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Reducing Carbon Footprints with On-Grid Photovoltaic Systems: A Path to Sustainability

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Abstract: The unrelenting effort to mitigate carbon emissions has gained crucial momentum in establishing a secure and sustainable environment. Significant emphasis is being placed on achieving environmental sustainability and enhancing carbon capture. This study highlights the critical importance of solar photovoltaic (PV) energy systems in addressing environmental concerns and strengthening energy sectors. It specifically focuses on the emergence of connected photovoltaic systems and their potential to supply the energy sector while reducing carbon dioxide emissions. Through the design of a connected photovoltaic system with a maximum operating power of 584 kW under conditions of 1000 W/m² and 50°C, consisting of 1,095 modules covering an area of 2,994 m², the study demonstrated the system's ability to save between 13,636 and 23,117 tons of carbon dioxide. These results indicate that photovoltaic systems are a sustainable and transformative solution capable of maintaining the energy sector's balance by 2050. Furthermore, they serve as a pivotal link in promoting environmental enhancement through renewable, inexhaustible energy sources.

Keywords: Carbon emissions, Carbon footprint, Eco-friendly, Photovoltaic energy, PVsyst, Renewable sources, Sustainability.

1 INTRODUCTION

Currently, 770 million people globally do not have access to electricity. By 2035, global energy consumption is expected to rise by a third. However, the global energy landscape is undergoing a substantial upheaval due to the growing momentum behind the switch from fossil fuels to renewable energy sources [1-3]. Renewable energy alternatives are becoming increasingly available, and solar energy is one of the most cost-effective ways to handle rising global energy demands through photovoltaic (PV) energy [4-5]. Further, solar energy is a significant solution to address the growing demand for energy and the depletion of fossil resources [6]. Photovoltaic (PV) solar systems offer an efficient route to generate energy due to the absence of moving parts, contaminants, or noise. They convert abundant sunlight without practical limitations [7].

By 2050, the total installed capacity of photovoltaic (PV) modules is predicted to reach 4,500 GW at the current pace of installation [8]. Numerous countries are suffering from an enormous gap in the energy sector due to global fluctuations, such as conflicts and wars, including the Russian invasion of Ukraine on 24 February 2022 [9], as well as ongoing conflicts in the Middle East, including Palestine and Lebanon in 2024 and the Syrian crisis. Accordingly, many countries have continued to rely on fossil fuel energy sources, such as the Kingdom of Saudi Arabia, Iraq, and the United Arab Emirates. Therefore, diversifying energy sources is one of the promising routes to shift to sustainability, diminish reliance on fossil fuels, and equip Gulf countries (e.g., the United Arab Emirates, Saudi Arabia, and Iraq) to advance green energy by 2050. Additionally, this transition addresses political, economic, and environmental issues [10].

Solar energy PV systems are characterized as clean, eco-friendly, energy-efficient, long-lasting, requiring little maintenance, and having no detachable parts [13]. Moreover, enhancing energy via solar energy systems offers numerous solutions, such as augmenting energy security in countries and geopolitical positions. Additionally, in addressing emissions, solar energy represents a significant opportunity to reduce environmental impact [14]. Fig. 1 illustrates the rate of installation of photovoltaic energy systems worldwide by region from 2010 to 2030. Fig. 2 demonstrates the rate of capacity of photovoltaic energy systems, with projections indicating a significant rise by 2050.

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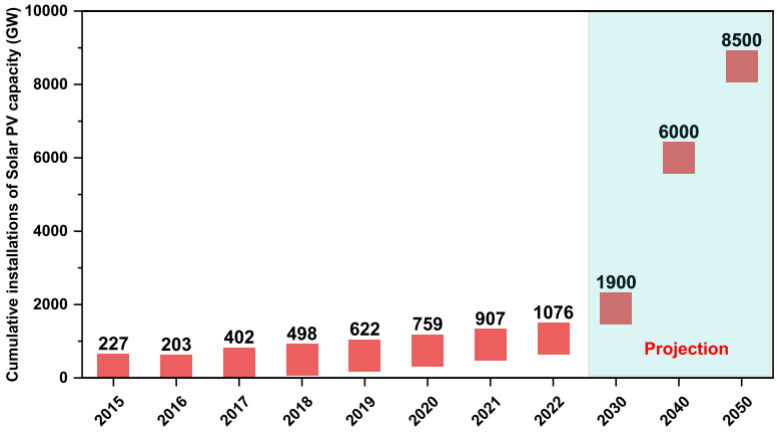

Fig. 1. The total installed capacity of solar PV [11]

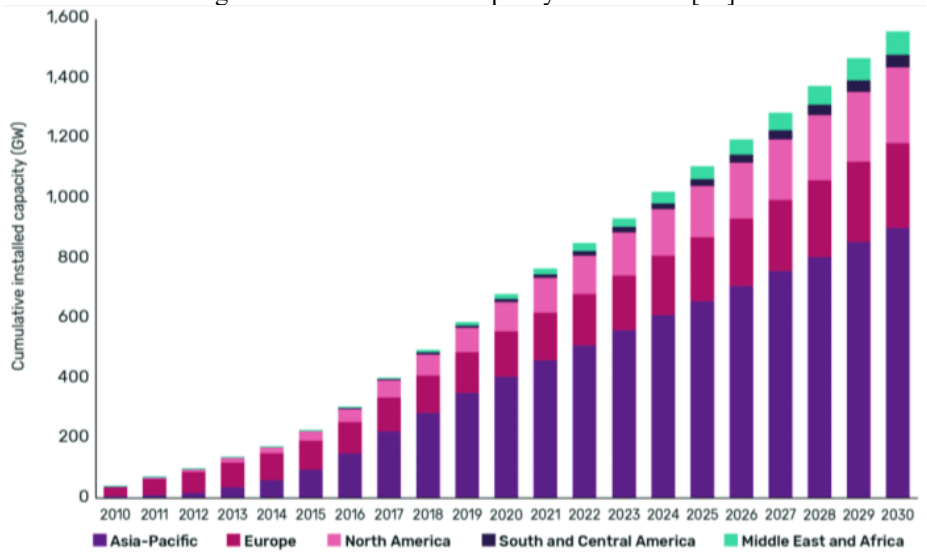

Fig. 2. The total number of solar PV systems [4-12]

2 THE ROLE OF SOLAR ENERGY IN ADVANCING ENVIRONMENTAL SUSTAINABILITY

Solar energy plays a critical role in enhancing environmental sustainability by providing a clean and renewable source of energy. It creates opportunities for countries worldwide to improve current energy reserves. Solar PV acts as a vibrant energy artery that delivers electricity from renewable sources and serves as an alternative to traditional sources. Additionally, the production of renewable energy, represented by solar energy, significantly mitigates global warming. The Intergovernmental Panel on Climate Change (IPCC) in 2023 predicted a 130% growth in greenhouse gas emissions due to a 70% increase in energy demand by 2050 [15]. Consequently, using solar energy is a key strategy for promoting sustainable energy [16].

2.1 The Potential and Visibility of Solar Energy

The current dimensions of solar energy demonstrate that it is a rapidly growing renewable energy source due to significant price reductions. Solar energy plays a crucial role in enhancing the efficiency of solar power plants and improving grid integration [17-19]. Moreover, the gradual advancements in solar energy technologies and the emphasis on renewable energy in the global energy landscape underscore the broad prospects for solar energy and its emerging role in transforming energy sectors [20]. Solar energy has enormous potential to reduce carbon emissions and achieve environmental security [21]. In summary, solar energy represents the future of energy, with potential applications like generating green hydrogen (H_2) energy. This makes it a promising solution for energy generation over the next two decades.

2.2 Mechanism to Enhance Sustainability via a Photovoltaic System

A photovoltaic (PV) system is a device that uses solar radiation to generate electricity. It operates using the photovoltaic effect, where photon energy is transmitted to charge carriers when sunlight strikes a photovoltaic cell [22]. Photovoltaic systems, particularly solar PV, are gaining popularity as a sustainable energy source. Their rapid adoption has attracted enormous investment, estimated to reach $170 billion by 2025 [23].

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Since photovoltaic energy systems depend directly on solar energy, all renewable energy sources are ultimately linked to solar radiation. Approximately 1.8×10^{11} megawatts of solar energy reach the Earth, which is significantly higher than the current global energy consumption rate [24]. Furthermore, solar PV has emerged as a transformative technology in the clean energy transition, playing a pivotal role in combating climate change and supporting environmental sustainability [25].

2.3 Solar Radiation

Solar radiation occurs when a large number of sun rays fall on a specific region, generating electrical power. Solar radiation refers to the radiant energy emitted by the Sun due to nuclear fusion events [26-27]. Solar radiation has a high energy concentration in the visible spectral region (350-750 nm), distinguishing it from other thermal radiation types (e.g., lights, heated surfaces), which are primarily concentrated in the infrared spectral region (wavelengths longer than 2,500 nm) [28].

Variations in the Earth-Sun distance and, to a lesser extent, daily spectral fluctuations caused by solar activity, affect the amount of solar radiation intercepted by the Earth. The solar radiation that strikes a plane at the top of the atmosphere increases with the Earth's proximity to the Sun [29].

2.4 Photovoltaic System

An on-grid solar photovoltaic system utilizes solar photovoltaic harvesters to produce electricity, which is then sent to an electric utility [30]. This system is characterized by accuracy and cost-effectiveness, reducing the burden on electrical energy sectors. These systems can optimize sunlight periods, enhance energy sectors, and provide economic benefits, thus encouraging broader adoption and reducing dependence on non-renewable energy sources. As a sustainable and clean system [31], photovoltaic energy is a pathway to a sustainable future [32]. Additionally, it helps mitigate the effects of climate change by reducing greenhouse gas emissions and accelerating the shift to green electricity [33-37]. Grid-connected photovoltaic systems have recently gained popularity due to their durability, reliability, simplicity, and ease of use [38].

3 METHODOLOGY

To address the challenges of finding alternative sources to fossil fuels and mitigating climate fluctuations, a solar photovoltaic energy system was designed to provide sustainable solutions for reducing global warming. Achieving this goal requires continuous research to identify sustainable alternatives to fossil fuels. The system was designed in accordance with the verification standards for solar photovoltaic energy systems using the PVsyst program for the geographical site of Kaṭbīyah in Iraq. This study also explores the mechanism of reducing carbon dioxide emissions through the connected system.

4 SYSTEM SIMULATION FOR ON-GRID SYSTEM

The designed system refers to the role of connected- photovoltaic systems characterized by performance criteria according to the standard conditions of the system based on the criteria conducted through the program (PVsyst) where the system performance and efficiency in generating electrical energy through the system connected to the grid are shown in Fig. 3.

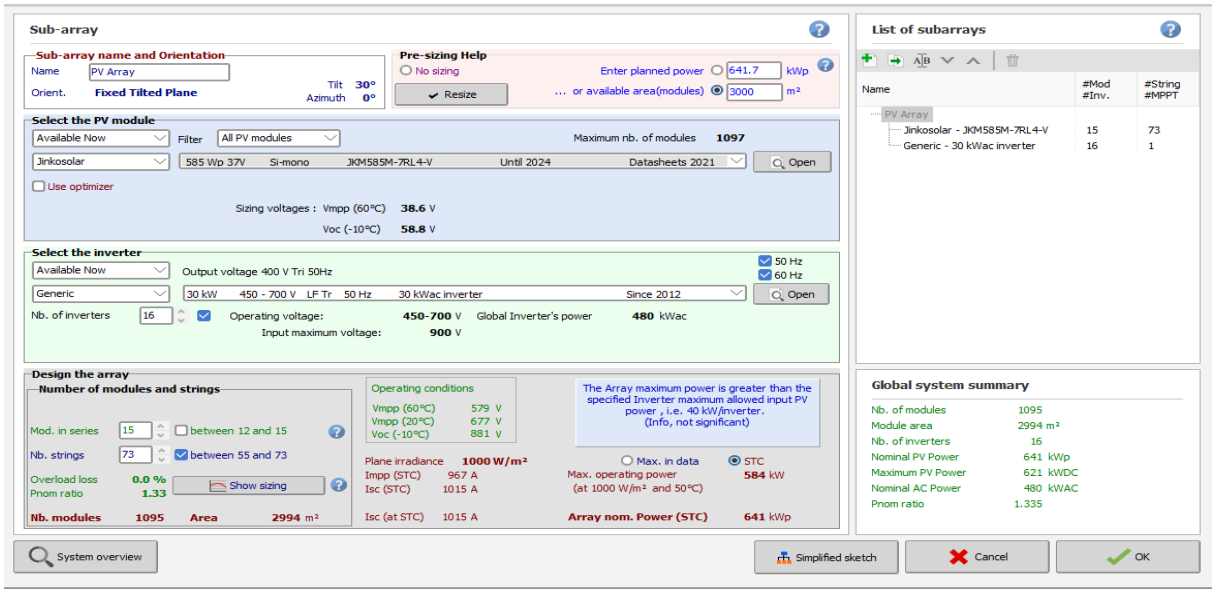

Fig. 3. System Design Grid-connected PV

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Fig. 3 shows the basic layout such as the name of the sub-array its orientation is the extension of the PV array and the orientation of the system where the tilt is 30° and the azimuth is 0°in this system, Where the planned energy input which was the target was 641.7 with an area of 3000 m^2 (i.e. available area) the selected photovoltaic module in the system has a capacity of 585, and the inverter capacity is 30kW, The number of photovoltaic modules is 1095 with an area of 2994 m^2, In addition, the array maximum power is greater than the specified inverter maximum allowed input PV power, i.e. 40kW/inverter. Hence This is a useful indicator in the system. Fig. 4 demonstrates the distribution of incident irradiation and the relationship between array temperature and effective irradiance during system operation. The distribution of reference incident energy in the collector plane and incident irradiation is presented in Fig. 5. Fig. 6 shows the daily energy output and power distribution of the photovoltaic array. The tail distribution of system output power and the corresponding array voltage distribution are illustrated in Fig. 7. Fig. 8 provides insights into the array temperature variations during operation and the cumulative saved CO_2 emissions over time. Normalized energy productions and the performance ratio of the system per installed kilowatt peak (kWp) are detailed in Fig. 9.

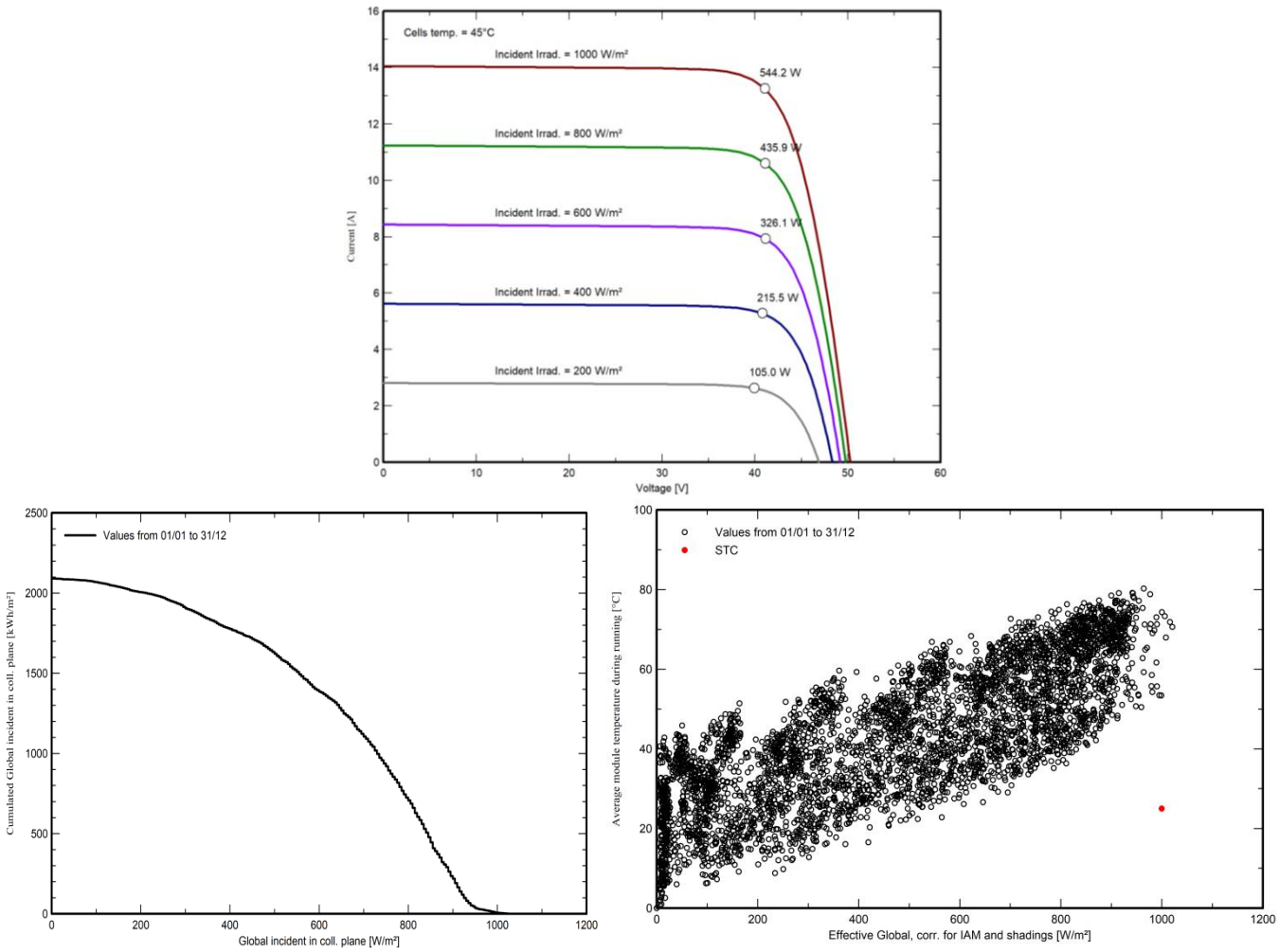

Fig. 4. Incident Irradiation Tail Distribution and Array Temperature vs. Effective Irradiance

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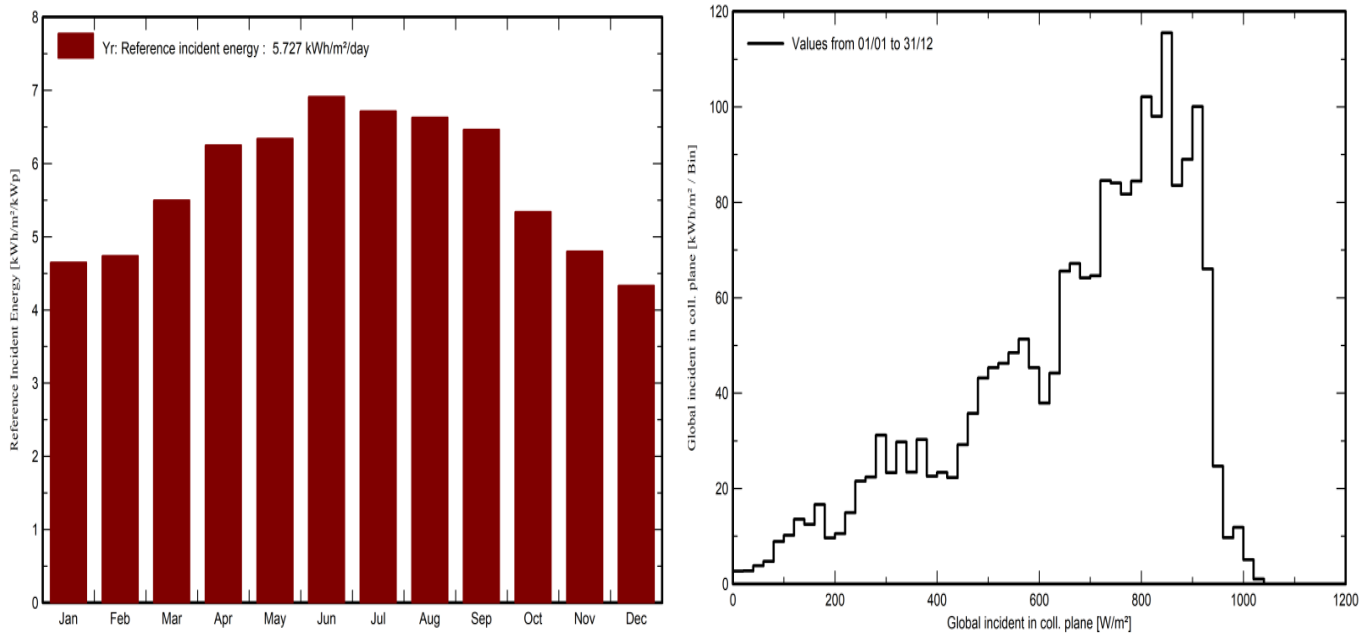

Fig. 5. Reference Incident Energy in Collector Plane and Incident Irradiation Distribution

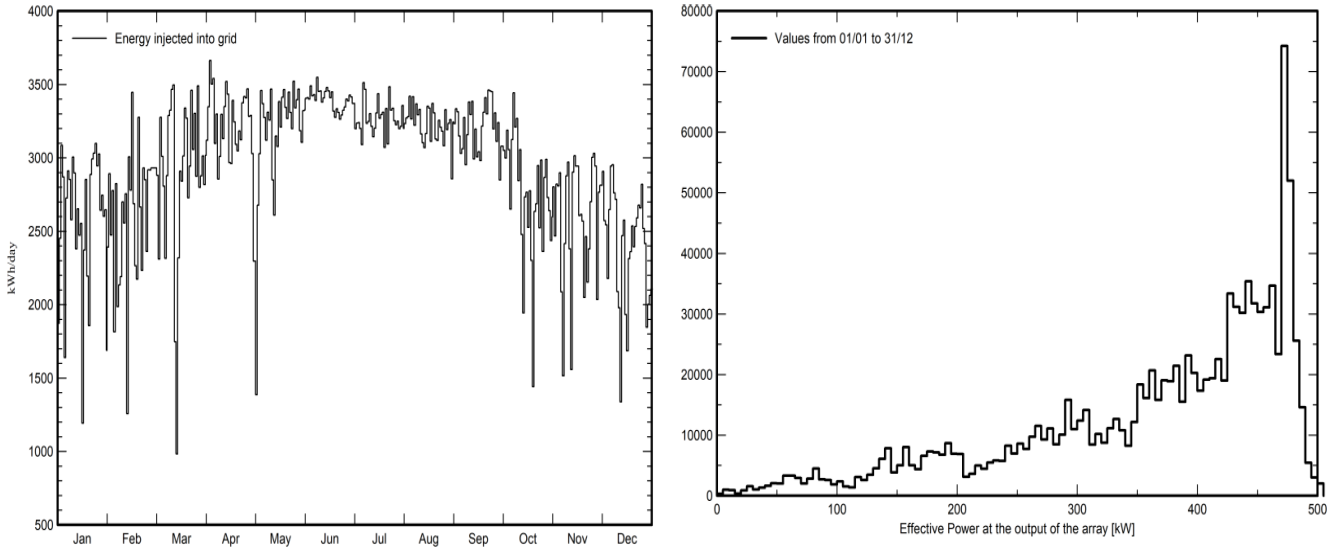

Fig. 6. Daily System Output Energy and Array Power Distribution

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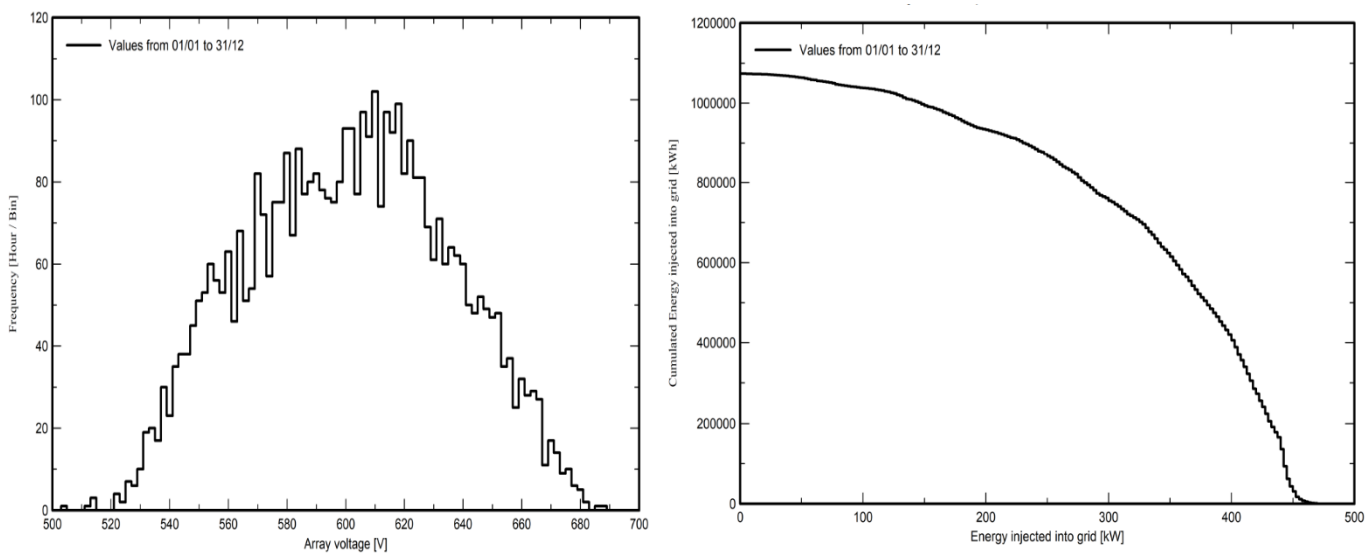

Fig. 7. System Output Power Tail Distribution and Array Voltage Distribution

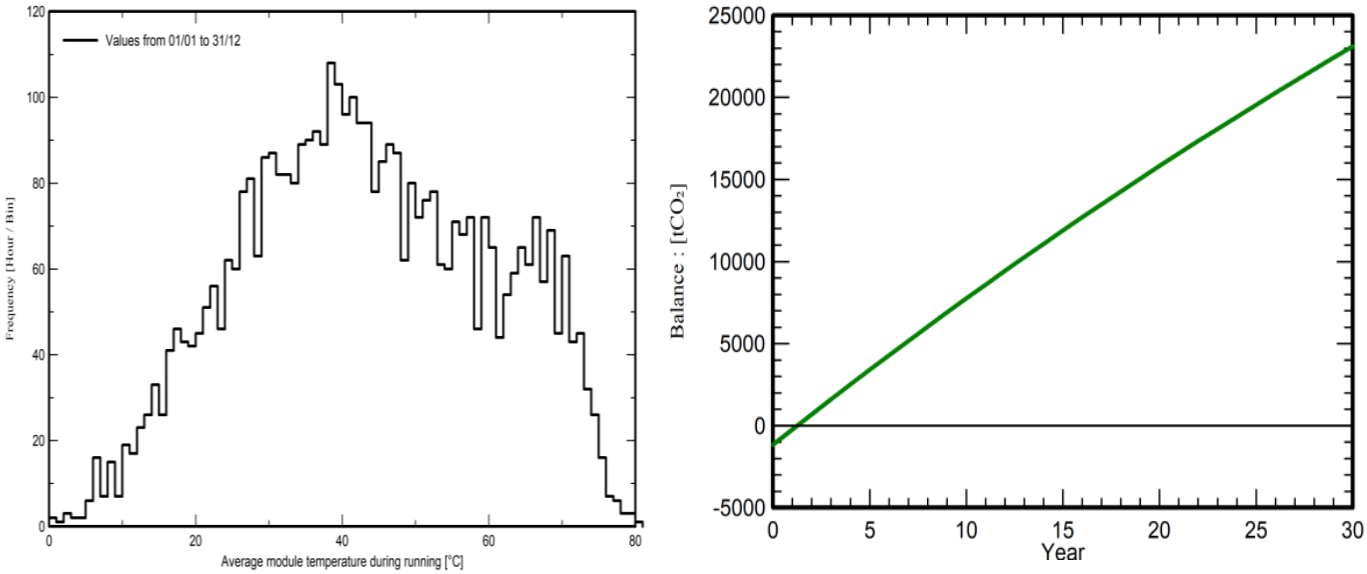

Fig. 8. Array Temperature Distribution during running and Saved CO_2 Emission vs. Time

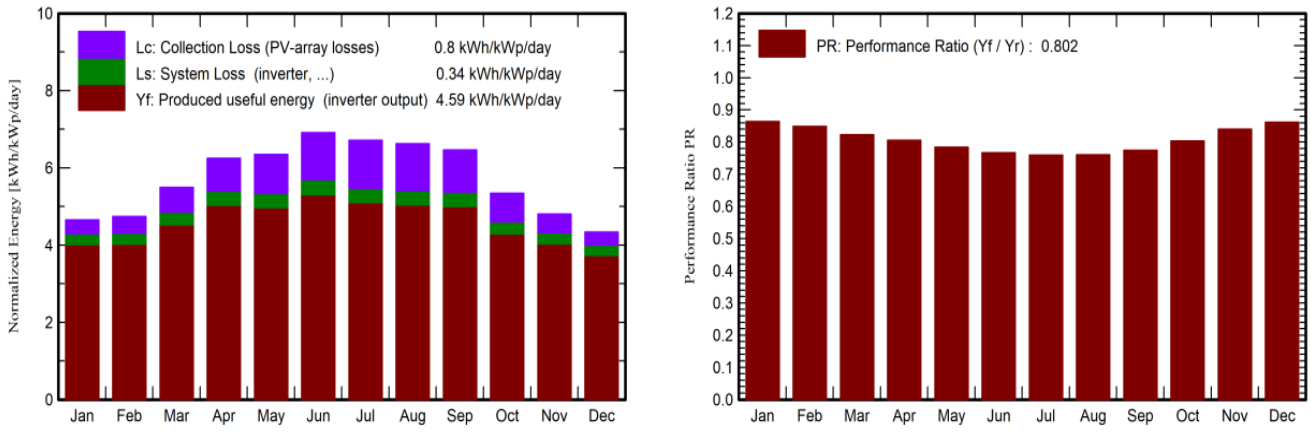

Fig. 9. Normalized productions (per installed kWp) and Performance Ratio of the system

The data in Table 1 highlights the environmental benefits of the designed photovoltaic system in terms of carbon emissions. The total generated emissions of 23,117.1 tCO_2 represent the emissions incurred during the system's lifecycle. However, the total replaced emissions of 27,991.1 tCO_2 significantly exceed this value, demonstrating the net environmental gain achieved by adopting the system. With an annual system production of 1,073.69 MWh and grid lifecycle emissions of 869 gCO_2/kWh, the system showcases its capability to reduce carbon footprints effectively. This table underscores the pivotal role of photovoltaic systems in mitigating climate change, particularly for regions like Iraq with a high dependence on fossil fuels.

Table 1. Balances and Main Results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	Globinc kWh/m²	GlobEff kWh/m²	Earray MWh	E_Grid MWh	PR Ratio
January	93.6	34.8	8.38	144.1	142.1	85.5	79.7	0.864
February	100.8	48.61	11.44	132.7	130.7	77.5	72.2	0.849
March	145.3	70.46	16.39	170.4	167.4	96.5	89.9	0.823
April	177.6	85.46	21.15	187.5	183.8	103.9	96.7	0.805
May	203.2	96.6	27.33	196.6	192.4	106.2	98.7	0.784
June	222.6	91.8	32.1	207.4	202.9	109.6	101.9	0.767
July	219.9	91.36	35.09	208.2	203.6	108.8	101.3	0.759
August	201.2	86.34	34.68	205.5	201.4	107.6	100.2	0.761
September	169.1	64.88	29.82	193.9	190.3	103.3	96.2	0.774
October	130.2	58.59	24.54	165.5	163	91.4	85.3	0.804
November	97.5	38.77	14.86	144.1	141.9	83.2	77.5	0.84
December	85.2	32.92	9.94	134.3	132.6	79.6	74.1	0.861
Whole Year	1846.5	800.65	22.21	2090.3	2052.2	1152.9	1073.7	0.802

5 DESIGN MODELING

The simulation project using the PVsyst program is a model that can be adopted for data analysis and real-world applications. Solar photovoltaic system standards are based on selecting the geographical location using Meteo data, after which the appropriate tilt angle is determined. In this system, a tilt angle of 30° was selected. Subsequently, the basic standards for the photovoltaic system were established. The basic properties of the PV module were determined as follows: model (JKM585M-7RL4-V), number of PV modules (1,095), and unit nominal power (585 Wp). The nominal capacity (STC) is 641 kWp. The system includes 16 inverters, each with a nominal power of 30.0 KWac, resulting in a total power output of 480 KWac, with an operating voltage range of 450-700 V.

Table 2 provides a detailed breakdown of the lifecycle emissions associated with key photovoltaic system components, including modules, supports, and inverters. The highest contribution to emissions is from the modules, with 1,097,126 $kgCO_2$ over 641 kWp of capacity. Supports and inverters contribute 63,469 $kgCO_2$ and 9,188 $kgCO_2$, respectively. These figures highlight the importance of focusing on sustainable manufacturing practices for modules, as they dominate the lifecycle emissions. This breakdown is instrumental in identifying areas for optimization and further reducing the environmental impact of photovoltaic systems.

Table 2. CO_2 Emission Overview

Parameter	**Value**
Total Generated Emissions	23,117.1 tCO_2
Total Replaced Emissions	27,991.1 tCO_2
System Production	1,073.69 MWh/yr
Grid Lifecycle Emissions	869 gCO_2/KWh
Country	Iraq
Lifetime	30 years
Annual Degradation	1.00%

The emissions distribution in Table 3 reflects the key components contributing to the lifecycle carbon footprint of the photovoltaic system. Modules account for the largest share of emissions at 1,713 $kgCO_2$ per kWp, emphasizing their critical role in system sustainability. Supports and inverters, while contributing less, remain essential elements for performance and system stability. These insights pave the way for innovations in material usage, manufacturing processes, and recycling strategies, ensuring that photovoltaic systems become even more eco-friendly over their operational lifespan.

Table 3. System Lifecycle Emissions Details

Item	Subtotal	Quantity	LCE
Modules	10,97,126	641 kWp	1,713 $kgCO_2$/kWp
Supports	63,469	10,950 kg	5.80 $kgCO_2$/kg
Inverters	9,188	16.0 units	574 $kgCO_2$/unit

5.1 Significance of the Study

Enhancing energy sources is a noble goal to address the electricity crisis in numerous countries. Encountering alternatives that enable diversified energy sources is a critical factor in strengthening the energy sector. Additionally, it opens economic prospects that improve regional conditions and provides a clear vision for how developing countries can enhance energy security in the long term through renewable energy sources.

5.2 Roadmap for Enhancing Sustainable Energy

Promoting sustainability largely depends on the actions of major fossil fuel-consuming countries and the success of global climate initiatives. Continued reliance on fossil fuels hinders progress toward achieving global climate goals. To achieve sustainability, promoting sustainable energy sources is essential to reducing greenhouse gas emissions, which are projected to increase by 50% by 2030 [39]. Furthermore, the EU-Russia energy divergence has crucial effects on carbon emissions and global fossil fuel trade. Due to the efforts by European nations to transition to renewable energy sources, this shift in energy trading patterns is anticipated to mitigate approximately 2 gigatons of CO_2 in cumulative global emissions by 2050 [40]. The global effort to combat climate change and achieve sustainable development is at a pivotal point. However, identifying quick and effective alternative methods is crucial for achieving sustainability and reducing carbon emissions [41]-[43].

6 CONCLUSIONS

Countries are accelerating toward renewable energy horizons, enhancing the sustainable development movement, and leveraging photovoltaic energy systems to create opportunities for life sustainability. These efforts aim to establish integrated energy strategies free from geopolitical interference while enhancing energy security, the environment, and the economy. A key priority is the creation of inexhaustible energy sources. From this standpoint, we focused on highlighting the role of connected photovoltaic energy systems in addressing environmental concerns, particularly global warming, and their impact on sustainability. Replacing traditional energy sources with renewable options such as photovoltaic energy can serve as a radical solution for the future. Despite this progress, reliance on fossil fuels remains one of the most prominent challenges, particularly for oil-exporting countries. Additional challenges include conflicts in the Middle East, which pose threats to energy-consuming nations dependent on fossil energy sources.

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ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this study.

LICENSING

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