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► **To cite this version:**

Mena Maurice Farag, Abdul-Kadir Hamid, Tareq Salameh, Essam M Abo- Zahhad, Maryam Nooman Almallahi, et al.. ENVIRONMENTAL, ECONOMIC, AND DEGRADATION ASSESSMENT FOR A 2.88 KW GRID-CONNECTED PV SYSTEM UNDER SHARJAH WEATHER CONDITIONS. 50th International Conference on Computers & Industrial Engineering (CIE50), Computers and Industrial Engineering; American University of Sharjah, Oct 2023, Sharjah, United Arab Emirates. pp.1722-1731. hal-04489315

**HAL Id: hal-04489315**

**<https://hal.science/hal-04489315>**

Submitted on 7 Mar 2024

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## ENVIRONMENTAL, ECONOMIC, AND DEGRADATION ASSESSMENT FOR A 2.88 KW GRID-CONNECTED PV SYSTEM UNDER SHARJAH WEATHER CONDITIONS

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### ABSTRACT

Photovoltaic (PV) systems have been at the forefront of renewable energy technologies due to their ease of deployment and zero fuel cost, leading to widespread in the United Arab Emirates (UAE) and other regions around the world. Although PV systems have proven effective, the durability of such systems needs to be investigated to assess their rate of degradation over their period of installation, as well as their economic payback time that indicates their energy efficiency. This work conducts an environmental, degradation, and economic assessment on a 2.88 kW on-grid PV system under the weather conditions of Sharjah, UAE. A complete experimental state-of-the-art is established at the University of Sharjah main campus, where the annual measured data from August 2021 to July 2022 is extracted and analyzed. The annual mean degradation rate computed was 2.4 % of the maximum power after one year and about 0.568 % on average over the system lifespan, which is consistent with PVsyst simulation. Furthermore, the economic assessment was conducted and evaluated based on the Energy Payback Time (EPBT) metric. The PV has the shortest EPBT, about 4.6 years. In addition, the on-grid PV system was evaluated for its contribution to carbon emissions reduction, where the system exhibits a gradual decline in annual CO<sub>2</sub> emissions, starting from 4080.40 kg/year in the first year and reaching 163 kg/year in the 25<sup>th</sup> year.

Keywords: Solar PV Systems, Grid-Connected Systems, Annual Degradation, Economical Assessment, Harsh Weather Conditions

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## 1 INTRODUCTION:

Electrical energy has been progressively expanding globally due to its excessive demand, leading to the substantial depletion of conventional energy resources such as coal, oil, and natural gas [1]-[3]. These energy resources are classified as non-renewable fossil fuels that have a leading impact on climate change due to the exponential increase in carbon emission, contributing to the leading phenomenon of global warming [4], [5]. In this notion, the global initiative to shift from conventional energy resources to clean energy sources known as renewable energy sources (RES) has been pursued to tackle the negative contributions associated with conventional resources and integrate clean energy resources within large scale electrical networks [6]. In recent decades, particular interest has been focused on solar energy as a popular renewable energy source due to its competitive merits amongst various other RES [7], [8].

Solar Energy is typically harvested through Photovoltaic (PV) systems to convert it to clean electricity, providing a sustainable solution for the upcoming years [9]. Moreover, PV energy systems have been rapidly deployed recently due to their minimum dependence on fuels and vast availability of solar energy, serving the escalating demand for electrical energy worldwide [10]. PV system installations have reached up to 627 GW worldwide in 2021, as reported in [11], with an anticipated expansion of 125 GW in the following 5 years. In particular, the United Arab Emirates (UAE) has been following the footsteps of developing initiatives for green energy generation, particularly using solar energy due to their major exposure of sunlight [12]. Furthermore, the UAE has set initiatives to tackle the carbon footprint and to diversify the energy share by relying on sustainable energy generation. This has been particularly sought for with on-grid PV system integration to encourage users to supply and support the electrical grid with clean energy generation [13], [14].

Although solar energy has gained major attention over the past few years, there are several challenges related to the durability of grid-connected PV systems. A major challenge is the degradation of PV modules, which contributes to the overall lifetime of PV modules and systems [15]. PV modules degrade over time due to exposure to sunlight and temperature changes due to their semiconductor behavior, particularly under harsh climatic conditions such as the UAE [16], [17]. Moreover, environmental factors contribute to the lifetime of PV modules such as Dust, dirt, bird droppings, and heavy rains that lead to corrosion of metallic parts present in PV modules [18]. Furthermore, PV systems may experience electrical and mechanical failures, such as short circuits, broken wires, and loose connections that reduce their productivity and efficiency. Finally, electrical grid compatibility is essential for on-grid systems to maintain their interconnection and to avoid disconnection of the DC-AC power inverter from the electrical grid [19]. In this notion, several researchers have sought to study the degradation of PV modules and the impact of aging on installed PV systems. Aboagye et al. [20] investigated the degradation rate and predicted lifetime for 16 installed PV systems to determine their long term behavior under the climatic conditions of Ghana. The study quantified different degradation rates for different PV module technologies such as monocrystalline, polycrystalline, and amorphous silicon reporting a mean power degradation rate of 1.37%/year, 1.44%/year, and 1.67%/year, respectively. The investigation of polycrystalline silicon PV module technology was also investigated for different manufactures under the same climatic conditions as reported in [21]. The study identified that a mean degradation rate between the modules varied from 0.79 and 1.67%/year, dependent on the manufacturer. Additionally, the investigation of rooftop PV installations was analyzed and the modified methodology for degradation rate computation was proposed by [22]. The study assessed two rooftop PV installations in the climatic conditions of Germany. The investigation reported a yearly degradation rate of 0.11%/year and 0.2%/year, for both systems

respectively. Moreover, the thermal impact on the performance of PV systems was assessed and reported in [23]. The study reported that the performance ratio is comparatively higher during Spring and Summer seasons as compared to Autumn and Winter. Furthermore, an investigation on the PV inverter lifetime and reliability was assessed based on PV array tilt [24]. The study discussed the lifetime of the PV inverter under variation of tilt angles under the profile of Algeria. As a result, the study revealed that the PV module orientation severely impacts the PV inverter performance and lifetime.

In this notion, this study investigates a rooftop grid-connected PV system with a rating of 2.88 kW under the harsh weather conditions of Sharjah, UAE. The study investigates and assesses degradation rate, environmental impact, and economic payback for a given solar PV grid-connected system across its installation period. The experimental data is extracted across a calendar year, from August 2021 to July 2022, to present variability in environmental parameters and power generation characteristics. In addition, the grid-connection proposal targets a sustainable approach in optimizing clean energy integration with local utility grid and its expansion on the long-term and minimizing the carbon emissions across system lifetime.

## 2 EXPERIMENTAL STATE-OF-THE-ART AND MEASUREMENTS

The developed 2.88 kW grid-connected photovoltaic system is installed on the rooftop of central laboratories building (Latitude 25.28° N and Longitude 55.48° E) at the main campus of the University of Sharjah, UAE [25]. The on-grid PV system is illustrated in Figure 1, presenting its actual location and configuration. The experimental data is recorded at regular intervals daily across the whole year. In this study, the environmental and economical analysis is conducted from August 2021 to July 2022, providing sufficient variability in environmental parameters that impact the PV module performance and degradation [26]. The installed on-grid PV system comprises nine PV modules connected in series with a power rating of 320 W each. The on-grid PV system is equipped with azimuth single-axis solar tracking to harness maximum solar energy throughout the day [27]. The PV modules technical specifications are demonstrated in Table 1.

**Table 1: PV Module technical specifications and electrical characteristics**

Electrical characteristics at STC	
Open circuit voltage ( $V_{oc(STC)}$ )	45.7 V
Short circuit current ( $I_{sc(STC)}$ )	9.04 A
Rated Power ( $P_{max}$ )	320 W
Fill Factor ( $FF$ )	0.775 %
Voltage at nominal power ( $V_{mp}$ )	37.1 V
Current at nominal power ( $I_{mp}$ )	8.63 A
Module efficiency (%)	16.49 %
Maximum system voltage ( $V_{DC}$ )	1000 V
Electrical characteristics at NOCT	
Open circuit voltage ( $V_{oc(NOCT)}$ )	42.1 V
Short circuit current ( $I_{sc(NOCT)}$ )	7.32 A
Voltage at nominal power ( $V_{mp}$ )	33.8 V
Current at nominal power ( $I_{mp}$ )	6.98 A
Temperature characteristics	
Nominal operating cell temperature ( $NOCT$ )	45 °C ± 2 °C
Temperature coefficients of ( $P_{max}$ )	- 0.41%/ °C
Temperature coefficients of ( $V_{oc}$ )	- 0.31%/ °C
Temperature coefficients of ( $I_{sc}$ )	0.05%/ °C

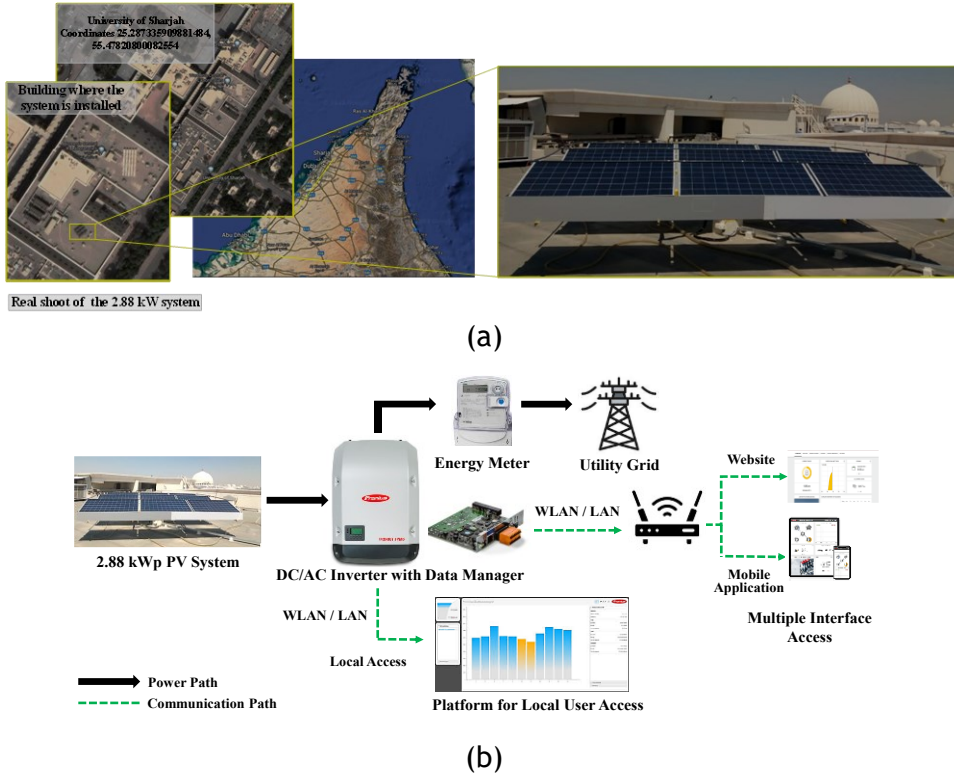


Figure 1: Demonstration of (a) Established on-grid PV system (b) Power and Communication Loop

As demonstrated in Figure 1(b), the system is equipped with a DC/AC power converter of 3.7kWac rating to supply AC power to the local electrical grid. The inverter is essentially in compliance with the local grid requirements to ensure safety during AC power generation and injection. Moreover, the DC/AC power converter is equipped with an internal DC-DC boost converter with Maximum power point tracking (MPPT) to precisely locate the global optimum MPP at rapid changes in environmental conditions [28].

Moreover, the on-grid PV system is configured based on a real-time monitoring unit to simultaneously store electrical and environmental parameter measurements to maintain the system's performance. In this experimental investigation, multiple sensors are deployed to record data in real-time, such as Solar insolation, Module and Ambient Temperature, Wind Speed, and DC/AC electrical characteristics [29]. The data is stored for over the year range to successfully assess the system in terms of its degradation, economic payback, and environmental impact. The technical specifications of the on-grid rooftop PV system and the deployed measurement sensors are demonstrated in Table 2.

### 3 THEORETICAL ANALYSIS

Field-acquired current-voltage (I-V) data were adjusted to standard test conditions (STC) using the specific conversion of the following equations [30].

$$V_{oc(mean)} = V_{oc(STC)} - n_s \times 2.3 \times 10^{-3} \times (T_{Panel} - 25^\circ C) + \frac{KT_{Panel}}{q} \ln C \quad (1)$$

$V_{oc(meas)}$  and  $V_{oc(STC)}$  denote the open-circuit voltage under the observed field conditions and standard test conditions (STC), respectively.

**Table 2: PV Module technical specifications and electrical characteristics**

State-of-the-Art		
Device	Purpose	Specifications
PV System	Designated for DC Power Generation Based on Solar Insolation	9 PV modules connected in series with a rating of 320 W each
DC-AC Power Converter	Designated for DC to AC power conversion and regulating grid requirements	Nominal Rated power of 3.7 kWac
Solar Cabinet	Point of common coupling between PV system and grid	Three-phase power distribution
Data-Storage Interface	Designated Data Manager for measurement storage	802.11 IEEE wireless protocol for data transmission
Measurement Sensors		
Solar Irradiance Sensor	Measurement of Solar Insolation in W/m <sup>2</sup>	Monocrystalline Silicon sensor, Tolerance of ± 5%.
Anemometer	Measurement of Wind speed (m/s)	Tolerance of 5% from 5 m/s Threshold of 2.5 m/s windspeed, 1 m/s resolution
Ambient Temperature Sensor	Measurement of Ambient Temperature	PT-1000 Technology, Accuracy: ± 0.8 °C Measurement range: -50 °C to +230 °C
PV module Temperature Sensor	Measurement of PV module operating Temperature	PT-1000 Technology, Accuracy: ± 0.8 °C Measurement range: -20 °C to +150 °C
DC/AC electrical sensors	Measurement of DC and AC electrical energy	Current signal of 0 mA to 20 mA, 4 mA to 20 mA

In the Equation, the variables are defined as follows:

- $C = I_T \times 10^{-3}$  in kW.
- $T_{Panel}$ : represents the solar panel temperature in degrees Celsius.
- $K$  is the Boltzmann Constant =  $1.38 \times 10^{-23}$  J/K.
- $n_s$  is the number of cells connected in series.
- $q$  is the charge of an electron, quantified as  $1.602 \times 10^{-19}$  C.
- $I_T$  indicates the irradiance, measured W/m<sup>2</sup>.

The short-circuit current at STC,  $I_{sc}(STC)$ , is calculated from the following Equation:

$$I_{sc(mean)} = I_{sc(STC)} \times (1 + h_f \times (T_{Panel} - 25^\circ C) \times C) \quad (2)$$

Where  $h_f = 6.4 \times 10^{-4} \text{ k}^{-1}$  and maximum power under STC ( $P_{(STC)}$ ) calculated from  $I_{sc(STC)}$ ,  $V_{oc(STC)}$ , and the fill factor ( $FF$ ) as per the following Equation:

$$P_{STC} = FF \times I_{sc(STC)} \times V_{oc(STC)} \quad (3)$$

The annual mean degradation rate for the module's peak power output,  $DR_{Max}$ , is calculated using Equation (4).

$$DR_{Max} = \left( \frac{P_{Max,ref} - P_{STC}}{y \times P_{Max,ref}} \right) \times 100\% \quad (4)$$

## 4 RESULTS AND DISCUSSION

### 4.1 Weather and System Data from Measurement facilities

The weather measured data from the installed weather station at the University of Sharjah is demonstrated in Figures 2 (a)-(c). Environmental Parameters such as wind speed, solar irradiance, and ambient temperature recorded in 5 min intervals daily across the whole calendar year. Variation in parameters such as wind speed, solar irradiance, and ambient temperature providing accuracy in the computation of the degradation factor expressed in

equation (4). Moreover, the system data is recorded in terms of the PV module operating temperature and Apparent power injected to the utility electrical network is demonstrated in Figure 2 (d) and (e), respectively. It can be depicted that the PV module operating temperature is abrupt during harsh summer conditions, hence contributing to the reduction in electrical energy injected into the utility grid, hence increasing the degradation rate at such harsh weather conditions.

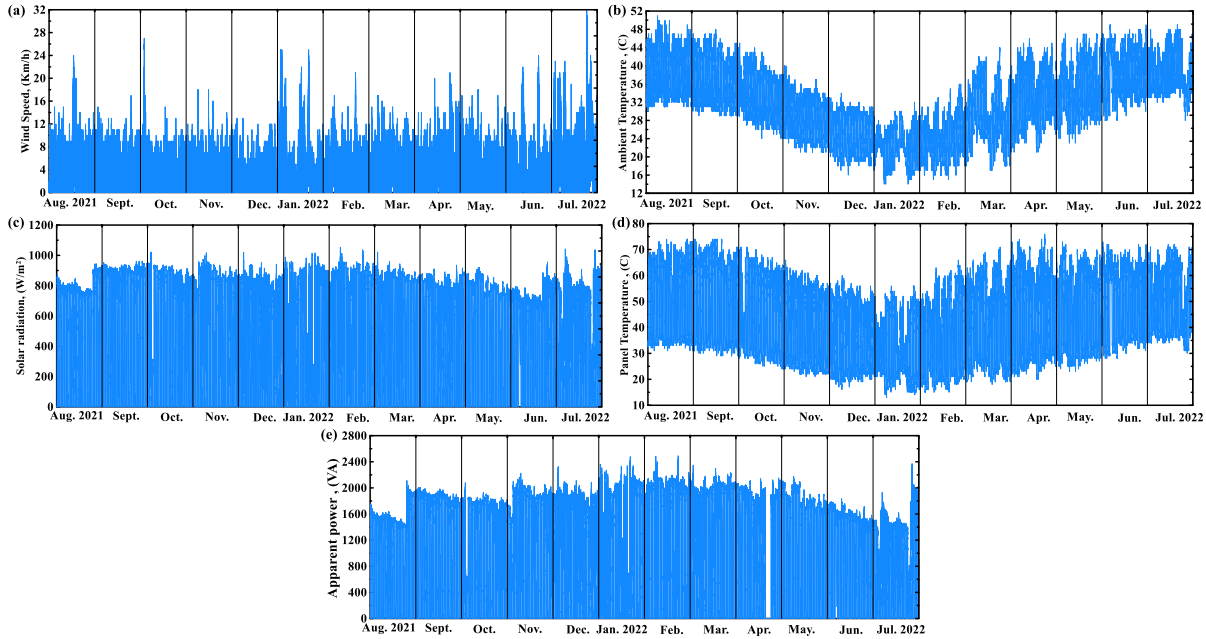


Figure 2: Weather and System Data for on-grid PV system (a) wind speed (b) ambient temperature (c) solar irradiance (d) module temperature (e) Apparent Power

#### 4.2 Degradation rate analysis

Figure 3. shows the estimated trends in the annual degradation rate of the module's peak power output. As shown in the figure, the installation degradation rate was about 2.4 % of the maximum power after one year and about 0.568 % on average. The value is consistent with that estimated by the prior literature work and as comparable to PVsyst simulation [31].

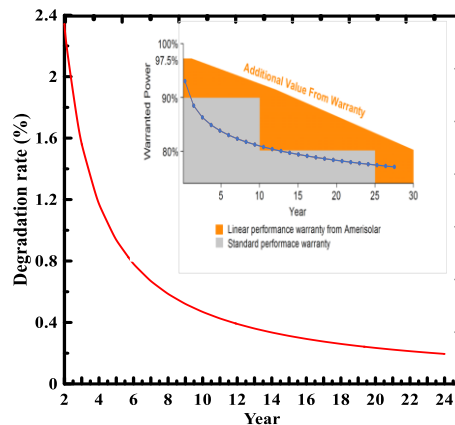


Figure 3: The annual degradation rate of PV module's maximum power

### 4.3 Energy Payback Time and Environmental Impact

The energy requirement for PV manufacturing is used to evaluate the energy payback time (EPBT) and CO<sub>2</sub> emissions. This evaluation considers the embodied energy of various components, including the system [32], [33]. Notably, the net energy yield of the photovoltaic system has not yet substantially surpassed the cumulative energy expenditures incurred throughout its lifecycle, encompassing stages from manufacturing and installation to operation and ultimate decommissioning.

#### 4.3.1. Energy payback time (EPBT)

The EPBT is quantified as the quotient of the system's embodied energy to its annual aggregate energy production, as delineated in the subsequent equations [34]. This value of EPBT is an indicative metric for the period required for the system's yearly energy output to equalize with its annual energy input. The cumulative energy yield for each system configuration was subsequently assessed to derive the energy payback metrics, as tabulated in the ensuing Table 3.

**Table 3: PV Module technical specifications and electrical characteristics**

The system life period is 25 years.
Measured overall energy output = 322.97 kWh/m <sup>2</sup> /year
Total embedded energy of the module production = 2588 kWh/m <sup>2</sup> [32], [34]

The EPBT represents the duration needed for the system's annual energy output to offset its initial energy expenditure. Conversely, the energy yield factor is the quotient of the system's lifetime energy generation to its total embodied energy. This metric indicates energy efficiency, shedding light on the net energy gain relative to the initial energy invested over the system's operational lifetime. A superior energy yield factor denotes a more efficient system, which generates more energy relative to its initial input.

$$EPBT = \frac{\text{Embodied energy requirements (kWh/m}^2\text{)}}{\text{Annual total energy output (kWh/m}^2\text{)}} \quad (5)$$

#### 4.3.2. Carbon dioxide (CO<sub>2</sub>) emissions

The cumulative CO<sub>2</sub> emissions attributable to the photovoltaic system's energy use should be markedly lower than those from equivalent fossil fuel alternatives in electricity generation. As documented by Dwivedi Tiwari [35], the mean CO<sub>2</sub> emission intensity is roughly 0.98 kg of CO<sub>2</sub> per kWh for coal-fired electricity. It is crucial to factor in additional losses—estimated at 40% during transportation and distribution and about 20% due to residential appliances. Consequently, the adjusted average CO<sub>2</sub> intensity for fossil fuel-based electricity production is estimated to be around 1.58 kg of CO<sub>2</sub> per kWh.

$$\text{Annual CO}_2 \text{ emission by the system } \left( \frac{\text{kg}}{\text{year}} \right) = \frac{\text{Embodied energy (kWh/m}^2\text{)} \times 1.58}{\text{Lifetime of the total system (years)}} \quad (6)$$

A longer EPBT suggests that it takes more time for the system to break even in terms of energy production and energy invested. The current PV has an estimated EPBT, about 4.6 years under Sharjah weather conditions.

According to Tiwari [36], the annual yearly CO<sub>2</sub> reduction attributable to a photovoltaic system, expressed in kilograms of CO<sub>2</sub>, is computed as the product of the system's annual



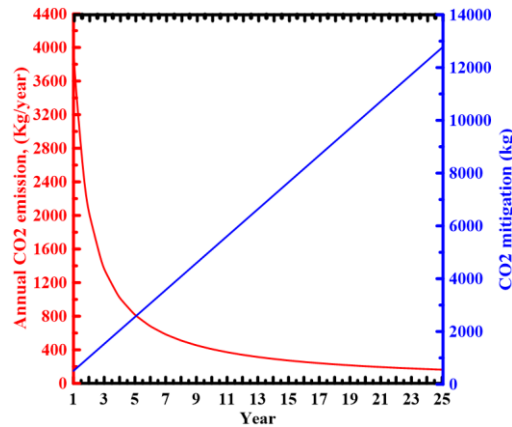
energy yield  $E_{out}$ , and the adjusted average CO<sub>2</sub> emission factor for fossil-fuel-based electricity generation, approximately 1.58 kg of CO<sub>2</sub> per kWh.

$$\text{CO}_2 \text{ mitigation during the lifetime of the PV system (kg)} = E_{out} \times 1.58 \times \text{lifetime (25year)} \quad (7)$$

**Table 4: Annual Thermal, Electrical, and Total Energy/Exergy output per m<sup>2</sup> of the PV system**

Average Solar radiation = 533.32 Wh/m <sup>2</sup>		
Average ambient Temperature = 318.52 K		
Average Wind speed = 1.41 m/s		
PV	$\eta_{el}$	<b>Total Energy (KWh/m<sup>2</sup>)</b>
	15.95%	322.96

Figure 4 presents the variation of CO<sub>2</sub> emissions and CO<sub>2</sub> mitigation open for all systems with a lifespan. The PV system, representing the photovoltaic setup, exhibits a gradual decline in annual CO<sub>2</sub> emissions, starting from 4080.40 kg/year in the first year and reaching 163 kg/year in the 25<sup>th</sup> year. On average, the PV system emits approximately 6.6 tons of CO<sub>2</sub> annually throughout its lifetime.



**Figure 4: The CO<sub>2</sub> emissions and mitigations (measured in Kg) per m<sup>2</sup> over the system's lifespan.**

## 5 CONCLUSION

This study investigated an established rooftop 2.88 kW grid-connected PV system under the harsh weather conditions of Sharjah, UAE. The study assessed the economical payback, PV system's environmental impact, and the degradation rate across PV system lifetime through the system's annual measured environmental and electrical data extracted from August 2021 to July 2022. The system's annual degradation rate coincided to 2.4% of the maximum power after one year and 0.568% on average, being consistent with the prior literature and as comparable to PVsyst simulation factor. Moreover, the study computed the energy payback time (EPBT), which is an important metric that indicates system's efficiency. This metric coincided to approximately 4.6 years in payback time, making it relatively short in return. Additionally, the on-grid PV system contributes to the clean energy metric, where 6.6 tons of carbon emissions are emitted through its lifetime. As a future work, further research will be conducted to investigate long-term performance of the on-grid PV system through the exploration of microcrack detection, assessment of different environmental parameters, and exploring new materials and technologies for PV system components, through the incorporation of machine learning techniques. As a result, extensive research and innovation is essential to address the possible challenges related to the durability of PV systems and to maximize their potential lifetime and productivity.

## 6 ACKNOWLEDGEMENT

This work was financially supported by the University of Sharjah, the Research Institute of Sciences & Engineering.

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