Performance Analysis with Risk Identifications and Its Economic Impact on PV Plant in Harsh Climates: Baghdad_site Case

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September 14, 2023

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Abstract

PV system reliability and durability investigations are essential for industrial maturity and economic success. Recently, PV systems get a big interest in Iraq due to many reasons for instance, power shortage, global warming, pollution, etc., Solar PV is promising in Iraq, assuming the PV module's efficiency equal to 16%, each 10 km² has the potential to produce estimated energy of about 3.4 billion kWh/year, equivalent to a total capacity of 5.9 GW.

The primary objective of this work is to measure the energy and the performance indices of an existing PV plant and identify the most common shortcomings, failure modes and their economic impact on the energy yield and LCoE. Through delivering lifetime energy based on FMEEA by pointing out all the related failure modes in harsh climates like those of Iraq. A comprehensive data base python program is written and implemented for calculation the energy and performance indices of the PV plant. A 850 kWp, government-asset, flat roof, grid-connected PV plant installed over 6000m² in Iraq/Baghdad-Ministry of Electricity facility was inspected, which is denoted as BWh hot arid with rare to very little precipitation. Comprise of 4812no., of 205Wp Si-module and 36no., of 25kW SMA inverter. Data measured and calculated factors revealed a degradation rate of the PV system above the recommended industry values was 3.325%. Moreover, poor system performance reaching 84% power losses. In addition, with an augmentation in O&M costs range from 45% to 60% of the total CAPEX were noticed after only 36 months of operation. Also, the study identify and specify the main failures mode and components lifetime respectively.

Keywords

PV, FMEEA, failure, cost impact, RPN.

Nomenclature

ASC Anti-soiling coating
BoS Balance of system
CAPEX Capital cost
CPN Cost priority number
EPC Engineering, procurement and construction
EVA Ethylene Vinyl Acetate
FMEA Failure mode effect analysis
FMEEA Failure mode effect/energy analysis
JB Junction box
KPI Key performance indicator
LCoE Levelized cost of electricity
LID Light-induced degradation
MPPT Maximum power point tracking
MTBF Mean time between failure
O&M Operation and Maintenance
OPEX Operational cost
PID Potential-induced degradation
PV Photovoltaic
R.P.N Risk priority number
UV Ultraviolet

1. Introduction

Renewables, specifically PV systems have taken over the new additions to the world's power generation mix and largely in Asia over the past years. PV presents as the most promising technology; globally, PV installation capacity reaches 1 TW and could power 13% of the world by 2030[1]-[2]. Since 1991, electricity blackouts, rolling blackouts and brownouts remain a common event at grid-connected settlements. Leaving Iraq rely on expensive and polluting diesel generators as the electricity demand exceeds generation by about 15,000MWat the end of 2021. In summer months the power crisis is exacerbating as Iraq's electricity consumption has been annually increased at an average compound growth rate of 6 – 7 % since 2003[3].

Iraq has been globally endowed with vast oil and gas reserves so fossil fuels are the main energy source and form 96% of the total power generation in Iraq [4]. Over the past decade, PV systems have got a lot of interest in Iraq, due to many reasons thereof, global warming, air pollution, lack of power generation, financial capabilities, etc., To produce a new power generation approach which shall be competitive, reliable and economically feasible. Iraq is ahead to implement 10 GW of PV plants by end of 2030 [5]. Hot and humid regions have the main challenging conditions for solar PV applications and lead to high energy loss[6] .Adopting the climate classification plot created by Köppen – Geiger, Iraq was classified as a BWh zone, namely arid, desert and temperature as hot arid [7]. Iraq has abundant of solar energy potential with extensive sunlight throughout the year as it lies in the global sunbelt. Solar energy generation can be deployed extensively in the western and southern regions of Iraq[8]-[9]. In harsh climates, PV plants implementation faces many challenges and sometimes be problematic. Because of the influence of high daily ambient temperatures, a wide difference of temperatures intraday, high progressive soiling rate, and high levels of UV hereinafter called " climate stress factors". Also maintenance and cleanings concepts, these challenges lead to high degradation rates, less reliability and spin up the LCoE[10] . Therefore, the assessments of performance risk measures like reliability and quality of its components are vital concern that poses a challenge and pressing questions, especially in harsh climates like in Iraq. About 70% of the loss of power encountered in PV plants is due to soiling alone [11]. The soiling effect exceeds the power loss to initiate system degradation and failures. Installed systems observation, degradation rates measure and checking the commercial warranty returns from different climates regions leads to reliability enhancement[12].

So far, the long-term reliability and durability of the manufacturer offering 25 years for PV modules are still unclear, especially in harsh or hot climates like Iraq. For many reasons researchers, investors and business developers face difficulties in accessing the performance data of PV plant's components worldwide. Like they have so far only been operated for short periods or the tendency between the owners and manufacturer to keep such data covered. In harsh climates, the short circuit current (I_{SC}) plays the main role to contribute power loss (Pmax) degradation due to delamination, cell cracks and discolouration[6]. The manufacturer warranty margin increased from 5 years in 1980s to 10 years in 1990s, reaching currently 30 years [13] .Studies showed that the degradation of PV modules deployed in harsh or hot climates is three times faster than the moderate regions. In the same context, the number of PV modules commercially returned was more than $3X10^6$ module-year and pointed out about 66% of these returns were due to problems in cell interconnection(cell-ribbon-solder) failures, <1% due to front contact and 20% with problems in back sheet or encapsulation[14]. Studies present that the most common infant failure modes of PV modules were JB failure, front glass damage, internal interconnections, defects in the frame and delamination. The study mentioned that more than 2% of fielded PV modules fail after 11-12 years [15] .Module's MTBF was 552 years for residential and 6666 years for a utility-scale system, in turn, found that 90% of the failure was due to inverter issues[16]. In the utility-scale fielded systems, the MTBF of inverters has been recorded as 300 to 500 times shorter than the modules [17]. Whilst, a study for 2 years revealed module failure produces 5% of total energy losses, whereas, inverters failure forms about 36% of the loss's energy based on the same period [18]. The most common types of inverter failure modes in harsh climates are bus capacitors, switches, MPPT and printed circuit boards. Meanwhile, the most common failure modes of PV modules in harsh climates are delamination and encapsulant discoloration[6]. Moreover, fan failure due to dust cause an inverter to overheat and damage its lifetime and reliability [19]-[20]. Studies showed that an efficiency reduction of PV system up to 5% can occur after few hours of light exposure with higher rate of degradation reaching 10%/year[21] . Other also presents that the efficiency is reduced by 69% at 64°c[22] .In KSA showed that the average reduction rate of the efficiency is 6-7%/month[23]. A review study demonstrate that the output power varies and degrade with time of operation under site conditions[24]. This study is mainly based on the report of the International Energy Agency of Photovoltaic Power Systems (IEA PVPS) Task-13 and its subsequent versions, where the most common failure modes of PV modules were described and listed [25]. Entails the methodology based in this study as per demonstrated in item (2). Item (3), assesses in detail the proper technical approach of risk identifications and list the technical gaps. Furthermore, quantify the performance and energy indices. while, item (4), review the conducted results whereas, item (5), recommend the methods to improve the grade of PV in harsh climates. Finally, item (6), summarize the results obtained. The study aimed to increase the knowledge of techniques to assess technical risks and alleviation measures for an existing PV plant in Baghdad-IRAQ. An 850 kWp, government-asset, flat roof, grid-connected PV plant installed over 6000m² in Iraq/Baghdad-Ministry of Electricity facility was inspected over four months. The main energy and performance indices were measured and calculated. Through extensive visual inspection, I-V curve measurements, IR imaging and Electroluminescence (EL). In this work, we will define the pathway to reduce the performance risks of PV plants to be deployed and operated in harsh environments, which is supported by risks identification that arise from system planning, installation and operation. The end product is providing support to improve the operation, reliability and quality of PV systems (components)and quantifying the risk analysis and its impact on the quality cost and LCoE. To enhance the future outlook of PV plant in harsh climate by improving the long-term viability of modules and BoS.

2. Methodology

A classical semi-quantitative FMEA/FMEEA method is used in technical risk assessments, which identifies the various failure modes affecting each part along, with the cause and consequences on the entire system. In this approach each identified risk is evaluated to Risk Priority Number (R.P.N.) which is a result of the Severity of the failure (S), Detection of the failure (D) and Occurrence of the failure (O), calculated through the following formula[26]:

$$R.P.N. = S * D * O \tag{1}$$

Results indicate the relevance of each failure mode in affecting the PV system. So, a high ranking of R.P.N. indicates large damage, a high frequency of failure occurrence and difficulty in detecting the root cause of the failure [27]. The gap in this approach is subjectively assigned based on engineering judgments and qualitative analysis. To access the cost impact due to a certain failure(s), a quantitative CPN is implemented based on the total loss of energy production due to time down of the system and the cost of repairing the failure[28]. Failure modes, failures effect, R.P.N. ranking moreover, and the no. of tickets from a platform called Photovoltaic Failure Sheet (PVFS) which are listed and tabulated in Table (1). The proposed system adopts by substituting the no. of the tickets (alarms) with the ranking of the occurrence of the failure (O) and take place instead of no. of fail in cost damage calculations. Since the adoption of the new approach gives the support to move from subjective assignments of FMEEA to objective assignments far from the engineering judgments. Moreover, it lead to deep understanding of site environments and their impact on the entire system performance and durability. Also, form the main input data to calculate the O&M costs and figure the project financial model far from assumptions as currently in force.

Table (1), PVFS of 850kW PV Plant.

	Failure Mode	S	O	D	R.P.N.	No., Tickets/unit	R.P.N. (Modify)
Module	Metallization/Corrosion	3	3	3	27	9	81
	Delamination	4	3	2	24	148	1184
	Defect J.B.	5	4	3	60	11	165
	Discolouration in back-sheet	4	3	2	24	>2000	16000
	Cell browning	4	4	2	32	1117	8936
	LID	3	3	4	36	>4000	48000
	PID	3	3	4	36	0	0
	Back-sheet defect	4	3	2	24	18	144
	Hotspot	3	4	3	36	0	0
	Soiling	3	5	2	30	72	432
	Solder bond fatigue	5	3	5	75	8	200
	Snail tracks	4	2	4	16	72	1152
	Broken module	5	4	2	40	6	60
	Bypass diode defect	3	4	4	48	1	12
	Glass damage	3	3	2	18	21	126
Inverter	Over-heating (Fan problem)	5	4	4	80	5	100
	Failure of IC	5	3	4	60	2	16
	Short-circuiting	5	4	4	80	2	40
	Corroded terminals	5	3	4	60	3	144
	Dust on the combiner box	3	3	4	36	12	240
	O/P disconnect	5	3	4	60	12	240
	Inverter	5	4	4	80	12	900
	Inverter/malfunction	5	5	5	125	36	8
Wiring	Sheath damage	4	3	2	24	1	416
	Connector failure	4	3	2	24	52	6
	Under sizing	3	2	2	12	1	375
H.S.	Block the site	5	5	5	125	15	2
Structure	Contact corrosion	2	2	2	8	1	81

3. Risk Identification

A typical PV Park comprises individual systems/subsystems, like modules, conversion power units (inverters, transformers), cables, mechanical structures, ...etc., and serves at the site for a lifespan of 25-30 years. Fielded PV systems can experience different types of failure modes and degradation mechanisms depending on site climate conditions, design and installation. So, its performance and durability are highly connected to those factors and are expected to change over the lifetime of operation. In turn, this will accelerate the ageing mechanisms and trigger failures of different modes [29]. Coincide with failure incidence cost damage that happens either due to the downtime of the system or due to damage in system component(s). Downtime influences the energy yield from the plant, while the cost damage results from the amount of energy lost and the price of the component(s) as repair or replacement. Figure (1), shows an overview of different time values that start with the failure occurance and detection, end up with fixing time and get back to the fit state again, corresponding with related cost values and impacts.

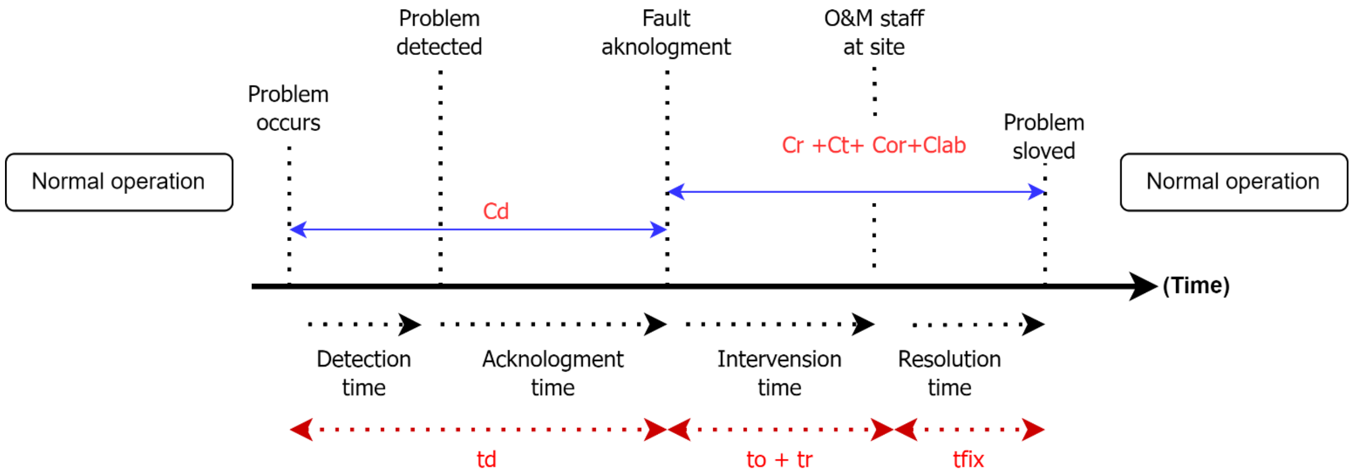

Figure 1, Failure cost and time progress pattern.

The technical risks based on technical gaps of a certain PV project can be classified as before and after the operation where Y_0 and Y_N respectively as per addressed in Table (2), where, the most common technical gaps are addressed in accordance to it implementation phase during the project life-cycle.

Table (2), Gaps in a Certain Plant Phase.

Risk	Phase/field	Identified the technical gap
Y_0 EPC-Phase	Design / Procurements and inspection.	1. Limited EPC specifications to ensure that selected components are suitable to use in specific PV climate conditions. 2. Unqualified design or unauthorized. 3. Poor component(s) testing to inspect deviations after manufacturing. 4. Missing the delivery acceptance test and criteria.
	Planning/lifetime energy yield estimation.	5. The effect of long-term trends in solar resources is not fully encountered. 6. Exceedance probabilities are often calculated for risk assessment assuming a normal distribution for all elements contributing to uncertainty. 7. under-estimating the degradation rate and behaviour over time are assumed in the projected figure. 8. Poor input data to estimate the initial yield for project investment financial model.
	Transportation.	• Failure to adopt standardized transportation and handling protocol.
	Implementation /commissioning and final approval.	1. Weak protocol or equipment for plant acceptance visual inspection. 2. Missing the short-term KPI factor calculations. 3. Missing the final check and guaranteed performance.

Missing or inadequate storage scenario

Y_N O&M-phase	Operation	1. Missing or poor monitoring system not capable to detect/identifying faults. 2. Missing or lacking knowledge of devices to catch hidden defects/failures. 3. Incorrect or missing specifications related to data collecting.
	Maintenance	1. Missing or poor monitoring system for maintenance alarms. 2. Late intervention in case of failure. 3. Missing or poor module cleaning process.

3.1 Energy and performance indices

Energy yield and performance measurements are essential for the evaluation of the energy amount that is generated, utilized. Also, to measure the quality of the system through presenting a combination of the effect of all losses occurring in the system including the modules and BoS. These may also be referred to as KPI which are defines as: Final PV system Yield (Y_f), system Reference Yield (Y_r), Overall system Performance Ratio (PR) and system efficiency (ƺ), and calculated using [30]:

$$Y_f = \frac{\text{Energy generated } (E_a \text{ kWh})}{\text{Rated power } (P_o \text{ kW})} \quad (2)$$

$$Y_r = \frac{\text{In plane irradiation } (H_{in})}{G_o \; (1000 \frac{w}{m^2})} \quad (3)$$

$$PR = \frac{Y_f}{Y_r} \quad (4)$$

$$ƺ = \frac{\text{Energy generated } (E_a \text{ kWh})}{A_{PV} * H_{in}} \quad (5)$$

Where, H_{in} is the incident energy in the array plane (kWh/m^2), while A_{PV} is the total area covered by PV modules (m^2). Stipulated in the international standards those parameters are commonly measured and calculated on long terms periods namely, yearly or longer, but it was found that short-span measurements can help to reveal hidden failures. The decision to invest in an energy project depends not just on whether it is viable, but on the profitability that it is likely to achieve over its designed lifespan. The way to determine that is by assessing a few key financial metrics, including the LCoE, which is calculated below[31]:

$$LCoE = \frac{CAPEX + \sum_{n=1}^{n} \frac{OPEX}{(1+r)^n}}{\sum_{n=1}^{n} \frac{E_a (1-DR)^n}{(1+r)^n}} \quad (6)$$

Where n is the design lifespan of the PV plant which is usually 25-30 years, DR is the degradation rate (%), E_a is the energy generated from the plant (kWh) and r is the discount rate (%).

3.2 Obligations for PV plant in harsh regions

To maintain and keep the performance of the PV plant as per designate and satisfy with the requirements, two things we shall keep in mind. These are the EPC and O&M obligations, the EPC ensure how considerably the PV plant is designed and constructed, whereas the latter maintains safe and functional operation. The reason behind following the above-mentioned concepts is to guarantee PR, guaranteed plant availability and quick response time.

To perform those obligations, the following scenarios shall be considered during the planning phase of the PV plant:

i. The best-case scenario of a PV plant
   To get the ultimate goal of a PV plant installation, the CAPEX and OPEX costs shall be minimized as much as possible and get higher energy production. To get this end by establishing the plant inside or so close to the cities. There, is enough vegetation, close to different power configurations, short transportation time and ensure quick intervention. Simultaneously, site management plays a significant role in terms of spare parts storage scenario, where at least 10% of the main critical components shall be at the site available to minimize the downtown can be happened because of failure.

ii. The worst-case scenario of a PV plant

The implementation of PV systems usually needs vast areas due to the low conversion efficiencies of present PV modules. The high rates of land inside the cities push the invertors and decision-makers to choose uninhabited areas to build the PV plants. There is enough cheap space available to reduce the CAPEX on one hand. On the other hand, low vegetation means a high soiling rate leads to abrasion and safety problems. Civil work in addition to O&M is relatively much expensive due to longer transportation time.

3.3 Cost damage calculations

Major cost damage usually occurs during the implementation and operation phase of the PV plant. Failure(s) causes complete and/or partial downtime or damage to the system. So, failure consequences can be one of the following or all combined, loss of part or all the generated power, malfunction in the system components and can lead to damage the asset powered by the PV plant in some cases only. As a result, failure produce cost damage. Meanwhile, the cost of damage increased by increasing the time of repair. Table (3), summarize all the related parameters used in PV plant cost damage calculations. Mathematically, the cost damage can be calculated following the below listed equations eq.7 – eq.15 [32]-[28]

- Failure due to a specific component causes a system downtime can be calculated through:

$$T_C, \text{down} = (t_d + t_t + t_o + t_{fix}) * PL * M \qquad (7)$$

Where, PL means the performance loss as per mentioned in table (4), which are highly related with the severity of the failure. While, M means a multiplier always equal to 1.

- In case of several components are affected by the same failure (n fail) through 1 year of operation, in this case, the total downtime can be calculated through the:

$$T_{CN}, \text{down} = T_C, \text{down} * nC\,\text{fail}, 1\text{year} \qquad (8)$$

- But, the downtime of the total same kind components which are intact and affected by the failure can be calculated through:

$$T_{CT}, \text{down} = T_{CN}, \text{down}/nCT \qquad (9)$$

- The occurrence over time indicated as (%) equal to:

$$O = T_{CT}, \text{down}/t_{ref.} \qquad (10)$$

- The loss of production that happened due to the failure can be calculated through the:

$$L = O * E_a \qquad (11)$$

- The cost damage result via the specific failure can be calculated through the:

$$C_{down} = L * (FIT + PPa + RCE) \qquad (12)$$

- Finally, the total costs of fixing the failure and getting back the normal operation status in addition to, the CPN calculation:

$$C_{fix} = \{(C_d + C_r + C_t + C_c) * nfail\} + (C_{lab} * t_{fix} * nfail) \quad (13)$$

$$CPN = C_{down} + C_{fix} \quad (14)$$

Table (3), Definitions of Parameters in CPN Calculations[28].

L	Production loss (kWh)	t_t	Transport time (h).	t_{ref}	No. sunny hours per year.
FIT	Feed in Tariff ($/kWh)	t_o	Time of component ordering (h).	C_{fix}	Cost of fixing the failure ($).
PPA	Power purchasing agreements ($/kWh)	t_{fix}	Total fixing time (h).	C_{down}	Cost due to downtime ($/kWp).
M	= 1.	$T_{CN, down}$	Total downtime for the affected components only (h).	C_d	Failure detection cost ($/component/kWp).
PL	performance loss (%).	$n_{C fail, 1 year}$	Number of failed components over 1 year.	C_r	Failure cost repair cost ($/component/kWp)
RCE	Retail cost of electricity ($/kWh)	$T_{CT, down}$	total downtime for all components (h).	C_t	Component transport cost ($/component/kWp).
$T_{C,down}$	failure time of a specific component (h).	n_{CT}	A number of the total components.	C_C	Cost of component ($).
t_d	detection time (h).	O	Occurrence overtime.	C_{lab}	Cost of the laboratory ($/h/kWp).
tref	No., of sunny hours per year.	r	Solar panel efficiency (%).	A_{PV}	Total solar panels area (m^2).
H	Annual average solar radiation.	Ea	Annual production of the plant.	CPN	Cost priority number.

Table (4), Performance Loss due to Failure[33].

Failure mode	PL (%)	Max., PL (%)
Metallization/corrosion	1	40
Delamination	1	30
Defect in J.B.	40	40
Discolouration in back-sheet	1	10
Cell browning	1	10
PID	10	70
Back-sheet defect	1	20
Hotspot	2	20
Soiling	30	70
Solder bond fatigue	1	30
Module's broken	100	100
Bypass diode defect	40	40
Glass damage	10	50
Shading	10	40
Snail track	1	10
Cell cracks	1	20
Damage by snow	100	100
Complete the module's damage	100	100

4. Results and Discussions

PV system's basic principles of operation are highly dependent on the site environments where the system is to be deployed and operated. In the same context, the PV module's energy yield and performance are quite different from moderate regions in comparison with harsh regions. Indeed, the latter is worse. Also, the inverters are highly responsive to microclimate.

This study results are to be discussed, weighed, and compared to those of PV systems installed in similar environments [30,32,32,33]. Anticipating low power efficiency when the site operating temperature would be higher than 36ºc[34]. About 84%-92% of light transmittance reduction can be occurred due to dust accumulation over seven days, leading to 30% of output reduction[35]. Due to the combination of high operating temperatures, humid site and high-rate frequency of soiling.

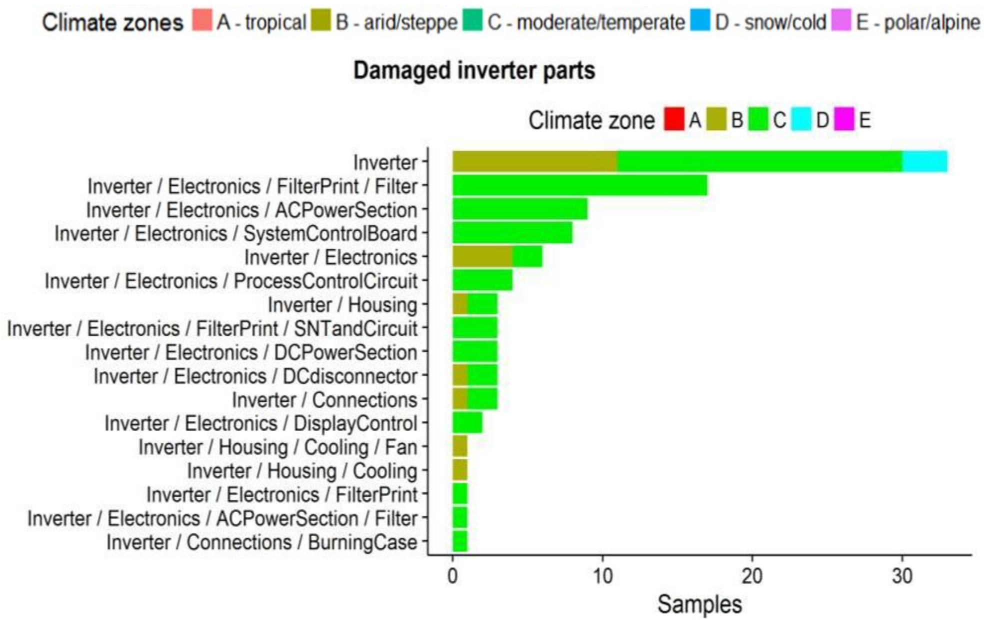

Figure 2, Inverter Failure Modes in Different Climates Regions[6].

The major maintenance cost went to the inverter, soiling maintenance and cleaning respectively with the power losses reached 76% of the total energy yield. Keep in mind, high degradation occurs due to LID and cannot be considered a failure. The alarm and/or failure rate of PV inverters usually are triggered by two main reasons, namely the design or manufacturer quality under the heading of internal reasons. Meanwhile, the quality of installations and maintenance concepts are under the heading of external reasons. An extensive study based on FMEA was carried on 488 systems, 1243 failure entries from 40 countries focuses on the inverter's failure are shown in Figure (2).

Here, a detailed overview of the inverter's failure modes which are arise from different climate zones are listed and addressed. Showed that arid/steppe climate zone compose the main challenge climate zone to the PV inverter.

This study analysis is mainly based on a modified FMEEA method. Where the most common failure modes are listed and objectively ranked to its R.P.N. Assuming that reliable storage scenario of PV spare parts is available on site. In fact, we cannot touch the data related to (t_O). However, the downtime will be longer than presented. In reality, all the current PV plants in Iraq are with base scenarios. On-Grid, flat roof, 850kWp, governmental PV plant, installed over 6000m² in the same building of the Ministry of Electricity in Baghdad. The plant comprises 4812 no., PV modules 205Wp and 36 no., 25kW SMA PV inverters. The plant is in operation since 2020 with basic scenario form. Theoretically, the plant generates 1315730 kWh/year with PR 0.76%. Table (1), shows the main PVFS including the failure modes in addition to the number of tickets (alarms). The classic R.P.N and modified R.P.N are calculated as well. Figure (3), depicts the ranking of classic R.P.N with the modified R.P.N, which is leading to a deep understanding of the site circumstances, impacts and reprioritization of the failure modes concerning its severity and frequency.

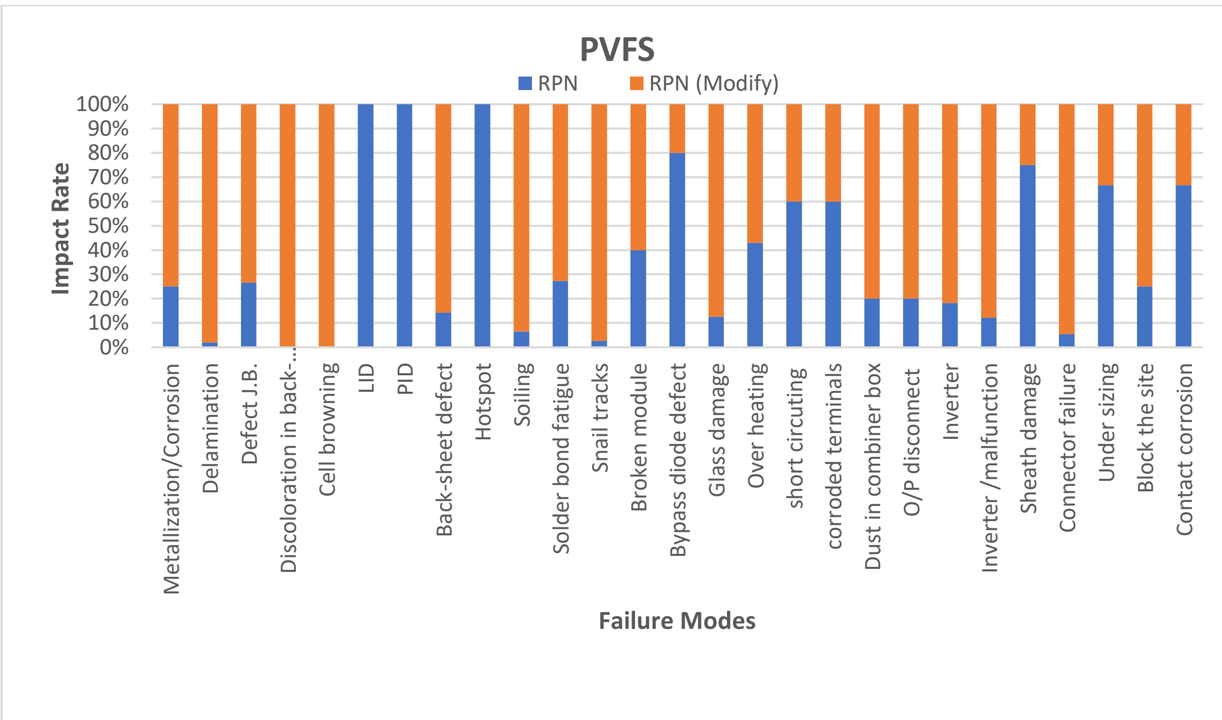

Figure 3, PVFS of 850kW PV Plant.

In Figure (3), the disparity between the classic R.P.N and the modified comes from the objectively assignments of the failure. Which is based on actual site environments and their impacts on the entire system performance and functionality.

After three years of operation in a harsh climate, the measured and calculated data revealed a degradation rate with very high percentages above the standardized manufacturer values with poor system performance. The calculated degradation rate was 3.325%/year leading to a 22-37% power drop in the PV modules. In turn, decline in the quality of the modules if its run below 80% of the manufactured power value [36]

Due to internal and external impairments, the energy yield decreased sharply after 12 months of operation. The measured energy yield was 859.0683MWh, 459.61MWh and 32.3378MWh throughout 2020, 2021 and 2022 respectively. Combined with high augmentation in O&M costs. knowing that, labour and land costs are excluded from this analysis. The combined loss's effect of all the PV system components is represented by the calculated PR, where 63%, 34% and 3% in 2020, 2021 and 2022 respectively. A survey study carried out in moderate regions showed the premise that 25 years is the life span of the PV plant, inverter's life cycle is 10-11 years[29]. Thus, the project's financial model shall entail a double number of the designed inverters to cover the whole project lifespan. But this study revealed that the inverter life-cycle is 3-5 years tops. For such kind of paradox this study doesn't comply with the common notion about O&M costs are about 20%-25% of the CAPEX [37]. The present study showed that the number of the maintained inverters were 14, 29 and 35 in 2020, 2021 and 2022 respectively. The same concept applies for the other system components or BoS, like modules, cables, structure, etc., for the inspected plant. Indeed, O&M costs in harsh climates are much higher than the costs in moderate regions for the same plant size. Consequently, the project's financial model will be affected and the feasibility studies need a deep review. For instance, with a BWh zone and very low precipitation the inspected plant needs about 16000m³ of water needed every 14 days to clean the modules, with cost damage calculated for maintenance as about 1808.5 ($/m²). Figure (4), shows the annual energy production of the plant in regard with the O&M costs.

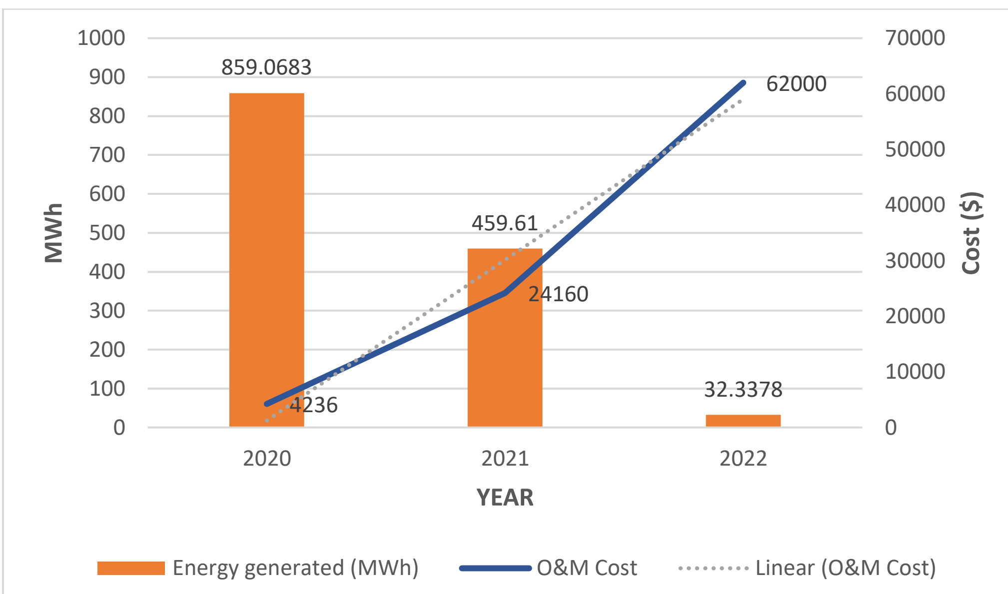

Figure 4, Annual O&M Costs.

In any shape of form with this high degradation rate recorded after only three years of operation. The PV modules will not cover 25 years as per specified in the warranty period. From technical point of view, the understanding of degradation mechanisms is vital imperative due to they may ultimately lead to system's failures. Thus, because of the climate stress factors, weak O&M strategies and high number of failures, the high O&M costs and low plant energy productivity sketched in Figure (4) are explained. Table (5), presents all the time parameters required to calculate the total downtime of the plant, which later on, used in CPN calculations.

Table (5), Time Parameters used in CPN Calculations.

	Failure Mode	t_d(h)	t_t(h)	t_o(h)	t_{fix}(h)	PL (%)	M
Module	Metallization/Corrosion	8760	--	--	1	40	1
	Delamination	8760	10	--	1	30	1
	Defect J.B.	720	--	--	1	40	1
	Discolouration in back-sheet	8760	--	--	--	10	1
	Cell browning	8760	--	--	--	10	1
	PID	8760	10	--	2	70	1
	Back-sheet defect	8760	10	--	2	20	1
	Hotspot	8760	--	--	8	20	1
	Soiling	360	10	--	5	70	1
	Solder bond fatigue	17520	10	--	5	50	1
	Snail tracks	8760	--	--	2	10	1
	Broken module	720	--	--	2	100	1
	Bypass diode defect	720	--	--	5	40	1
	Glass damage	720	--	--	5	50	1
Inverter	Over-heating (Fan problem)	48	--	--	5	100	1
	Failure of IC	48	--	--	5	100	1
	Short-circuiting	48	--	--	5	100	1
	Corroded terminals	48	--	--	5	100	1
	Dust on the combiner box	48	--	--	5	100	1
	O/P disconnect	48	--	--	5	100	1
	Inverter	48	--	--	5	100	1
	Inverter/malfunction	48	--	--	5	100	1
Wiring	Sheath damage	17520	--	--	5	50	1
	Connector failure	8760	--	--	2	50	1
	Under sizing	17520	--	--	4	10	1
H.S.	Block the site	720	--	--	48	100	1
Structure	Contact corrosion	17520	--	--	24	10	1

Some failures can be detected by visual inspection like the module being broken, soiling, etc., while, the major problem occurred with hidden failure like solder bond fatigue, PID, etc., which led to unseen PV system degradation and weak system performance and longer downtime. Spare parts and maintenance team in site availability play a significant role to minimize downtime through minimising the time of order (t_O) and transport time (t_t), also ensuring quick intervention in case of failure. The same is applicable in the case of cost damage calculations, hidden failures need a higher cost of repair due to an additional cost of the lab. Table (6), shows the cost parameters needed in cost damage calculations.

Table (6), Cost Parameters used in CPN Calculations.

	Failure Mode	$Cd+C_{Lab.}$	Cr	Ct	Cc	CPN
		($/component)				
Module	Metallization/Corrosion	100	10	10	150	477
	Delamination	100	10	10	150	425.3
	Defect J.B.	10	5	10	50	270
	Discolouration in back-sheet	25	10	10	150	247
	Cell browning	15	10	10	150	237
	LID	225+100	10	10	150	--
	PID	175+100	10	10	150	807
	Back-sheet defect	15	10	--	150	234.5
	Hotspot	100+100	10	10	150	473.5
	Soiling	10	0.55	150	--	3735.5
	Solder bond fatigue	100+125	10	10	150	912.318
	Snail tracks	100	10	10	150	321.9
	Broken module	5	10	--	150	207.6
	Bypass diode defect	50+20	10	5	15	117.15
	Glass damage	5	10	--	150	186.4
Inverter	Over-heating (Fan problem)	50+25	75	--	3000	10168
	Failure of IC	50+25	75	--	3000	10168
	Short-circuiting	50+25	75	--	3000	10168
	Corroded terminals	50+25	75	--	3000	10168
	Dust on the combiner box	50+25	75	--	3000	10168
	O/P disconnect	50+25	75	--	3000	10168
	Inverter	50+25	75	--	3000	10168
	Inverter/malfunction	50+100	75	--	3000	102.3
Wiring	Sheath damage	75	25	--	4	97.8
	Connector failure	5	10	--	7.5	114.6
	Under sizing	4	--	--	6	816.2
H.S.	Block the site	--	--	--	--	66.41
Structure	Contact corrosion	20	25	25	75	477

Major cost damage occurred in the case of the inverters and transformers since it has always a high severity impact causing complete shutdown to the system, high sensitivity with the climate conditions and high component cost (C_C). Figure (5), depicts the CPN for each failure mode listed in the PVFS. Due to the climate stress factors the most common failure modes of the PV system found:

Solder-bond fatigue, discoloration of the encapsulant, delamination in PV modules. While, over heating (fan problems) and general malfunction in the inverters.

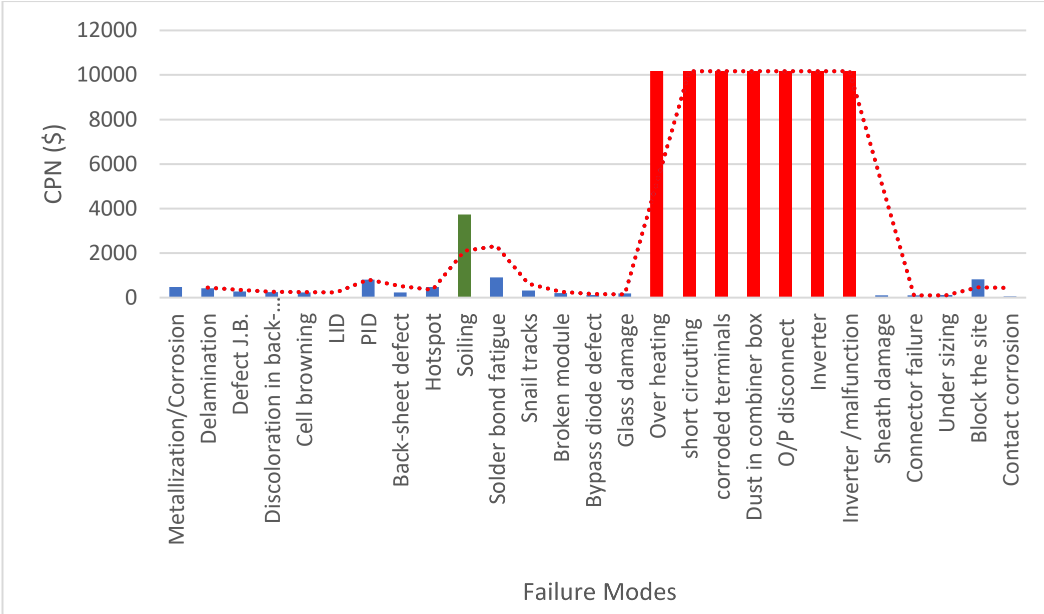

Figure (5), CPN of the PV Plant.

Consequently, The PV modules installed in Iraq are degrading faster than the standard warranty rate mean of degradation (0.8%/year). It was found that about 80% of the installed modules will be fail before 10 years of operation in site, which is hinder the future of PV implementations in Iraq.

5. Soiling Impacts Alleviation

Soiling is a significant and frequent climate challenge for solar PV in harsh climates like in Iraq. In moderate regions, the soiling influence recorded in 2018 was about at least 3%-5% of the annual energy yield. While, the estimated cost impact due to soiling losses is about 3-7 billion € in 2023 for moderate regions[38]. The soiling effect boost the power loss to initiate system degradation and failures. Which is primary influence the EVA, back-sheet and front glass, etc. Resulting in defects in EVA and back-sheet, in addition abrasion in front glass which reduce the light transmittance process. The study revealed that the power losses reached 84% through four months without cleaning. Figure (6), shows the influence of soiling in respect of solar irradiance and cleaning process. So, soiling impact mitigation is essential for increase the PV plant profitability and minimize the failure's occurrence in harsh climates.

Despite the inevitability of ASC as it increasing the time between the cleaning cycles, the soiling alleviation modes can be divided mainly into preventive and corrective modes: -

a. Preventive alleviation modes: all can be in the framework of project and site management. Begins with planning, design and implantation of the PV plant. Concerns about soiling shall be considered in the planning phase, moreover deep understanding of site metrological data is required in regards to wind direction, precipitation, etc.,
   In the design phase, appropriate materials and components like, frameless modules, ASC, half-cut with bypass diode modules, etc. shall be implemented.

In the construction phase, lining the fence of the PV plant with vegetation will help in minimizing road soiling. Meanwhile, due to gravity, the tilt angle plays a sufficient role in soiling deposition. Study presented that the annual energy losses can be decreased from 34% to 5% by shifting the tilt angle from 0^{o}c to 45^{o}c [39] .

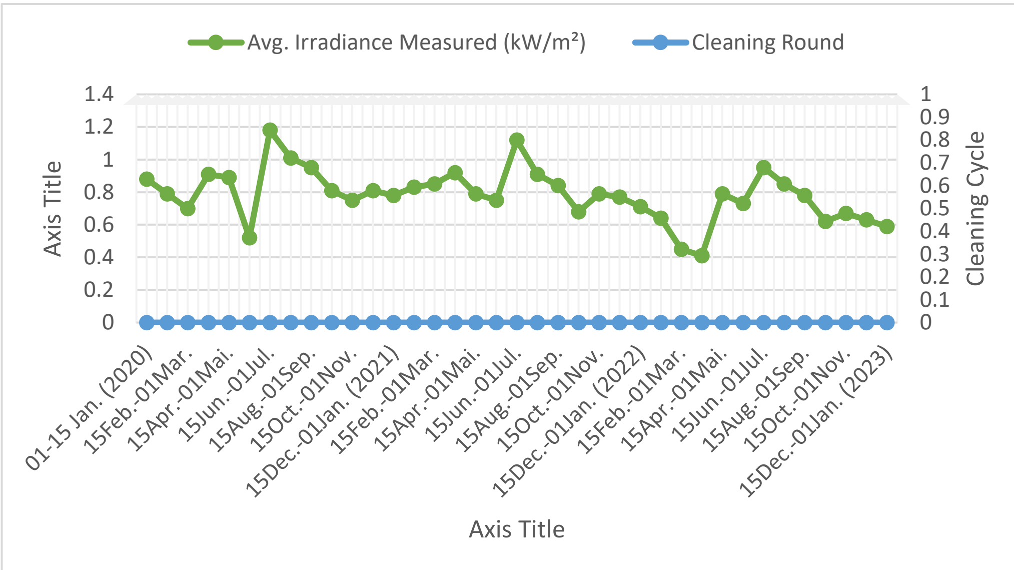

Figure (6), Soiling impact on 850kWp PV Plant in Baghdad 2020-2023.

b. Corrective alleviation modes: all within the O&M framework. Hot, arid and dry site environments, will influence the PV modules by caking and cementation creation. So, active cleaning is highly required to get maximum plant profitability. The most recommended cleaning techniques, which are effective in BWh zones are vibration of the surface, robotic-cleaning, Electrodynamic system (EDS) and sprinkler.

6. Conclusion

With all the global widespread availability of PV plants, their durability and reliability in harsh climates like Iraq are still unclear and pose a huge concern for investors and/or decision-makers.

The high operating temperatures, wide temperature difference intraday, high and frequent soiling rate and high UV levels can accelerate the degradation of polymers for PV cell packaging such as encapsulates, back-sheets and internal cell connections. Which is poses particularly a clear climate challenge to every single component of solar such as inverters, mounting structures., etc and absolutely for PV modules. Hence, a significant energy loss occurrence and faster failure modes initiation. So, the reliability and durability of solar PV form a major challenge for commercial success in Iraq or other similar climates. Nevertheless, the enormous promising Iraq´s location may hold for the potential implementation of PV technology, where unutilized 100km² has the potential to produce an energy equivalent to 30 million tons of oil equivalent (MOTE) per year using the PV modules. The majority of PV installations in Iraq are deployed extensively in the western and southern regions, assuming PV modules efficiency equal to 16%, each 10 km² has the potential to produce estimated energy of about 3.4 billion kWh/year, equivalent to a total capacity of 5.9 GW. Consequently, Iraq is ahead to implement 10 GW by end of 2030. So far, adopting O&M strategies to maximize plant profitability is not a high priority in Iraq and is pointed out as an extra added value. In turn, the PV market in Iraq is considered an emergent market in the field of renewable energies. Furthermore, O&M often follows standard approaches established in need climates with few annual cleanings. Reliability enhancements of solar PV in harsh climates need to:

- Establish a specific criteria of PV plants to be installed in harsh sites.
- Address the issues of manufacturing and installation like lining the fence with vegetation, landscape orientation, spare parts availability, surveillance, tilt angle, etc.
- Define the PV modules in terms of ACS, frameless, half-cut and choosing the right encapsulation materials, etc.
- Establish extended qualification tests based on IEC 61215. Figure the realistic input data to create the financial model far from assumptions or data specified for moderate sites. A new roadmap for installation and manufacturing of inverters.

The data conducted from this study showed that the frequent soiling and high ambient temperature pose the main climate challenge of PV exploitation. Due that, the inverter lifetime is 5 years tops and about 43404 ($. year) is the cleaning cost impact. Furthermore, the study demonstrates that the solider bond fatigue, discoloration, delamination and encapsulant yellowing forms the main failure modes in harsh climates like in Iraq. The typical remote nature of the PV plant's location and availability of materials (water, spare parts), entails significant transportation and logistics costs combined with longer downtime resulting in cost damage much higher than presented in this study. The O&M costs of a PV plant in Iraq are estimated between 45%-60% of the CAPEX.

7. Acknowledgement

The authors are sincerely appreciating the Ministry of Electricity-IRAQ, especially the centre of renewable energy for realistic discussions and for rendering the necessary assistance and support during testing to execute the investigations of the PV plant.

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