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Analyzing the Optimal Tilt Angles of Solar Panels to Improve the Efficiency of Solar Energy Production in Iraq

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Abstract

Considering the aspiration to achieve sustainability in various fields, including energy, this study aims to identify the optimal angles for solar panel tilt in Iraq, specifically in three cities: Baghdad, Basra, and Mosul, with the aim of promoting the use of solar energy as a clean, renewable energy source. In light of the global energy crisis, a quantitative analytical methodology was used, utilizing historical solar radiation data spanning 18 years (2006-2024) to determine the optimal angles for receiving the best amount of solar radiation. The results showed that the optimal angles ranged between 28° in Basra, 31° in Baghdad, and 33° in Mosul. The results also indicated that various climatic influences, such as high temperatures, dust, and wind speed, affected the performance of solar panels, especially in the summer and winter. Therefore, the study recommends the use of a monthly angle adjustment system to achieve solar radiation utilization using Mono-Si solar panels, given their high efficiency under the prevailing climatic conditions.

Keywords: *(Optimal Tilt Angle - Solar Panels - Solar Radiation - Efficiency - Iraqi Cities).*

Introduction

Iraq enjoys high levels of solar radiation throughout the year, making it a fertile environment suitable for exploiting solar energy, a clean and renewable resource that contributes to solving the fossil fuel crisis in Iraq in general and the world in particular. In light of the aspirations to achieve sustainability in the Iraqi energy sector, efforts have begun to focus on research and development in the field of solar energy. Solar energy is one of the richest energy resources that can be used efficiently and sustainably on the planet. Thanks to the global political trend towards integrating renewable energy into the energy mix, solar energy has received significant attention due to its environmental benefits and reduced dependence on fossil fuels. Given its abundant solar resources, the use of solar energy in Iraq is promising to supplement energy supplies, promote development, and prevent further environmental degradation.

This study aims to evaluate and compare the performance of solar energy systems installed in three Iraqi cities: Baghdad, Mosul, and Basra, when changing the cell tilt angles, and to determine the optimal angle for cell orientation, which absorbs and receives the largest amount of solar radiation. The thesis also aims to clarify the most important obstacles and challenges facing the use of solar energy in Iraq, despite the excellent and fertile environment for solar radiation, and to present proposals and solutions to overcome these obstacles. Therefore, the importance of this study lies in its comprehensive nature, as it addresses the topic of enhancing solar cell performance, determining the optimal angle, and presenting proposals to solve the challenges and obstacles facing the performance of solar systems in Iraq, especially during the summer and winter seasons, such as sandstorms, wind, dust, and rain.

The main research problem is related to Iraq's reliance on different types of traditional fossil energy systems to produce electrical energy and use it for domestic, industrial and other purposes, as Iraq is the largest oil producer in the world. This has led to the lack of development of the renewable energy sector in Iraq, especially in light of the political conflicts witnessed in Iraq, the Kuwait War and the American occupation of Iraq. However, in this recent period, efforts have begun to move towards the use of clean renewable energies to achieve economic and environmental sustainability, as solar energy is clean energy. In addition, the research that addressed the subject will not be comprehensive, and some of it was characterized by bias in data and results. In addition to the existence of some economic challenges such as the high initial cost,

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lack of funding and government support, the existence of a dilapidated infrastructure, in addition to the absence of clear legislation and laws, weak public awareness of the benefits and use of solar energy, the fragile security situation, and the poor investment situation in Iraq [2].

2. Theoretical background and literature review

This section will review the relevant literature and present the basic concepts and analytical theories in a flexible manner that enables the reader to form an insightful view of the study procedures, its objectives, its importance, the most important results it indicates, and the recommendations it offers.

Theoretical Background

The theoretical background provides a scientific basis for understanding how to efficiently exploit solar radiation, taking into account geographical, climatic, and technical factors. It also provides a framework for determining optimal angles, analyzing performance, and improving the design of solar systems in Iraq, especially under challenging environmental conditions.

Basic Concepts Solar

Energy Basics

Solar energy is radiation converted into heat energy or light from the sun for use in heating, electricity, or chemical processes. Solar energy is an abundant and renewable energy source that can be exploited at all. Solar energy can be generated from nuclear fusion in the sun, where four hydrogen protons fuse to produce helium, releasing a large amount of energy. The energy travels through space in the form of electromagnetic radiation [3]. • Solar constant: Griswold and Jain concluded that the average solar irradiance is about 1361 W/m² at the Earth's outer atmosphere perpendicular to the sun's rays. • Solar spectrum: Solar radiation covers the entire electromagnetic spectrum; ultraviolet: ~5%, visible light: ~43%, and infrared: ~52%. • Solar irradiance: The total amount of solar radiation falling on the Earth's surface over a given surface area during a given period of time. It varies with location, time of day, and prevailing atmospheric conditions at the time of occurrence.

Components Of PV Systems Solar

Panels:

These panels consist of a number of solar cells, and work to capture sunlight and convert it directly into electrical energy.

• Inverters: Convert the electricity obtained from solar panels, which is direct current (DC), into alternating current (AC) suitable for home and commercial appliances.

• Battery storage: 79 The utility company stores excess electricity produced during sunny times for use during cloudy times or at night [4].

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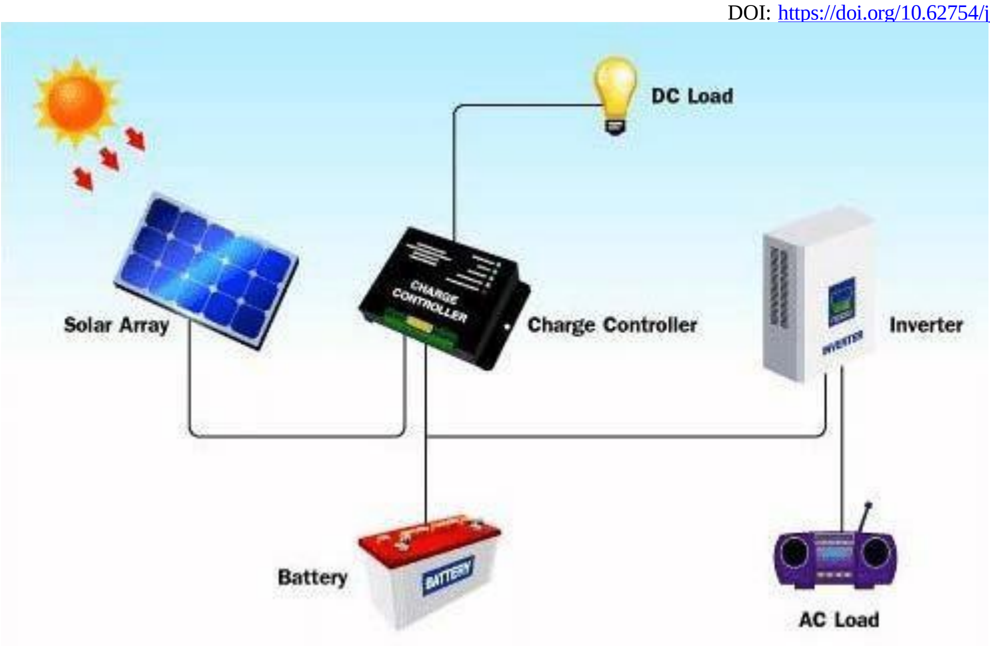

Figure 2: Shows Components of PV Systems

Optimal Tilt Angle for Solar Panels

To obtain the highest solar energy production, solar panels must be oriented at an appropriate tilt angle, which is calculated using the following equations [5]:

Optimal annual angle:

$$Tilt\ Angle\ (yearly) = |\ Latitude - 23.5\ \circ|$$

Optimal monthly angle:

$$Tilt\ Angle\ (monthly) = |\ Latitude - 23.5\ \circ \times sin(122\pi \times Month)\ |$$

Solar Energy Technologies

Solar energy can be harnessed through various technologies:

• Photovoltaic (PV) Systems: Capture sunlight more directly, turning them into electricity using solar cells.
• Solar Thermal Systems: Utilize solar radiation to heat air, water or any other fluid(s) for direct use of heat in applications such as water heating or to produce electricity (concentrating solar power systems) [6].

• Passive Solar Design: Dependent on building design for the control of solar heat collection, storage and distribution without involving mechanical systems. Such fundamentals are critical in managing and enhancing utilization of solar energy in renewable energy systems. These and other issues such as efficiency and storage make it possible for solar energy to greatly contribute to meeting the world's energy needs [7].

The importance of maintenance and operational factors (O&M):

Regular maintenance of solar energy systems plays a major role in maintaining their long-term efficiency. The most important maintenance factors include [8]:

Cleaning panels from dust and dirt

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Monitoring electrical wires and connections

Check batteries and storage systems

Factors Affecting the Efficiency of Solar Systems.

The efficiency of solar photovoltaic (PV) systems is defined by several technical, environmental, and operating factors. These factors need to be known to optimize energy production, reduce losses, and ensure long-term system efficiency [9]. The following offers a detailed overview of the key factors affecting solar system efficiency, taking lessons from your thesis material.

Environmental Factors Temperature

Effect: Efficiency of solar panels will reduce with rising temperature.

Explanation : A higher temperature increases the internal resistance of the solar cell and reduces the voltage output and efficiency.

Mathematical Representation :

$$\eta T = \eta 0 \times (1 + CT \times (T - Tref))$$

Where:

ηT: Actual efficiency at a particular temperature

$\eta 0$: Nominal efficiency under standard test conditions

CT: Temperature coefficient (usually negative, e.g., -0.4%/°C) T:

Operating temperature

Tref: Reference temperature (25°C)

Dust Accumulation

Effect : Dust deposition significantly reduces the level of sunlight incidence on the solar cells.

Explanation : Dust produces a shadow which blocks solar radiation, leading to loss of power.

Cleaning Factor :

$$\eta C = \eta 0 \times (1 + CC \times CF)$$

Where:

CF: Cleaning effectiveness factor (0 to 1) CC:

Coefficient representing dust effect

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Humidity

Effect : Condensation or corrosion on the panel surface due to high humidity. Impact

: Slightly impacts efficiency but is responsible for long-term degradation. Wind Speed

Effect : Wind cools the panels, which negates the adverse effect of hot temperatures.

Benefit : Enhanced heat dissipation improves panel efficiency.

Technical Factors

Type of Solar Panel

There are different types of solar panels with different efficiencies: Monocrystalline

(Mono-Si) : 19–22%

Polycrystalline (Poly-Si): 16–18%

Thin-FilM: 10–12%

Mono-Si panels are best suited for Iraq because they have improved efficiency and are more efficient at high temperatures.

b. Tilt Angle (Angle of Inclination)

The tilt angle has a major influence on the quantity of solar radiation received. Ideal

tilt angles depend on location:

Basra : ~28°

Baghdad : ~31°

Mosul : ~33°

Tilting the system each month can increase energy production by a maximum of 10% than systems having a single tilt.

Orientation (Azimuth Angle)

Panels should be placed south in the Northern Hemisphere to gain maximum sun.

Deviation from the ideal will lead to reduced energy output.

Operations and Maintenance-related factors Cleaning

Frequency

Regular cleaning increases panel efficiency because it removes dust and dirt. Without

cleaning, efficiency can drop by up to 30% over time.

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Cooling Mechanisms

Active cooling methods such as water spray or ventilation help reduce panel temperature and maintain efficiency.

Especially important in hot climates like Iraq.

c. System Design and Sizing

Proper system sizing ensures maximum utilization of available solar resources. Oversized

or undersized systems lead to inefficiencies and increased costs.

Geographical and Climatic Conditions

Solar Irradiance Levels :

Basra receives the highest solar irradiance (~7.68 kWh/m²/day in June).

Mosul gets minimum irradiance since it is located in the north and has a lower temperature. Weather

Patterns :

Solar availability is impacted by cloud cover as well as seasonal changes.

For instance, December is the poorest month in terms of efficiency because of low irradiance but high diffuse fraction.

Degradation Over Time

All solar panels degrade over time at a rate of around 0.5–1% per year.

Degradation is hastened by environmental stresses such as high temperatures and mechanical abrasion.

Obstacles and Challenges

There are always many challenges and obstacles in the energy sector in Iraq, whether it is traditional energy or renewable energy. The most important of these obstacles and challenges, if overcome, will enhance the performance of the energy sector in Iraq and achieve sustainability. The most important of these obstacles and challenges are:

1. Economic challenges: These challenges relate to the initial cost and the lack of investor interest in such projects, especially given the high initial cost. In addition, the operating and maintenance costs of such stations are also high.

2. Environmental challenges: Challenges related to environmental pollution and global warming, which causes air pollution when using fossil fuels. In addition, there are other environmental challenges related to renewable solar energy systems, including wind, dust, and rain, which require the formulation of strategies and visions to overcome them.

3. Technical challenges: Renewable solar energy systems and the use of smart and automated control technologies require extensive expertise to deal with them and overcome their problems, in addition to the lack of Iraqi factories specialized in solar cells, their spare parts, or the manufacture of power generation station components such as storage batteries, generators, etc., in addition to the weakness of the infrastructure in Iraq and resources [10].

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4. Societal challenges: such as the lack of awareness among most of the population of the importance of solar energy as a clean energy that does not cause environmental pollution, and that it is the future of energy, as one day non-renewable fuel sources will run out.

5. Political challenges: These are related to the political circumstances that the country is going through, which make the security situation extremely fragile, which does not encourage investors to come to Iraq, nor even Iraqi investors themselves to invest in such fields [11].

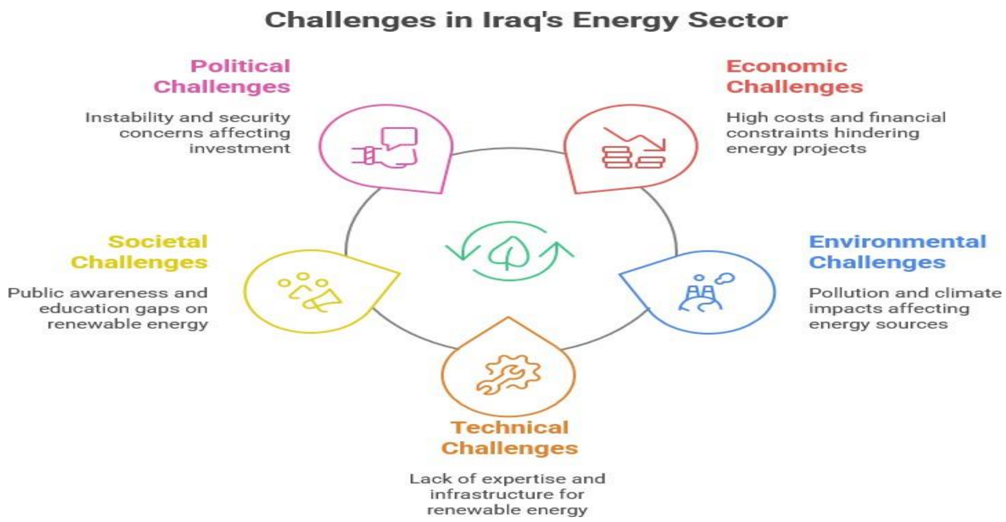

Figure 2. Shows Obstacles and Challenges

Critical Analysis of Some Previous Studies

Previous studies on the use of solar energy in Iraq present a collection of studies that focused on improving the efficiency of solar systems and addressing challenges. The following is a concise summary of the main points[12]:

Situation in Iraq: Iraq has high sunshine hours, making it ideal for solar energy applications. However, efficiency is affected by tilt, climate, and dust.

Evaluate the impact of tilt angle and climatic conditions on solar system performance and provide solutions to improve efficiency.

Use engineering management concepts to solve energy problems and provide recommendations to decision makers.

Integrating solar energy with storage and orbital energy systems, and analyzing its economic feasibility under price fluctuations.

Using solar panels on small satellites, balancing solar input against air resistance to reduce fuel consumption.

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Table 1: Shows The Strengths of Previous Studies[13-17].

Strengths	*Weaknesses*
- Context-specific to Iraqi conditions.	*- Limited to theoretical analysis and short-term measurements.*
- Provided practical recommendations for system optimization.	*- Lacked implementation data.*
- Holistic view combining technical and managerial aspects.	*- Generalized findings, not focused on specific technology.*
- Offered actionable insights for stakeholders.	*- No cost-benefit analysis.*
- Detailed economic modeling.	*- Applicability to Iraq not directly addressed.*
- Compared multiple technologies under real market conditions.	*- Lacked operational/implementation data.*
- Innovative AI-based solutions.	*- AI models not trained on Iraqi-specific data.*
- Combined qualitative and quantitative methods.	*- Focus not limited to solar energy.*
- Outperformed existing algorithms in simulations.	*- The study is technical but disconnected from real Iraqi grid data.*
- Tested on IEEE 30-bus system.	*- Focused on algorithm performance more than real-world deployment*

Methodology and Approach

The study methodology is a combination of methodologies where the descriptive methodology was used to describe the data, the analytical methodology was used to analyze the data, and the comparative methodology was used to compare the results with each other in order to achieve the main objective of the study, which is to determine the optimal cell tilt angles that make the cell absorb the largest amount of solar radiation in three major Iraqi cities: Baghdad, Mosul, and Najaf. HOMER Pro software was used to simulate hybrid systems combining solar panels and batteries. The economic and technological performance of different types of solar cells was evaluated.

Applied Framework of the Study

The applied framework of the study illustrates the study procedures and stages, starting from defining the study objective and formulating the research problem, through collecting data and processing this data statistically and manually to ensure the absence of bias in the data and results and obtaining accuracy and reliability that enhances the strength of the study. Data was collected from several different sources such as online databases, previous studies and books. The tools and materials used in the study were identified, whether simulation or statistical analysis programs, then the mathematical model and simulation model were formulated, followed by conducting the simulation, recording the results, analyzing them and evaluating them to extract conclusions and present the proposed recommendations. Figure 3 illustrates the applied framework of the study.

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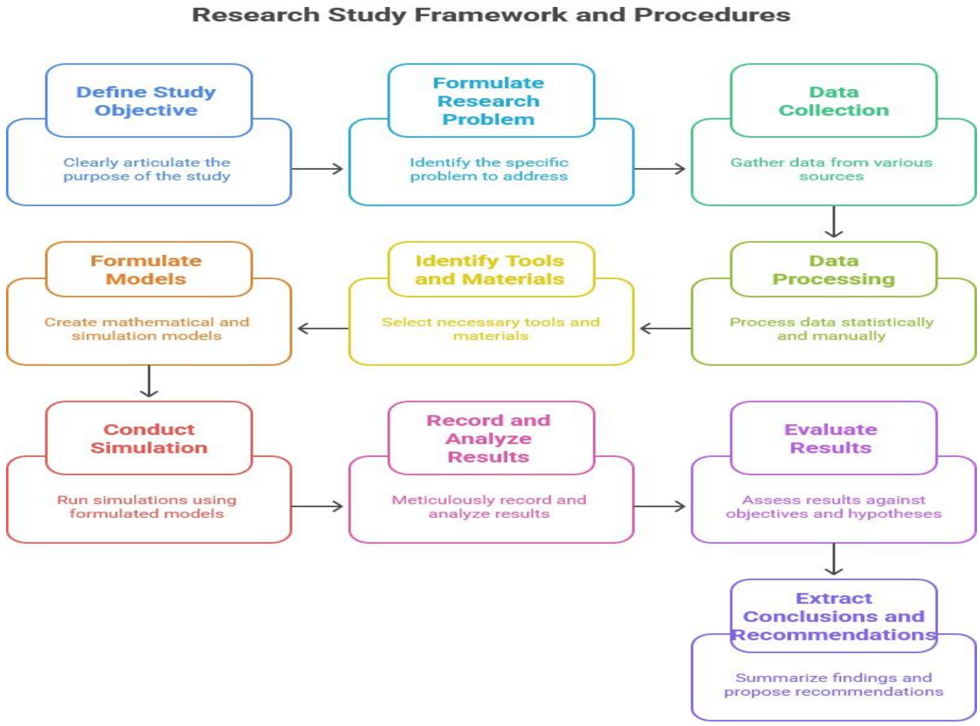

Figure 3: Shows Applied Framework of the Study

Procedures

After defining the goal and formulating the research problem related to the challenges and obstacles, whether economic, environmental, technical, or even societal or legislative, a set of steps and procedures were carried out, as follows:

1.Data Collection: Data on solar radiation on horizontal and inclined roofs were collected from official sources in three Iraqi cities: Mosul, Baghdad, and Basra Methodological data on temperature, humidity, wind speed, and dust concentration were also recorded for the past 18 years. Data were collected from various sources, including online databases, previous books and studies, the Iraqi Ministry of Electricity and Energy website, and the Iraqi Meteorological Department website.

Materials and Materials

Where a set of tools was relied upon, the most important of which are:

Data

Data related to meteorology, climate and solar radiation in the three cities

Data related to the simulation mechanism, data processing mechanism, simulation implementation, and evaluation of its results.

Tools

Where a set of tools was relied upon, the most important of which are software tools such as SPSS and statistical programs in addition to simulation programs.

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HOMER Pro software was used to simulate the system and determine the optimal cell angles in three Iraqi cities.

Formulating the Mathematical Model

A mathematical model was formulated to determine the optimal angles and the amount of radiation and energy produced throughout the year.

All of this depends on geographic location, weather conditions, and seasonal solar inclination. 1. Main Variables:

Optimal solar panel tilt angle (θ)

Incident solar radiation (H)

Annual energy production (E) ϕ:

Latitude of the site

θ: Tilt angle

δ: Declination angle (varies depending on the day of the year)

Ht: Total solar radiation on the tilted surface (kWh/m²)

Hh: Solar radiation on the horizontal surface

Rb: Ratio of direct radiation on the tilted surface to the horizontal surface A:

Solar panel area (m²)

η: System efficiency

Optimal Tilt Angle:

The optimal tilt angle is often calculated as follows:

θopt=ϕ±15∘

θopt=ϕ±15∘

In winter: θ=ϕ+15∘

θ=ϕ+15∘

In summer: θ=ϕ−15∘θ=ϕ−15∘

Annually (approximate value): θopt≈ϕ

Calculate solar radiation on an inclined surface:

$$Ht = Hh(\rho \cdot 1 - (co\ s\ \theta)/2) * ((1 - (Hh/Hb)) + (Rb \cdot (Hh/Hb) * (1 - cos\theta)/2)$$

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Where

Hb: Direct radiation

ϱ: Ground reflection coefficient (usually 0.2)

4. Calculate power output Annually:

Eyear=∑i=1365(Ht,i·A·η)

Or approximately if we have a monthly average:

Eyear≈12·(Ht,monthly avg·A·η)

Statistical Analysis

inclination. The most important of these tests are:

1. Analysis of variance (ANOVA): The aim of this test is to determine whether there are significant differences in the amount of energy produced at certain angles of inclination, where the energy produced at several different angles is calculated and the averages of the energy values at these angles are calculated, and if there are any significant differences, the energy produced at these angles is calculated[18]. If the result is significant (p-value < 0.05), it means that the angle actually affects the output power. The threshold p- value is 5%.

2. *Linear Regression or Nonlinear Regression*

Where the linear relationship between the angles of inclination of the cells and the amount of energy produced is determined, and this is done through the equation:

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \cdots + \beta kXk + \varepsilon$$

Where:

Y: Dependent variable (e.g., energy produced)

X1,X2,...,XkX1,X2,...,Xk: Independent variables (e.g., slope angle, number of sun hours, temperature)

β0: Intercept

β1,β2,...,βkβ1,β2,...,βk: Slope coefficients ε:

Random error

3. Two-sample T-test Comparing power output between two specific angles. Where one angle (such as 30°) is better than another (such as 45°), a T-test can be used to check for a significant difference.

4 Correlation Analysis: This test determines the extent of the relationship between the angle of inclination and other factors such as the amount of radiation, temperature, dust, humidity, and wind. Pearson's coefficient is used to measure the strength of the relationship between the angle and ∑XY−∑X∑Y the amount of energy produced.

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$$R = \frac{n\sum XY - \sum X \sum Y}{\sum(xi-x^{-})2\sum(yi-y^{-})2\sum(xi-x^{-})(yi-y^{-})0.5}$$

Where:

r: Correlation coefficient (ranging from -1 to +1) n:

Number of values

Xi,Yi: Individual values

X¯,Y¯¯: Arithmetic mean of X andY

Results and Discussion

Table (1) Mean and Standard deviation of H(h), H(i), H(im), and 24 hour average of temperature (degree Celsius) in 3 case studies; Basra, Baghdad, and Mosul

Variable	*Basra*	*Baghdad*	*Mosul*
Irradiation on horizontal plane (kWh/m²/mo) (MEAN ± SD)	*171.13 ± 53.188*	*165.94 ±56.490*	*156.86± 63.623*
Irradiation on optimally inclined plane (kWh/m²/mo) (MEAN ± SD)	*187.87± 33.303*	*185.50 ± 34.788*	*177.26 ± 44.582*
Irradiation on plane at angle (kWh/m²/mo) (MEAN ± SD)	*110.16± 33.303*	*113.07 ± 34.788*	*110.61± 44.582*
Monthly beam (direct) irradiation on a plane always normal to sun rays (kWh/m²/mo) (MEAN ± SD)	*161.95±33.303*	*167.05± 34.788*	*163.81 ±44.582*
24-hour average of temperature (degree Celsius) (MEAN ± SD)	*27.526± 9.889*	*25.646 ± 9.981*	*21.558±10.274*

Table (1) the radiation found in Basrah, Baghdad, and Mosul in January, the enhancement for the optimum tilt angle in terms of solar energy utilization is over and above the horizontal plane. In Basrah, where the slope optimum is 28°, the solar irradiation is always greater than horizontal type, with a varying from 120 to 170 kWh/m² for solar panels as against about 90 kWh/m² for horizontal surfaces. Likewise, the Baghdad with an optimum slope of 31° shows that the optimum slope leads to irradiation produced between 100 140 kWh/m², while a horizontal surface has fluctuating values of 70-90 kWh/m² only. Optimized for a slope of 33°, the irradiation values for a tilted surface reach 125 kWh/m², while horizontal surfaces range from 75 to 90 kWh/m². These results suggest the need for adjusting the tilt angle of solar panels depending on place; the overall radiation power at Basrah was determined to be the highest at a rate of 8.5 kW/m.h, followed by Baghdad at 7.4 kW/m.h and Mosul at 7.1 kW/m.h

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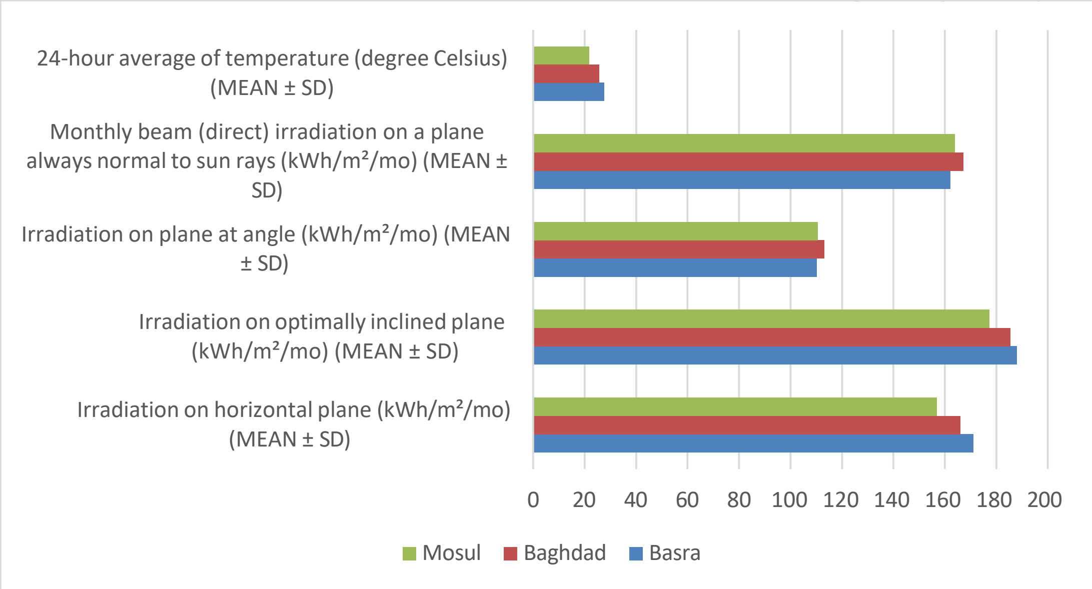

Figure 4: Comparison of the Amount of Radiation Received in Mosul, Basra and Baghdad Table

According to figure (4)Basra is the best city to be utilized for solar applications because it boasts a high average temperature during the day (~27°C) and the largest amounts of solar irradiation on every surface type, especially on optimally tilted and flat surfaces (~180 and ~160 kWh/m²/mo, respectively). Baghdad boasts moderate temperatures (~25°C) and solar irradiation levels, making it a good alternative, especially with optimally tilted panels. Mosul is the coldest (~21°C) and lowest in solar irradiation levels, representing lower solar potential with potential for improvement in efficiency by optimal panel orientation and maintenance. As expected, the overall positive relationship between temperature and solar irradiation is demonstrated, and the maximum tilting of panels maximally enhances solar energy capture for all the cities.

Table2: The Amount of Energy at the Ideal Tilt Angle Throughout the Months of the Year in Basra

month	irradiance on horizontal surface (kWh/m²/month)	Irradiance on optimum inclined surface (kWh/m²/month)	rradiance on surface at angle (kWh/m²/month)	Optimum angle	Annual irradiance at optimum angle (kWh/m²/year)
Jan	89.69	121.79	111.18	28°	2247
Feb	115.87	148.28	121	28°	2247
Mar	164.18	188.66	122.99	28°	2247
Apr	200.65	206.87	100.68	28°	2247
May	214.45	205.57	76.77	28°	2247
Jun	238.56	217.69	59.56	28°	2247
Jul	250.98	233.18	71.25	28°	2247
Aug	226.88	227.14	94.45	28°	2247
Sep	194.29	215.5	125.97	28°	2247

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Oct	148.19	182.32	137.21	28°	2247
Nov	107.78	147.87	132.96	28°	2247
Dec	103.15	152.08	149.51	28°	2247

Table 2 shows the solar radiation data for the year 2024 in Basra, with an ideal inclination angle of 28 degrees.where Annual irradiance at optimum angle 2247(kWh/m²/year) .

Table3 :The Amount of Energy at the Ideal Tilt Angle Throughout The Months of the Year In Mosul

month	irradiance on horizontal surface (kWh/m²/month)	Irradiance on optimum inclined surface (kWh/m²/month)	rradiance on surface at angle (kWh/m²/month)	Optimum angle	Annual irradiance at optimum angle (kWh/m²/year)
Jan	85.17	137.49	137.49	33°	2120.1
Feb	106.63	149.82	129.22	33°	2120.1
Mar	131.73	158.12	113.52	33°	2120.1
Apr	169.65	179.94	99.39	33°	2120.1
May	207.08	201.37	86.89	33°	2120.1
Jun	229.57	210.53	72.02	33°	2120.1
Jul	252.91	237.01	85.13	33°	2120.1
Aug	222.78	228.49	109.04	33°	2120.1
Sep	185.15	217.13	139.25	33°	2120.1
Oct	127.22	168.95	137.94	33°	2120.1
Nov	79.06	117.6	110.22	33°	2120.1
Dec	70.42	113.65	115.29	33°	2120.1

Table 2 shows the solar radiation data for the year 2024 in Mosul, with an ideal inclination angle of 33 degrees.where Annual irradiance at optimum angle2120.1(kWh/m²/year) .

Table 4: The Amount of Energy at the Ideal Tilt Angle Throughout the Months of the Year In Baghdad

month	(Optimal angle)	(Solar Radiation at Yearly Optimum Tilt Angle)
Jan	31°	2252.6 kWh/m²/year
Feb	31°	2252.6 kWh/m²/year
Mar	31°	2252.6 kWh/m²/year
Apr	31°	2252.6 kWh/m²/year
May	31°	2252.6 kWh/m²/year
Jun	31°	2252.6 kWh/m²/year
Jul	31°	2252.6 kWh/m²/year

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Aug	31°	2252.6 kWh/m²/year
Sep	31°	2252.6 kWh/m²/year
Oct	31°	2252.6 kWh/m²/year
Nov	31°	2252.6 kWh/m²/year
Dec	31°	2252.6 kWh/m²/year

Table 4 shows the solar radiation data for the year 2024 in Baghdad, with an ideal inclination angle of 31degrees. Where Annual irradiance at optimum angle2252.6.1(kWh/m²/year) .

Tables 2, 3, and 4 show solar radiation data for 2024 in Basra, Baghdad, and Mosul. In the left corner of each graph, along the horizontal axis, the "monthly optimum" and "annual optimum" solar radiation in kWh/m²/month are indicated. In the three cities, solar radiation follows a similar pattern: it rises from the first months and reaches its highest value midway through the year, especially in the middle of the second half, and its lowest value at the end of the year. Basra: Solar radiation peaks in the summer (around 250 kWh/m²/month in the case of monthly optimization), which corresponds to the highest solar exposure level in the city. The annual optimum remains significantly lower than the monthly optimum. Baghdad: Its trends are also similar to Basra's, but with lower values: Baghdad's maximum solar radiation reaches just under 250 kWh/m² per month and year, the monthly optimum in the middle of the year. Mosul: The direction of solar radiation received in Mosul is similar to that of Baghdad and Basra, but its maximum values are slightly lower, possibly due to the city's higher latitude.

The solar radiation levels for Basra, Baghdad, and Mosul across the months of 2024.

The graph illustrates monthly and yearly optimal rates of solar irradiation for Basra, Baghdad, and Mosul in 2024. Basra gets the maximum solar radiation throughout the year with a value of around 250 kWh/m²/mo in July in monthly optimal cases, and maintains high values (~200–220 kWh/m²/mo) during the entire year with annual optimum tilt. Baghdad possesses the same summer peak but slightly lower values overall. Mosul has the least solar irradiation, with the summer maximum around 220 kWh/m²/mo and major drops during winter. The difference between the optimum monthly and annual curves shows that the tilt angles of the panels should be adjusted monthly to attain optimal efficiency, especially where seasonality is high like in Baghdad and Mosul. Basra, due to its high and flat solar potential, remains the best location for solar energy installation[19].

Conclusions

Based on the results obtained, we can present the most important main conclusions of this study, which are as follows:

• The three cities—Baghdad, Basra, and Mosul—show strong suitability for solar energy deployment, with stable solar radiation levels throughout the year. Basra recorded the highest monthly average solar radiation at the inclined plane (187.88 kWh/m²), followed by Baghdad (185.51 kWh/m²), and then Mosul (177.26 kWh/m²).

The optimal angles ranged from 28° in Basra, 31° in Baghdad, and 33° in Mosul. The results also indicated that various climatic influences, such as high temperatures, dust, and wind speed, affected solar panel performance, especially during the summer.

• The data confirmed the impact of dust on solar performance, especially in southern cities such as Basra. This underscores the need to design cleaning strategies, and perhaps incorporate self-cleaning coatings or robotic cleaning systems in the future [20].

• Solar energy is a very promising solution for Iraq's energy future. Through appropriate design adjustments to suit each city's climate, including panel type, tilt angle, and cleaning procedures, Iraq can create a sustainable and reliable solar energy infrastructure that supports both on- and off-grid applications[21].

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The most significant challenges facing the use of solar energy in Iraq include:

Economic challenges related to cost, operation, maintenance, and high initial costs.

Environmental challenges related to wind, dust, and sand, which affect solar panels.

Political challenges related to the political and security situation.

Technical challenges related to dilapidated infrastructure, weak resources, and a lack of expertise. Legislative challenges related to the bureaucracy in Iraq and the lack of specific laws and regulations. Societal challenges related to the lack of awareness among Iraqis about renewable energy and its importance

Recommendations

Based on the results of the study, some suggestions and recommendations can be made to enhance the performance and integration of the solar energy system. The most important of these recommendations are:

Using artificial intelligence and deep machine learning techniques to formulate models that predict the performance of solar systems and determine optimal operating conditions, such as cell angles, energy storage systems, and other factors affecting solar system efficiency.

Integrating advanced storage systems, such as lithium-ion batteries or flow batteries, to improve outage management and enhance energy reliability.

To achieve maximum benefit from solar radiation, we use Mono-Si solar panels due to their high efficiency under prevailing climatic conditions.

Conduct further studies and research on the economic and social impact of solar energy projects in Iraq, as well as the most significant current and future obstacles and challenges and formulate visions and strategies to overcome these obstacles.

Conflict of Interest

There is no conflict of interest.

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