IEC 61724 (2016) standard which outlines terminology, equipment and methods for performance monitoring and analysis of solar PV systems has been used and several research reports have been perused and scrutinised. Following the analysis of literature the KPIs are identified and grouped into several categories. The Intermittent Demand category focuses on metrics related to the variable nature of energy generation from PV systems. Performance ratio is used for evaluating the efficiency of solar PV systems. It can indicate the overall effect of losses on the rated PV capacity due to system inefficiencies such as cell temperature effects, BOS faults, and system downtime (Pless *et al.* 2005). The second KPI in this category is the plant availability factor (PAF). The plant availability factor is used to determine the time duration that PV systems are not operating. This metric is crucial as the availability factor of any PV system cannot be assumed or kept constant. In real time conditions, due to the limitations of system reliability, running interruptions or component failures, the generation ability and generation period are reduced giving a scope for quantifying actual availability time of PV system (Kumar *et al.* 2018).

The performance assessment category includes a set of indicators which broadly assess the electrical performance of a PV system over a period of time. To determine the installed power load factor, average power has to be calculated. It allows comparisons between monthly/quarterly or annual results of the same power plant, or it can be used to compare the generating units' performance within the same power plant. Similarly, the installed power load factor can be calculated on a monthly, quarterly or annually basis and indicates the availability of renewable resources and production capacity of the solar PV system. Also, it can indicate the degree of generating units or equipment's ageing. The installed power load duration can also be calculated as it is able to indicate the according number of operating hours which can be reduced considering only those daytime hours when the PV system is operating (Odeh, 2018). In order to ascertain the value of solar PV systems, the power factor is evaluated. The power factor of a PV system is the ratio between the system's actual power (kW) and apparent power (kVA) (GSES, 2015). When a PV system is producing energy, it mainly produces active power and feeds it directly to the load, hence decreasing the active power demand from the utility. While reactive power needed from the load remains the same. This will result in a reduction in the power factor at the point of grid connection which in turn can lead to penalties that need to be paid to the grid operator. Calculation of the power factor therefore indicates whether measures should be taken to prevent any penalty (Elghobashy, 2020).

The third category depicts the indicators provided in the IEC 61724 standard. Performance Ratio (PR), as defined by IEC61724 and NREL, is the most used metric, however one shortcoming of this indicator is that normal temperature variation influences are not taken into consideration (Odeh, 2018). Unlike the performance ratio, the performance index is not affected by temperature variations and has been considered. In order to use a metric which is more indicative of system condition rather than design or environmental conditions, compensation factors can be added to the basic performance ratio equation. Such a metric as defined by IEC61724 is the temperature compensated ratio (Walker & Desai, 2021). Additionally, yield is one of the most used performance metric for solar PV systems. It is used to compare different locations and to analyse different engineering designs. Rather than performance, yield is a measure of the system value (Tiwari & Sodha, 2006). The normalised efficiency of a solar PV system as a metric allows the monitoring of PV systems on time scales ranging from seconds to days and longer. It also permits an improved qualitative and quantitative comparison of PV systems with different power ratings in graphical displays and numerical calculations (Herteleer *et al.* 2017). One of the shortcomings of both the performance ratio (PR) and the normalised efficiency is that they are sensitive to temperature variations, as the change in temperature leads to a change in efficiency and power, and subsequently energy. The temperature corrected power and efficiency as defined by the IEC 61724 has also been included.

The fourth category is the Environmental KPI category. The details the fundamental KPIs which reflect the positive environmental impact of the installed PV systems. The avoided carbon dioxide emissions represent the amount of CO_2 which has been avoided per unit of electricity generated by the PV system. The equivalent number of trees planted indicates the number of mature trees planted in a tropical environment due to the avoided CO_2 and carbon sequestration in trees.

The last category is the Financial KPI category. It includes the internal rate of return (IRR), the payback period (PBP) and the levelised cost of electricity (LCOE), Net Present Value (NPV) and Return on Investment (ROI) as the main financial indicators. The IRR indicates the discount rate which would result into a zero net present value at the end of the contract period. The pay back period indicates the amount of time required to recover the intial investment. The LCOE is defined as the charge per kilowatt-hour (kWh) that equates the discounted present value of revenues to the discounted present value of costs, including the initial capital investment and annual operating costs as well as any future replacement capital costs incurred over the life of a facility (Tamburini *et al.* 2015). The NPV is used to determine the profitability of the investment over the lifetime of the solar PV project. It is calculated by finding the difference of the present value of cash inflow and the present value of cash outflow, discounted to the present time (Mazumdar and Rajeev, 2015) The return on investment evaluates the profitability and viability of a PV project’s investment over its full term (Hoymiles, 2022).

Table 1: Description of Key Performance Indicators

SN	Key Indicator	Symbol	Unit	Formula
A	**Intermittent Demand**			
1	Performance Ratio PR_I is the ratio between actual electricity production and theoretical production during a reference period where E_{AC} is the total output energy, E_{POA} is the energy per unit area of solar radiation, H_{STC} is the standard test conditions for solar irradiance, typically 1000 Wm^{-2} and P_{DC_STC} is the DC output power under STC (Zenhäusern, 2020)	PR_I	%	$PR_1 = \frac{E_{AC}}{E_{PoA}} \times \frac{H_{STC}}{P_{DC\,STC}}$ (eq. 1)

2	Plant Availability PA is the ratio of plant's Operating Time, OT and the PV plant's Net Available Time, NAT (Klise *et al.* 2016)	PA	%	$PA = \frac{OT}{NAT}$	(eq. 2)
B	**Performance Assessment**				
3	Average Power P_{avg} is the ratio between the produced energy, W and power plant's runtime, (t) depending on the yearly power plant operational time (Pearsall, 2016).	P_{avg}	W s^{-1}	$P_{avg} = \frac{W}{t}$	(eq. 3)
4	Installed Power Load Factor K_u is calculated as the ratio of average power, P_{avg} and installed power, P_i (Oprea and Bâra, 2017)	K_u		$K_u = \frac{P_{avg}}{P_i}$	(eq. 4)
5	Installed Power Load Duration T_i is determined based on installed power load factor, (K_u) multiply by power plant's runtime, (t) (Pearsall, 2016)	T_i	s	$T_i = K_u \times t$	(eq. 5)
6	Maximum Power Load Duration T_{max} is calculated as ratio between generated energy, W and maximum power plant output, P_{max}. (Duffie and Beckman, 2013).	T_{max}	s	$T_{max} = \frac{W}{P_{max}}$	(eq. 6)
7	Performance Index PI is the ratio between the generated energy, W and forecasted energy, W_f (Kalogirou, 2014)	PI		$PI = \frac{W}{W_f}$	(eq. 7)
C	**KPI from IEC 61724 standard (IEC61724, 2016)**				
8	Performance Ratio PR indicates the overall effect of losses on the system output and is the quotient of the system's final yield Y_f to its reference yield Y_r. -Y_f represents the ratio between annual active energy and rated power. -Y_r is the ratio between insolation (kW h m^{-2}) and reference solar irradiance (1 kW m^{-2}).	PR	%	$PR = \frac{Y_f}{Y_r} = \frac{kWh_{AC}}{kW_{DC\ STC}} \times \frac{1\ kW}{kWh_{sun}}$	(eq. 8)
9	Temperature Compensated Performance Ratio, Offsetting factors such as cell temperature (K_{Temp}) can be applied to the PR formulae to adjust the rated power under STC. Where, $K_{Temp} = (T_{Panel} - T_{STC})$, (T_{STC} = 25˚C)	$PR_{TempComp}$	K	$PR_{TempComp} = \frac{PR}{K_{Temp}}$	(eq. 9)
10	Yield Yield is the actual net energy output during a certain period of time divided by the maximum installed power capacity of the PV array and can be measured on various time scales such as daily, monthly or annually	Yield	W h	$Yield = \frac{\sum_{i=1}^{t} kWh_{AC}}{kW_{DC\ STC}}$	(eq. 10)
11	Normalized efficiency η_N is the ratio of the output energy of the PV system to the energy of the incoming irradiation incident on the same PV panels' area	η_N	%	$\eta_N = \frac{P}{P_n} \times \frac{E_{ref}}{E_{PoA}}$	(eq. 11)

12	Temperature Corrected Power Impact of temperature variation is corrected using temperature corrected power	P(T)	K	$P(T) = P_{STC}(1 + \gamma \Delta T_{STC})$ (eq. 12)
13	Temperature Corrected Power	P*	(K)	$P^* = \frac{P(T)}{1+\gamma \Delta T_{STC}}$ (eq. 13)
14	Temperature Corrected normalized efficiency Seasonal variation of the efficiency is removed by calculating a temperature-corrected efficiency	$\eta_N(T)$	K	$\eta_N = \frac{P^*}{P_n} \times \frac{E_{ref}}{E_{PoA}}$ (eq. 14)
D	**Environmental Benefits**			
15	Avoided CO_2 emissions, The contribution in combating the effect of climate change due to avoided CO_2 emissions with the G_{ef} being the national electrical grid CO_2 equivalent emission factor (NREL, 2012)	$CO_{2\_avoided}$	Kg	$CO_{2\_avoided} = W \times G_{EF}$ (eq. 15)
16	Equivalent trees planted A mature tree can absorb around 48 pounds (or approximately 22 kg) of CO_2 per year. This is equivalent to about 0.022 metric tons of CO_2 per year (Toochi, 2018).	$Trees_{\_eq}$		$Trees_{\_eq} = \frac{CO_{2\_avoided}}{0.022}$ (eq. 16)
E	**Financial Aspects**			
17	Levelized Cost of Electricity LCOE takes into account the time value of money such as capital costs and operation and maintenance costs. It calculates the average cost per unit (Tamburini, Cipollina and Micale, 2021)	LCOE	USD W^{-1}	$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Q_{el}}{(1+i)^t}}$ (eq. 17)
18	Net Present Value NPV is used to determine the profitability of the investment over the lifetime of the solar PV project. It is calculated by finding the difference of the present value of cash inflow (CF_T) and the present value of cash outflow (CAPEX), discounted to the present time , r. The first indication of the profitability of RE investment is that it shows a positive NPV (Mazumdar and Rajeev, 2015).	NPV	USD	$NPV = \sum_{t=1}^{T} \left[\frac{CF_T}{(1+r)^t}\right] - CAPEX$ (eq. 18)
19	Internal Rate of Return, The IRR represents the discount rate at which the Net Present Value (NPV) of the cash flows from the investment becomes zero (NREL, 2011).	IRR	%	$0 = NPV \sum_{t=0}^{T} \frac{CF_T}{(1+IRR)^t}$ (eq. 19)
20	Payback period PBP indicates the time it takes to recover the initial investment in a PV system. Where CAPEX is the capital expenditure (UNL, 2013).	PBP	Years	$PBP = \frac{CAPEX}{Annual\ cash\ inflow}$ (eq. 20)

21	Return on Investment (ROI) The return on investment evaluates the profitability and viability of a PV project's investment over its full term (Hoymiles, 2022).	ROI	%	$\mathrm{ROI} = \frac{\text{Net income savings}}{\text{CAPEX}} \times 100$ (eq. 21)

3.3 Datasets

To effectively utilise the set of KPIs, it is highly recommended to assess and incorporate relevant solar PV system datasets. The latter serve as the fundamental source of information required for assessing and evaluation the overall performance of solar PV systems. Key types of solar PV datasets include:

3.3.1 Solar PV System Data

The technical details of the PV systems include the location, the date of installation, the details of the inverters, modules, mounting strategy, system rating and details of degradation. In addition to the aforementioned information, it is essential to incorporate financial data into the analysis, including capital costs (CAPEX), operational and maintenance costs (OPEX), discount rates, power purchase agreements (PPA), cash flows, loans, subsidies, relevant taxes, and electricity pricing. Sample description of two PV systems are introduced here. PV System 1 is located at Site 1 with coordinates 20.24° South and 57.50° East, PV System 1 was installed in 2017 and is a Small Scale power optimiser based grid connected PV system rated 20 kW_p with 62 (String 1: 20 Nos; String 2: 21 Nos; String 3: 21 Nos) Yingli 320 W_p (YL320P- 35b 320 W) multi-crystalline PV modules connected to one ABB string inverter (TRIO-27.6-TL-OUTD-S2J-400). The efficiency of the solar panel is 18.5% with a 25-year linear performance warranty and a degradation rate of 0.4825 % per year. PV system 2 was installed in 2019 and is located at Site 2 with coordinates 20.22° South and 57.39° East. It is a Small Scale grid connected string inverter-based PV system rated 50 $kW_{p.}$ It contains 130 (String 1: 34 Nos; String 2: 32 Nos; String 3: 32 Nos; String 3: 32 Nos) Jinko Solar Eagle 385 W_p (JKM385M-72H-V) monocrystalline PV modules connected to two SolarEdge inverters (SE25K) through 65 SolarEdge Power Optimizer (P850). The efficiency of the solar panel is 19.53 % with a 25-year linear performance warranty and a degradation rate of 0.495 % per year. According to prevailing exchange rates, the cost of PV system 1 amounted to USD 294,106, while PV system 2 costed USD 565,590.

3.3.2 Solar PV production data

Instantaneous, daily, monthly or yearly electrical PV performance data from solar PV systems provide valuable insights into the operating conditions of the PV installations. These data points help in measuring the efficiency and productivity of the PV systems over time. The electrical performance datasets include dc current, voltage and power input at each string of the inverters; ac current, voltage, frequency, power and power factor for each phase of each inverter. These datasets are normally captured by majority of the commercially-available inverters in the market and may be accessed over their web interfaces. However, the sampling rate of the instantaneous data should be configured to be at the minimum intervals. The most recommended sampling rate is 1-minute. However, many of the commercially available inverters may only provide these datasets at either 5, 15, 30 or 60-minute interval.

3.3.3 Weather data

Ground-based or satellite data offer crucial information regarding weather conditions that impact PV system performance. This includes factors such as solar irradiance, temperature, wind speed and direction, humidity and cloud cover. These weather-related datasets are essential for understanding how external factors impact the output of solar PV systems. The requirements of the measuring equipment that may be installed at the PV facilities is well captured in IEC 61724-1. It must be noted that commercially available inverters may display some weather conditions through their web platforms. Satellite based datasets may be procured from recognised data providers such as SolarGIS and Meteonorm amongst others. The utilization of performance metrics and actual meteorological data allows for a more precise evaluation of the performance of PV systems under real weather conditions and during varying durations. The outcome of this process enables decision-making and PV system optimisation. It must be ensured that the measuring equipment are calibrated as per prevailing standards applicable to the equipment in use and that the sampling rate is adjusted to that of the sampling rate of the electrical datasets. The datasets should also be quality control procedures. The reader is referred to Bangarigadu *et al.* (2020) and Ramgolam *et al.* (2020) for more details about the description and justification for the selection of the quality control procedures and techniques.

3.4 Computational tools.

In addition to utilizing relevant PV system datasets, the use of PV system modelling techniques and tools, such as PVsyst and SAM (System Advisor Model), are highly recommended for a comprehensive assessment of PV system performance. The aforementioned modelling tools offer valuable capabilities for the following:

- Performance prediction by providing estimates for energy prediction and system efficiency assessment through the simulation of PV systems under different weather conditions
- Financial analysis by using tools like SAM which can help evaluate the economic viability of PV projects by considering factors such as project costs, incentives, financing options, and return on investment (ROI)
- System design and optimisation by allowing determination of optimal PV panel placement and orientation, as well as the sizing of the system components to maximize energy output and minimize costs.

By incorporating PV system modelling techniques and tools into the assessment process, researchers and stakeholders can gain deeper insights into the expected performance, financial implications, and design considerations of PV systems. This holistic approach, which combines data-driven analysis with predictive modelling, supports more informed decision-making and helps optimize the planning and operation of PV installations. Excel based tools or any other mathematical package may be considered for evaluating the KPIs.

3.5. Guidelines for assessing the performance of PV systems using the KPIs

A set of criteria has been devised to facilitate a comprehensive assessment of solar PV systems. These guidelines have been condensed and presented in the form of a flow chart, as depicted in Figure 1. The first step entails the implementation of a thorough data warehousing to gather technical data, specifically E_{ac}, E_{POA}, H_{STC}, P_{DC_STC}, and P_{ac}, as outlined in Table 1. In a similar vein, this study incorporates weather data obtained from both ground-based measurements and satellite observations, specifically focusing on variables such as temperature,T and plane of array irradiance, POA. Additionally, financial data related to the PV system(s) being examined, including CAPEX, OPEX, electricity price, and price per watt, are also taken into consideration. In order to ensure the accuracy and reliability of the gathered data, a quality control is performed. This includes checking for data completeness, identifying and addressing anomalies, validating sensor and instrument calibration, and assessing data consistency over time.

Additionally, quality control may involve the removal of erroneous or duplicate data points and the application of statistical techniques to detect and rectify any data discrepancies. The goal of this rigorous quality control process is to enhance the integrity of the PV dataset. The subsequent process involves the system modelling of the PV system(s) through the utilization of modelling tools such as PVsyst and simulation techniques. The modelling and simulation of PV systems enable the emulation of system performance in diverse scenarios such as before and after implementation, hence providing valuable information for system optimization. The performance assessment is then conducted by computing the 21 KPIs described in Table 1. The latter facilitates the identification of disparities between the projected and actual performance data, thereby providing guidance to stakeholders on enhancing the operational efficiency of PV system(s).

A comparative analysis of the computed KPIs with respect to benchmark values is also performed. The latter facilitates the identification of disparities between the projected and actual performance data, thereby providing guidance to stakeholders on enhancing the operational efficiency of PV system(s). If the calculated KPIs deviate from the established baseline values, additional examinations such as Root Cause Analysis (RCA) or Fault Tree Analysis (FTA) may be conducted. Consequently, the flawed process will need to be re-executed. On the other hand, once the optimal KPI values are achieved, more optimization measures can be undertaken to improve the efficiency of the PV system(s). Alternatively, a comprehensive report can be prepared to monitor and assess the performance and feasibility of the system(s). The outcome of the report would provide insights into the overall technical, financial and environmental performance detailing whether the intended goals and KPIs are met. Ultimately, the outcome of the report aims to inform on the system's current status and guide future actions to ensure its continued success. By adhering to the guidelines developed in this study, stakeholders can harness the full potential of performance indicators and KPIs for PV systems, fostering informed decision-making, optimizing system performance, and ensuring the sustainability of solar energy endeavors on both environmental and financial fronts.

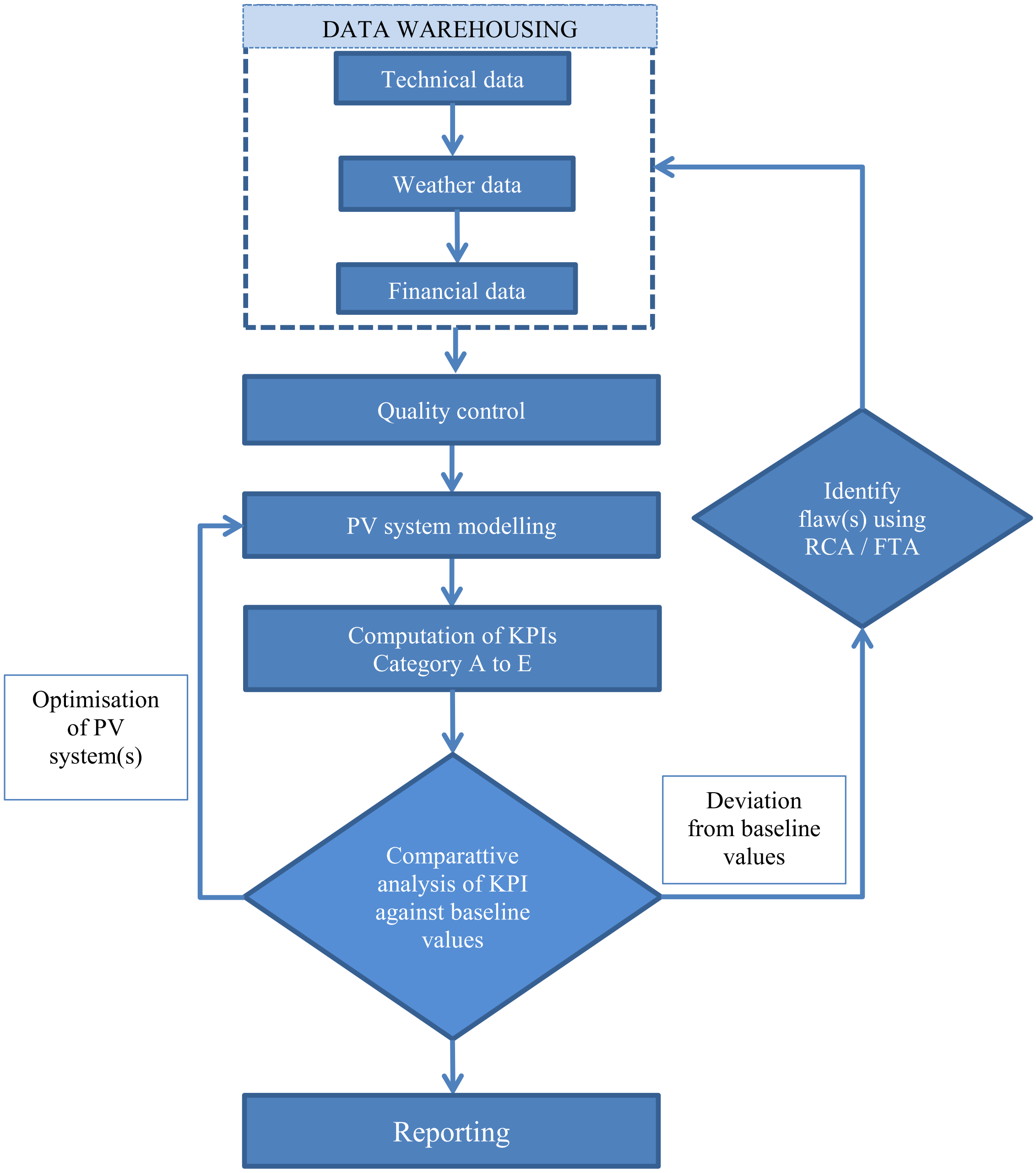

Figure 1: Guidelines for PV performance assessment

4. Conclusion

Solar energy is gaining more and more importance in the contemporary society and is perceived as the future leading source of energy that will revolutionise the global energy mix. PV technology has experienced phenomenal growth over the years due to an incredibly high penetration rate in countries' energy mix. However, it is more crucial for PV systems to perform optimally, rather than just increasing the installed capacity. In a bid to appraise the performance of PV systems, literature provides numerous KPIs. Nevertheless, synthesis of literature revealed that there exists no proper framework to guide the selection of KPIs for a given system. More so, for most KPIs, there are defined benchmarking or recommended values. By meticulously identifying and categorizing the KPIs, this framework provides a comprehensive and tailored approach to evaluate the different aspects of PV system performance. It goes beyond mere energy production metrics, incorporating factors such as reliability, financial viability, and environmental impact. This holistic perspective is crucial in addressing the diverse risks and impacts inherent in solar PV systems. The framework not only facilitates a thorough understanding of PV system performance but also acts as a guide for stakeholders, ranging from investors and policymakers to engineers and project managers, fostering informed decision-making and contributing to the sustainable growth of solar energy initiatives. As the global shift towards renewable energy intensifies, the implementation of this framework is poised to play a pivotal role in ensuring the bankability, efficiency, resilience, and overall success of solar PV systems on a broader scale.

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