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Validation of Designing a Photovoltaic Energy (PVE) System to Enhance Urban Life and Reduce Fossil Fuel Dependence in Tehran and Baghdad

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Abstract

Aim: This study aimed to design and validate a grid-connected photovoltaic (PV) system to assess its potential for reducing CO_2 emissions and enhancing urban sustainability in Tehran and Baghdad. Transformative Narratives Towards Psycho-Cultural Sustainability and Positive Gender Socialisation for Women in West and Central Africa

Methods: The study employed a tilt angle of 30°/0° for both sites. A total of 3,654 photovoltaic modules were installed, covering an area of 9,990 m², with 57 inverters integrated into the system. The total system power capacity was 2,138 kW, incorporating components for storage and self-consumption.

Results: The results demonstrated a significant reduction in CO_2 emissions over a 15-year system lifetime—amounting to 41,168.7 tons in Iraq and 25,814.1 tons in Iran. In terms of generated emissions, Iraq recorded 1,169.78 tons of CO_2, while the grid lifecycle emissions were 869 tons in Iraq and 575 tons in Iran. The annual system production was 1,833.9 MWh in Iraq and 1,663.5 MWh in Iran. These findings highlight the system's strong potential in mitigating carbon dioxide emissions and offering a sustainable energy solution for urban environments with high pollution levels.

Conclusion: This work serves as a foundational contribution to the broader understanding of how oil and gas exporting countries can harness photovoltaic technologies to address escalating energy demands. This is particularly in densely populated urban areas while simultaneously avoiding environmental crises, such as those currently experienced in Tehran.

Recommendations: There should be development and implementation of strategic approaches for integrating connected photovoltaic systems play a critical role in strengthening energy security. Addressing emerging challenges, and establishing effective pathways to reduce and prevent environmental degradation in the future.

Keywords: *Photovoltaic energy, environment, fossil fuel, electrical energy, carbon emissions, urban cities*

INTRODUCTION

The world is currently grappling with major challenges and crises that raise global concern, particularly in the areas of environmental degradation, public health, and economic instability. A significant contributor to these issues is the harmful emissions generated from the combustion of fossil fuels used for electricity generation and other applications. This dependency on fossil fuels poses serious environmental risks, including projected increases in global temperatures. It is anticipated that average temperatures may rise by more than 1.5°C within the next 15 to 20 years, potentially reaching 3°C or more if the heavy reliance on fossil fuel-based energy production continues. Deforestation further compounds these issues, accelerating the effects and contributing to the intensification of global warming across much of the planet [1], [2], [3], [4].

These environmental impacts are further exacerbated by the rapid growth of urban populations, which reached 4.2 billion people (55% of the global population) in 2018 and is expected to exceed 5 billion by 2030 [5]. This urban expansion places additional pressure on cities, as it increases the use of vehicles, public and private transportation, and fossil-fuel-dependent electricity generators, including power plants and industrial facilities - particularly in the energy sector. Given this accelerated urbanization, there is a pressing need to identify alternative energy sources that reduce our reliance on fossil fuels.

Photovoltaic (PV) systems emerge as a pivotal solution to the environmental challenges confronting urban centers. These systems hold the potential to significantly reduce carbon dioxide emissions and mitigate the adverse effects of fossil fuel usage. This paper will explore the design of grid-connected photovoltaic systems and demonstrate how they contribute to environmental sustainability.

Among the most prominent and harmful emissions is carbon dioxide, which plays a major role in climate change and the deterioration of air quality, thereby adversely affecting human health and the environment. At the same time, modern cities face mounting energy challenges due to the escalating demand for power, leading to a continued dependence on traditional fossil fuels with detrimental consequences. To alleviate pressure on the energy sector, it is essential to prioritize renewable energy sources, with solar photovoltaic technology standing out as a particularly viable option.

Photovoltaic systems (PVSYS) efficiently convert sunlight into clean, renewable electrical energy in a simple and cost-effective manner, making them a promising and sustainable solution to today's energy challenges [6], [7], [8]. By reducing dependence on conventional oil and gas-based energy, PV systems contribute to significant reductions in carbon emissions. Integrating these systems into urban infrastructure not only enhances environmental sustainability but also strengthens the resilience of cities to climate change and mitigates the growing challenges faced by urban environments [9].

Despite the clear and numerous benefits of photovoltaic energy, its widespread adoption in urban areas faces several challenges, including economic, technological, and social constraints. Therefore, it is crucial to conduct research into the deployment of photovoltaic energy systems as an effective strategy for combating carbon dioxide pollution. Such research represents a vital step toward fostering more sustainable and healthier urban environments. In this context, we will propose practical solutions aimed at reducing pollution in the cities of Tehran, Iran, and Baghdad, Iraq. The authors also presented photovoltaic system designs tailored to these cities, demonstrating their potential to significantly reduce carbon dioxide emissions.

Potential of Solar in Tehran and Baghdad

A crucial factor when evaluating solar energy systems is solar irradiance. Direct Normal Irradiance (DNI) refers to the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun. Global Horizontal Irradiance (GHI) refers to the total amount of shortwave radiation received from above by a horizontal surface [35]. Diffuse Horizontal Irradiance (DHI) denotes the portion of solar radiation scattered by molecules and particles in the atmosphere. Tables 1 and 2 present the solar energy potential in Tehran and Baghdad. These values are considered acceptable for various energy applications, including water desalination and other uses. Furthermore, the annual irradiance rates support the feasibility of transitioning to alternative energy sources in both Iran and Iraq.

Table 1. Characteristics of Map Data in Baghdad (Per Year)

Characteristics	Range
Specific photovoltaic	1689.2(KWh/KWp)
Direct normal irradiation	1814.6(KWh/m^2)
Global horizontal irradiation	1957.1(KWh/m^2)
Diffuse horizontal irradiation	794.2(KWh/m^2)
Global tilted irradiation at the optimum angle	2192.7(KWh/m^2)
Optimum tilt of PV modules	30/180°
Air temperature	25.5°C

Table 2.Characteristics of map data in Tehran (Per year

Characteristics	Range
Specific photovoltaic	1757.4
Direct normal irradiation	1902.8
Global horizontal irradiation	1924.7
Diffuse horizontal irradiation	742.7
Global tilted irradiation at the optimum angle	2199.2
Optimum tilt of PV modules	32/180°
Air temperature	15.8°C
Terrain elevation	N/A

The purpose of the Study

This study focused on the importance of photovoltaic energy in Baghdad and Tehran, given its paramount importance in achieving environmental balance and its role in advancing sustainable goals with the potential to reduce dependence on fossil fuel sources in both governorates. The current study has culminated in the proposal of a connected photovoltaic system, designed to provide electrical energy while achieving significant carbon conservation rates in Baghdad, Iraq, and Tehran, Iran.

Considering that these identified locations are urbanized and densely populated areas experiencing a notable increase in reliance on traditional fuels to meet rising energy demands - largely driven by continuous population growth -the proposed photovoltaic system will be of the grid-connected type. This system is illustrated in Figure 1 for both cities. The system's parameters will be defined based on the algorithms provided by the PVsyst program, which will serve as the primary tool for modeling the proposed system with a capacity of 2138 kWp.

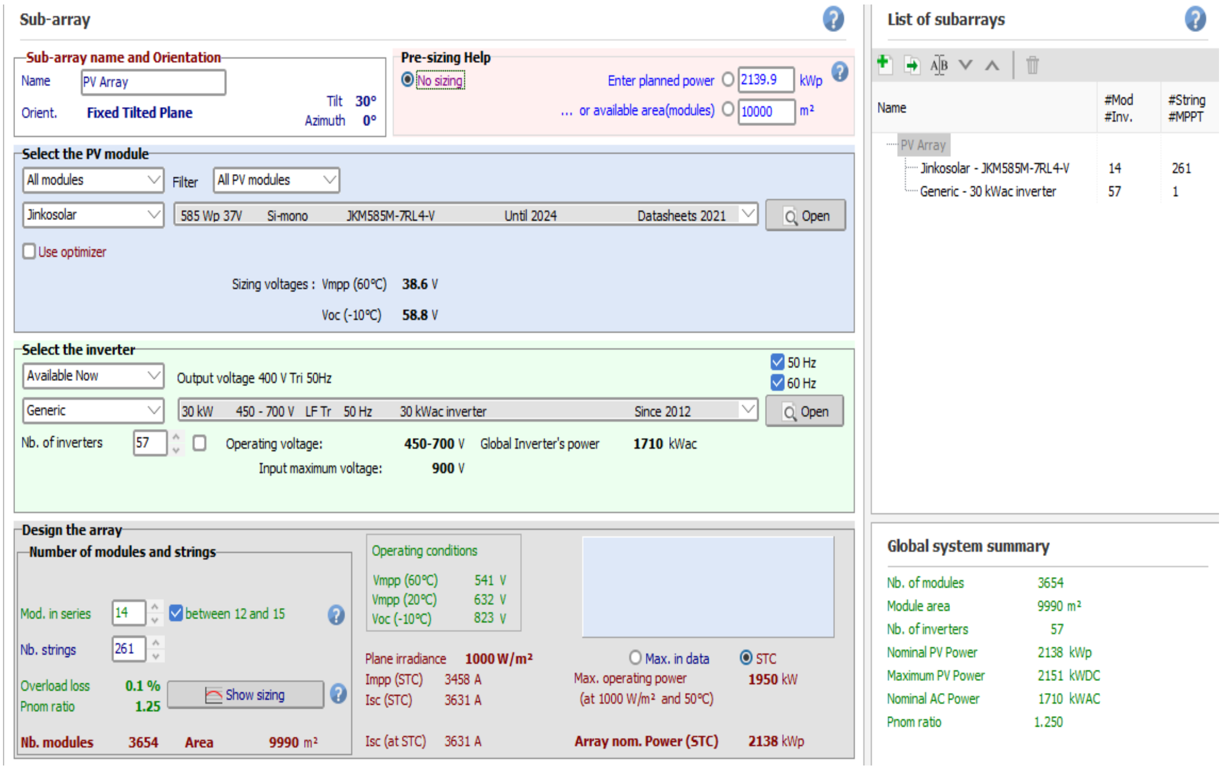

Fig.1. The Proposing Grid-Connected System Baghdad and Tehran

LITERATURE REVIEW

This study illuminated the researchers' perspectives on the origins of pollution in Tehran, Iran, and Baghdad, Iraq. However, this literature review will be the first to examine the researchers' perspectives on the pollution sources linked to fossil fuels, which are primary contributors to the heightened impacts of global warming due to the emissions caused by an increased dependence on these fuels. Mousavi *et al.* (2024) showed that carbon dioxide in the atmosphere, a greenhouse gas, is a cause of climate change, altering rainfall, storms, and droughts, and affecting ecosystems and communities [10].

Alcibahy *et al.* (2025), Althor Alcibahy (2016), and Liu *et al.* (2019) asserted that global climate change is caused by emissions of carbon dioxide and methane, which are the most influential on the phenomenon of global warming, posing some of the most prominent challenges of this century [11], [12], [13]. Haidari *et al.* (2025) view carbon sequestration in tree and plant biomass, along with underlying soils, as a simple and cost-effective method to reduce CO_2 emissions through Nature-based Solutions [14]. Yousefi *et al.* (2017) emphasized that focusing on policies to reduce emissions is essential, especially in Tehran. Solid fuels such as coal and wood contribute to air pollution from cooking and heating. Although natural gas is cleaner, it still emits carbon dioxide, methane, and nitrogen oxides, necessitating solutions to reduce emissions in crowded locations [15].

Nasehi *et al.* studied air pollutants in Iran during 2022 and 2023 and showed that Tehran and industrial cities represent high-risk areas for air pollution. The researchers emphasized the importance of increasing dense vegetation cover and proper land use management as effective strategies to mitigate air pollution [16]. Talkhabi *et al.* (2022) revealed that urban expansion is more intertwined and complex than urban sprawl [17]. Rabie *et al.* (2024) concluded that fossil fuel combustion is a major driver of climate change and urban air pollution [18]. Sobhani, Parvaneh *et al.* (2024) explore the growth and development of Tehran, focusing on contemporary issues arising from rapid expansion without comprehensive urban planning [19]. Hosseini *et al.* (2019) show that Iran's population growth reflects strong urbanization trends, causing challenges for cities due to inadequate urban management and planning priorities [20].

Ardalan *et al.* (2019) found that air pollution, water crises, waste management, and climate change are the main issues facing Iran -Tehran in particular suffers from severe air pollution that affects both health and sustainable development [21]. Atash *et al.* (2007) emphasized that the increase in population, economic activities, and the growing vehicle fleet have significantly contributed to high levels of air pollution in major cities in developing countries, such as Tehran, which suffers from severe air pollution [22]. Naddafi *et al.* (2012) conducted a study aiming to quantify the effects of air pollution on the health of Tehran's population, the most populous city in Iran [23]. Ghadami *et al.* (2019) also sought to measure the impact of air pollution on the health of residents in Tehran, the largest city in Iran [24].

Gheshlaghpoor *et al.* (2023) investigated how land use patterns impact air pollutants in the Tehran metropolis [25]. Waheeb, R. (2023) reports that Iraq is estimated to be the 10th most polluted country globally, with airborne particulate matter (PM2.5) levels reaching 39.6 micrograms per cubic meter [26]. Hassoon *et al.* (2015) outlined that population changes, economic growth, energy use, and technology are affecting air quality in Baghdad and other major cities due to emissions from fossil fuels and industrial activities [27]. Al-Kasser *et al.* (2021, June) revealed that the combustion of fossil fuels, industry, energy production, transportation, heating, the brick and cement industry, oil industries, agriculture, fires, dust storms, and household and public electricity generators are the main sources of pollutants released into the atmosphere, causing major impacts [28].

Hosseinalipour *et al.* (2024) highlighted the need for effective technologies that reduce energy demand and mitigate harmful climate impacts. Their study discusses the implementation and dynamic development of insulation technology to achieve a sustainable and energy-efficient future in the region, specifically in Iraq [29]. Abdulateef *et al.* (2025) found that rising temperatures in urban areas lead to outdoor thermal discomfort and concurrently increase energy usage within buildings [30]. Mohsin *et al.* (2020) proposed an extensive sustainability framework for urban development initiatives in arid, hot, developing areas. They argue that such a framework is necessary because these regions lack a comprehensive understanding of challenges such as population growth, traffic congestion, environmental pollution, water scarcity, and excessive energy consumption. Iraq, being a developing nation characterized by a hot, arid, semi-dry climate and distinct socio-cultural elements, has been affected by four decades of conflict. Although new development initiatives are in progress, little focus has been given to sustainability -particularly in urban areas like Baghdad [31].

Overall, this survey reviews the growth of urban areas due to a substantial rise in population, which contributes to the expansion of energy sectors reliant on fossil fuels and the increase in transportation methods that also rely on conventional sources, negatively impacting the environment.

METHODOLOGY

Geographical location and Potential in Tehran

Tehran Province is located between 50° and 53° east longitude and 34° and 36.5° north latitude. It spans an area of 18,814 square kilometers, with a population exceeding 13 million. Its elevation varies significantly, ranging from 758 to 4,336 meters above sea level, which makes Tehran a four-season region. The province is home to two major rivers: the Karaj and Jajrud rivers. Both originate in Alborz Province and flow northward into Tehran Province. Additionally, the Lar, Behlehrud, Shor, and Abharrud rivers are perennial rivers that pass through the area. This province also hosts three important dams: Amir Kabir, Letian, and Lar [32].

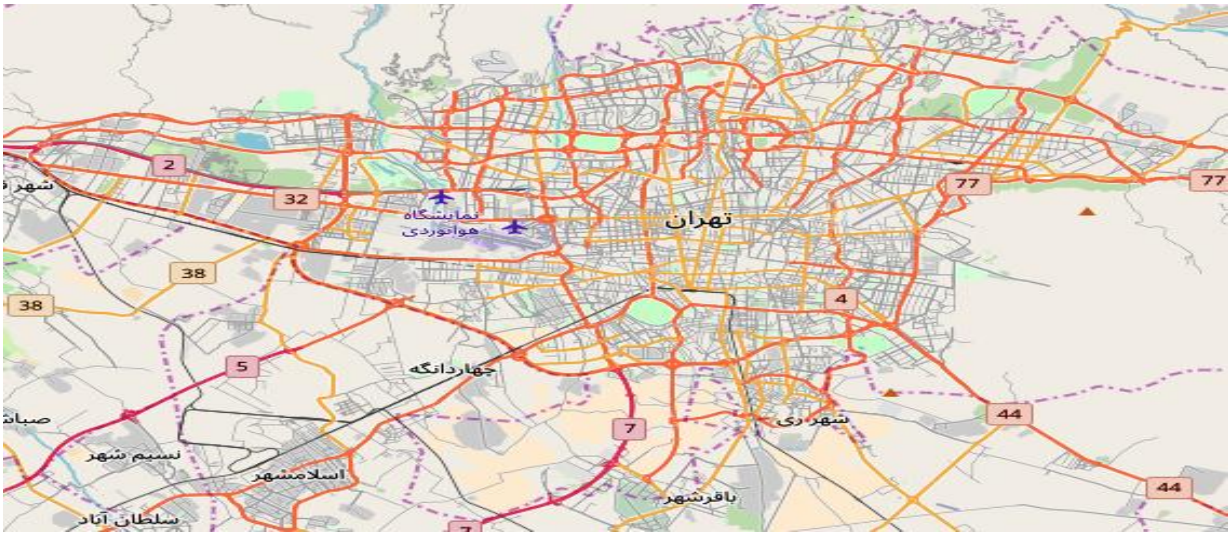

Fig. 2. Map of Tehran

Geographical location and Potential in Baghdad

Baghdad, the capital of Iraq, is an urbanized and densely populated city, covering approximately 204.2 square kilometers. Its geographical coordinates are 33.33333°N and 44.43333°E [33]. Located on the Tigris River, it lies about 530 kilometers from the Persian Gulf [34]. The city's population was estimated at approximately 8.5 million in 2016, representing about 21% of Iraq's total population.

Figure 3. Map of Baghdad

Source: [33]

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GHI in Tehran and Baghdad are suitable values if we examine the range of values based on the Global Solar Atlas, they are reliable. Therefore, understanding solar potential is an essential part of knowing the primary geographical features revealing the suitable conditions that countries enjoy in order to employ natural resources to serve their requirements.

Energy Vision in Iraq and Iran and Outlook Sustainability

Iran, being a country rich in fossil fuels, remains heavily dependent on these sources, as illustrated in Figure 4. The figure demonstrates that the majority of power plants operate using traditional energy sources. Additionally, Figure 4 reflects the growing energy consumption in power plants across the country. This increased reliance significantly contributes to environmental degradation due to the emissions produced by burning fossil fuels. Most power plants use natural gas and oil, which are among the most cost-effective and readily available energy sources. However, these plants are responsible for emitting approximately 180 million tons of carbon dioxide annually, a key factor contributing to global warming [36]. Despite the dominance of fossil fuel-based power generation, which produced approximately 313.5 TWh of electricity in 2020 and accounted for about 91% of the country's total electricity output, Iran faces increasing environmental challenges. Nevertheless, the country holds the potential to reduce its greenhouse gas emissions by up to 8% - and up to 12% overall - [37],[38],[39],[40]. Iran is now aiming to integrate renewable energy sources into its energy mix to tackle pressing issues such as air pollution and climate change, while also striving to ensure energy sustainability [41].

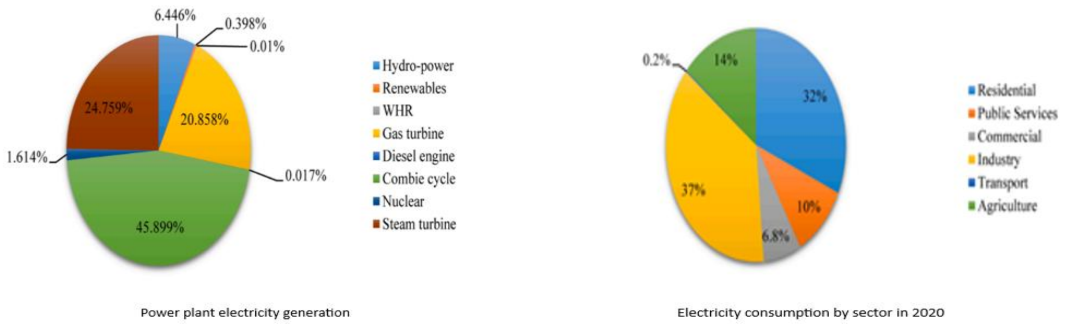

Figure 4. Electricity Generation Gwh Across Several Power Plant Types in Iran 2020 and Iran's Electricity Consumption by Sector in 2020

Source: [37],[38],[39,[40].

In Iraq, electricity production and consumption have witnessed a steady increase. Between 2000 and 2021, electricity production rose steadily from 66.4 terawatt-hours (TWh) to 198.5 TWh. Similarly, consumption increased from 60.1 TWh in 2000 to 176.5 TWh in 2021, following a similar trajectory. Iraq, like other countries, is also seeking to reduce dependence on fossil fuels and diversify energy sources by integrating renewable energy into the energy sector to reduce global warming and provide a safe environment [42][43].

OUTCOMES AND DISCUSSION

Table 3 shows the characteristics of the solar photovoltaic system proposed in this paper based on achieving the goals of reducing dependence on fossil fuel sources through sustainable sources that can alleviate the burdens of energy sectors in urbanized cities. This system aims to create great importance in solar energy and how it can be an important main axis in diversifying energy sources in countries that depend on traditional fuel sources. Table 4 shows the characteristics of

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the battery pack for the grid-connected system. While the Table 5 and 6 indicates the array losses and the system life cycle emissions in both sites. On the other hand, these characteristics are represented according to the geographical locations at (and longitude: 44.45°E, latitude: 32.20°N and Altitude:25m in Iraq) and at (Latitude: 36.49°N, Longitude: 49.44°E and Altitude:1403 m in Iran). According to this geographical information, the current system was designed. Depending on the parameters of the software PVSyst report.

Table 3. Characteristics of a System in This Work

System Information	Units
Type	Grid-Connected System
Tilt/Azimuth	30 / 0 °
PV Array	
Nb. of modules	3654units
Pnom total	2138kWp
Inverters	
Nb. of units	57units
Pnom total	1710kwac
Pnom ratio	1.25

Table 4. Battery Pack Characteristics in Grid-Connected System

Battery Pack Characteristics	Units
Storage strategy:	Self-consumption
Nb. of units	20 units
Voltage	256V
Capacity	99Ah
Temperature	Fixed20°C
Stored energy	19.6 kWh
Discharging min. SOC	22.00%

Table 5. Array losses of Grid-connected systems

Module temperature according to irradiance	Units
Uc (const)	20W/m²K
Uv (wind)	0.0W/m²K/m/s
DC wiring losses	
Global array res	2.7mΩ
Loss Fraction	1.5% at STC
Strings Mismatch loss	
Loss Fraction	0.10%
Module mismatch losses	
Loss Fraction	2.0 % at MPP

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Strings Mismatch loss	
Loss Fraction	0.10%
Module Quality Loss	
Loss Fraction	-0.80%
IAM loss facto	
Incidence effect (IAM)	
Fresnel AR coating, on(glass)	1.526, n(AR)=1.290

Table 6. System Lifecycle Emissions

Item	LCE	Quantity	Subtotal([kgCO_2])
Modules	1713 kgCO2/kWp	641 kWp	1097126
Supports	5.80 kgCO2/kg	10950 kg	63469
Inverters	574 kgCO2/units	16.0 units	9188

RESULTS

Investigation of various aspects of the system

Figure (3) shows the proposed grid-connected photovoltaic system in Tehran has a solar fraction of 64.02%, which is lower than the solar fraction of 64.54% in Iraq. The performance ratio is 83.45%, but it is lower in Iraq at 79.54%. In addition, the production energy in Iraq is 3482%, which is higher than the production energy in Iran. Also, the specific production ratio in Iraq is higher than in Iran. However. These variances in the system represent similar and expected differences due to the standards imposed by the geographical location and normal conditions of each country. While in figure (4) shows the rates of (Saved CO2 emissions) in Iraq according to the lifetime for both locations and the General emissions (tCO2) of the system provide higher rates in Baghdad than Tehran according to the Co2emisson balance. The connected photovoltaic system proposed in this work appears to be a suitable and effective option and provides good rates in both locations, as it is widely used in power generation and emission reduction provided by conventional power plants.

Results of the System

Figure 5 illustrates the performance characteristics of the photovoltaic systems installed in Tehran and Baghdad. Figure 5a and 5b presents the normalized energy production values from June to December in Tehran. Subfigure c and d presents the normalized energy production values from June to December in Baghdad. The Performance Ratio (PR) recorded in Tehran is 0.834, compared to 0.795 in Baghdad, indicating a slightly higher system efficiency in Tehran. Figure 5 further displays the reference incident energy on the collector plane, along with normalized production and loss factors. Figures 5a and 5b correspond to the grid-connected photovoltaic system in Tehran, whereas subfigures 5c and 5d represent the photovoltaic system in Baghdad. The reference incident solar energy values are measured at 5.608 kWh/m^2/day for Baghdad and 5.149 kWh/m^2/day for Tehran. Regarding normalized production and system losses, the Baghdad system exhibits a collection loss (PV-array losses) of 14.5%, system loss of 5.9%, and a useful energy output (inverter output) of 79.5%. In contrast, the Tehran system shows a collection loss

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(Lc) of 10.3%, a system loss (Ls) of 6.3%, and a final yield (Yf) of 83.4%, demonstrating slightly higher performance efficiency compared to Baghdad.

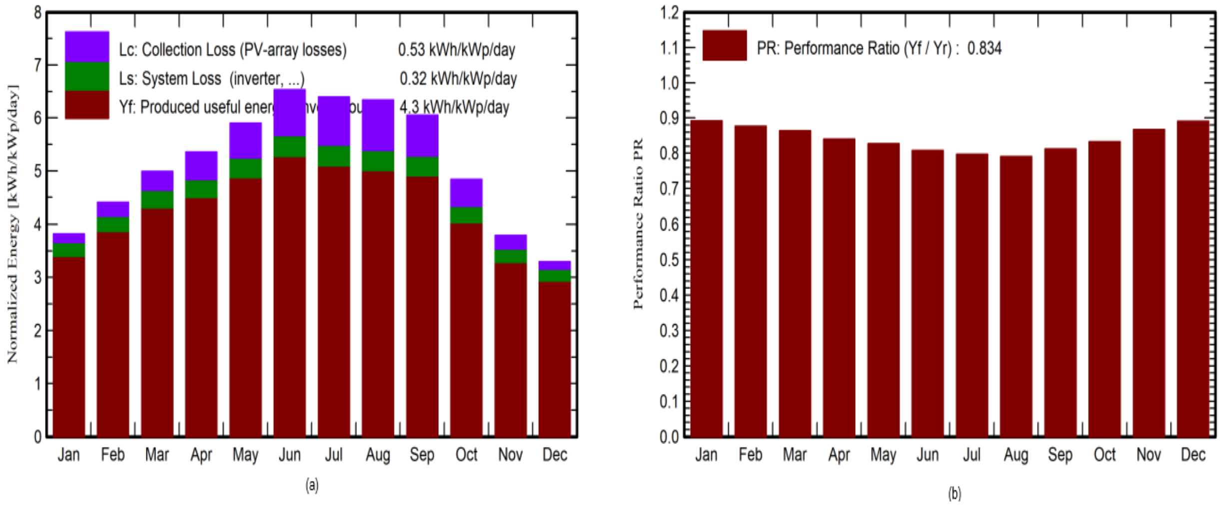

Figure 5. (a) Normalized productions (per installed kWp) and(b) Performance Ratio PR (Tehran)

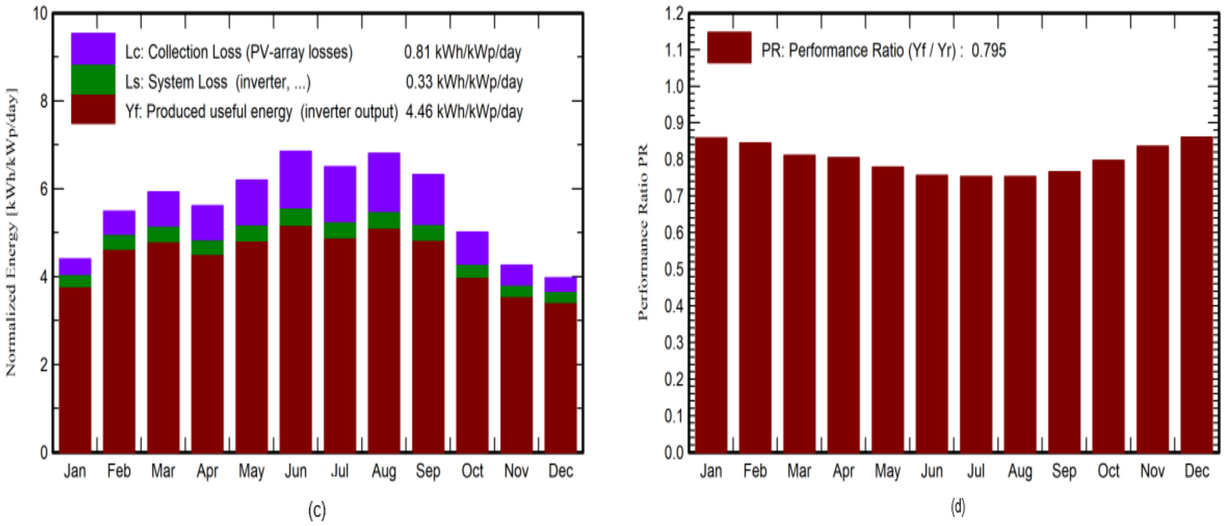

Figure 5. (c) Normalized productions (per installed kWp) and(d) Performance Ratio PR (Baghdad)

Table 7. The Balances and Main Results in the System in Iraq

Month	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_User MWh	E_Solar MWh	E_Grid MWh	EFrGrid MWh
January	91.8	39.69	9.77	136.4	134.0	268.8	3.720	2.113	248.2	1.607
February	112.8	45.92	11.53	153.5	150.8	297.5	3.360	2.009	275.2	1.351
March	154.4	57.24	16.22	183.6	180.0	342.2	3.720	2.366	316.1	1.354
April	161.7	71.11	23.06	168.3	164.6	311.2	3.600	2.385	287.2	1.215
May	200.9	70.88	29.10	191.9	187.4	343.9	3.720	2.718	316.9	1.002
June	226.8	63.39	33.38	205.5	200.2	357.3	3.600	2.640	329.5	0.960

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July	217.0	71.11	36.15	201.5	196.5	348.9	3.720	2.720	321.7	1.000
August	208.0	62.98	35.79	210.8	206.1	364.2	3.720	2.569	336.6	1.151
September	166.5	57.38	32.03	189.5	185.5	333.3	3.600	2.340	308.0	1.260
October	123.4	57.13	26.24	155.3	152.3	284.4	3.720	2.284	262.4	1.436
November	89.4	41.29	17.88	127.6	125.3	244.8	3.600	2.035	225.9	1.565
December	81.2	39.11	11.57	123.2	121.0	243.5	3.720	2.089	224.6	1.631
Year	**1833.9**	**677.24**	**23.63**	**2047.0**	**2003.6**	**3740.0**	**43.800**	**28.268**	**3452.2**	**15.532**

Table 8. The Balances and Main Results in the System in Iran

Iran	**GlobHor**	**DINHor**	**T_Amb**	**Globinc**	**GlobEff**	**EArray**	**E_User**	**E_Solar**	**E_Glicl**	**EFrGrld**
	kWhinf	**kWh/m'**	**°C**	**kWh/m^2**	**kWh/m^2**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**
January	77.5	35.41	0.21	118.4	116.4	242.6	3.720	1.996	223.8	1.724
February	91.3	44.45	0.98	123.6	121.2	249.1	3.360	2.018	229.7	1.342
March	130.8	62.39	4.75	154.8	151.7	307.2	3.720	2.328	283.6	1.392
April	152.7	74.98	11.43	160.8	157.3	310.4	3.600	2.440	286.2	1.160
May	186.9	80.93	15.85	182.9	178.7	347.9	3.720	2.728	320.6	0.992
Juno	209.7	70.24	20.01	196.0	191.3	363.9	3.600	2.645	335.7	0 955
July	208.3	67.59	21.43	198.4	193.8	363.8	3.720	2.709	335.3	1.011
August	190.3	65.41	21.11	196.7	192.3	357.4	3.720	2.571	329.6	1.149
September	155.7	56.22	17.47	181.6	177.8	338.8	3.600	2.350	312.9	1.250
October	114.4	44.77	12.64	150.1	147.5	287.8	3.720	2.237	265.1	1.483
November	79.5	40.89	6.98	113.9	111.7	227.0	3.600	2.017	209.1	1.583
December	66.3	35.32	2.28	102.2	100.2	209.4	3.720	2.000	192.7	1.720
Year	1663.5	678.60	11.32	1879.4	1839.9	3605.3	43.800	28.041	3324.4	15.759

Table 7 and Table 8 presents the photovoltaic system parameters and results in Tehran, Iran, and Baghdad, Iraq, per the PVsys software, detailing the basic values observed in this study.

CONCLUSION

This paper introduces a literature review that includes the reasons for the increase in the phenomenon of global warming due to the heavy reliance on traditional energy sources in urbanized countries due to the significant growth in crowded areas, which results in increased demand for energy sources and an increase in conventional energy sources, which has caused a marked increase in carbon emissions (Co_2) due to increased population activities in urbanized cities. On the other hand, the study sheds light on the researchers' visions of these challenges through previous studies, in addition to highlighting Tehran, Iran, and Baghdad, Iraq, in this study, as they are places that rely heavily on fossil fuel sources. We identified the solar energy potential of the two countries to propose a suitable photovoltaic system, as the system achieved acceptable carbon dioxide conservation rates.

Eventually, these systems are promising solutions that enable integration with national grids to meet the growing demand in crowded urban areas and reduce the exacerbation of pollution problems, especially in Tehran, Iran, as it relies on large amounts of energy from fossil fuel

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sources. Therefore, this work will be a promising step in opening sustainable horizons in Tehran and Baghdad, as it will provide a long-term green vision.

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