"تحديات وآفاق نظام الطاقة الكهربائية في محافظة الأنبار – العراق"

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Challenges and Prospects of the Electrical Energy System in Al-Anbar Governorate – Iraq

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المستخلص

تعاني محافظة الأنبار من تحديات جوهرية في منظومة الطاقة الكهربائية، تُعزى بشكل رئيس إلى تدهور البنية التحتية، وضعف كفاءة شبكات النقل والتوزيع، وارتفاع معدلات الفاقد الفني، فضلاً عن تزايد الطلب على الطاقة الكهربائية نتيجة النمو السكاني والتوسع العمراني.

تشير البيانات الإحصائية للفترة ٢٠٢٠–٢٠٢٤ إلى أن العجز السنوي في الطاقة بلغ ٦٨٤ ميغاواط خلال عام ٢٠٢١. كما بلغ إجمالي الفاقد الناتج عن الأعطال الفنية والحوادث التشغيلية نحو ٣,٨٤٧.٢ ميغاواط في عام ٢٠٢٤، إذ سجل الجزء الشرقي من المحافظة أعلى نسبة فاقد بلغت ٥٦.٤%،أوضحت الدراسة أن القصور الإداري، وغياب التخطيط الاستراتيجي طويل المدى، وضعف التنسيق المؤسسي بين الجهات ذات العلاقة، وتأخر تنفيذ المشاريع الحيوية، ساهمت مساهمة مباشرة في تدني كفاءة المنظومة الكهربائية. كما فاقمت من المشكلة الحوادث الأمنية التي استهدفت خطوط النقل والمحطات التحويلية، واعتماد العدادات التقليدية، وسلوكيات الاستهلاك غير الرشيد لدى المستهلكين ، بيّنت تحليلات مصادر الطاقة المتجددة وجود إمكانات واعدة للاستفادة من الطاقة الشمسية، إذ بلغ معدل الإشعاع الشمسي السنوي ٥٣٧.١ ميغاواط·ساعة/م²/يوم في محطة الرطبة. كما أظهرت مناطق القائم والنخيب إمكانية استغلال طاقة الرياح، حيث بلغ متوسط سرعة الرياح السنوي ٣.٨ م/ث. عليه، توصي الدراسة بضرورة تطوير البنية التحتية، وتحديث شبكات النقل والتوزيع، ونشر العدادات الذكية، وإنشاء محطات توليد شمسية ومزارع رياح، بما يسهم في تقليل الفاقد وضمان إمداد كهربائي مستقر ومستدام في المحافظة.

الكلمات المفتاحية: الطاقة الكهربائية؛ محافظة الأنبار؛ الفاقد الكهربائي؛ الطاقة الشمسية؛ طاقة الرياح؛ استدامة الطاقة

Abstract

Al-Anbar Governorate faces significant challenges in its electrical energy system due to deteriorating infrastructure, weak transmission and distribution networks, high rates of technical losses, and increased electricity demand driven by population growth and urban expansion. Data for the period 2020–2024 indicate that the annual deficit reached 684 MW in 2021, while the total losses from technical failures and accidents in 2024 amounted to approximately 3,847.2 MW, with the highest losses observed in the eastern part of the governorate at 56.4%.

The study reveals that administrative shortcomings, lack of strategic planning, poor coordination among authorities, and delays in implementing essential projects have directly contributed to the inefficiency of the electrical system. Additionally, security incidents affecting transmission lines and substations, the use of conventional meters, and improper electricity consumption by residents have exacerbated the problems.

Renewable energy analyses indicate the potential for solar energy utilization, with an annual radiation rate of 537.1 MW/m²/day at the Rutba station, and wind energy exploitation in areas such as Al-Qa'im and Nukhaib, where the annual average wind speed reaches 3.8 m/s. Accordingly, the study recommends developing infrastructure, upgrading transmission and distribution networks, installing smart meters, and establishing solar power plants and wind farms to reduce losses and ensure stable and sustainable electricity supply in the governorate.

Keywords: Electrical Energy, Al-Anbar Governorate, Electrical Losses, Solar Energy, Wind Energy, Energy Sustainability

بسم الله الرحمن الرحيم

Introduction

Electrical energy is considered the backbone of modern life, serving as a fundamental pillar for economic and social development and regarded as the primary indicator for measuring a country's level of progress. It is directly linked to the operation of industrial, agricultural, health, and educational sectors, while also contributing to improving quality of life and enhancing citizens' welfare. Reports from the International Energy Agency (IEA, 2021) indicate that the stability of electricity supply is positively correlated with higher economic growth rates and improved human development indices.

In Iraq, the electricity crisis has emerged as a major structural problem since the 1990s. Wars, international sanctions, and insufficient investment in the energy sector have exacerbated the challenges within the electrical system. These challenges span technical aspects, including outdated generation plants, frequent failures, and high transmission and distribution losses; administrative aspects, such as weak planning and poor resource management; and security-related issues, which have led to the destruction of extensive infrastructure, particularly in western governorates like Al-Anbar (Al-Janabi, 2019; Hassan et al., 2021).

Local studies have addressed this issue from various perspectives. Al-Shammari (2018) focused on technical losses in transmission and distribution networks, reporting that losses exceed 40% of generated electricity. Al-Janabi (2019) examined administrative shortcomings and weak governmental policies in the electricity sector, while Mohammed (2020) highlighted the impact of security conditions on the disruption of generation plants in Al-Anbar, Salahuddin, and Nineveh. Al-Obaidi (2022) investigated renewable energy alternatives in Iraq, noting limited investment in solar and wind energy despite significant potential. However, these studies often focused on Iraq as a whole, without deeply analyzing the specific conditions of Al-Anbar Governorate, which has experienced exceptional security and social challenges directly affecting electricity provision.

At the regional level, Abdul-Rahman (2017) addressed the electricity crisis in Egypt prior to the expansion of natural gas plants, highlighting the impact of transmission and distribution bottlenecks on economic performance. Al-Khaldi (2019) examined Jordan's experience in integrating solar energy into the energy mix, emphasizing the success of government policies in reducing dependence on fossil fuels. Globally, several studies have focused on chronic electricity challenges in developing and conflict-affected regions. Karekezi & Kimani (2019) discussed challenges in East African power networks, Bhattacharyya (2020) emphasized the effects of poor governance on spatial electricity distribution in South Asia, and Sovacool (2021) highlighted the environmental and social consequences of reliance on private generators in areas experiencing frequent power outages.

Comparing the situation in Al-Anbar with these international experiences reveals common challenges such as technical losses and weak management. However, the Iraqi context is distinct due to the added complexity of an unstable security and political environment. While countries like Egypt and Jordan have mitigated crises through strategic planning and investment in renewable energy, Iraq in general, and Al-Anbar in particular, continue to face accumulated structural problems hindering the stability of the electrical system.

A review of the literature indicates a knowledge gap: there is a lack of comprehensive studies that integrate technical, administrative, security, and consumption-related challenges facing the electricity system in Al-Anbar, while providing practical solutions aligned with sustainability and renewable energy integration. Based on this gap, the present study aims to analyze the current state of the electricity system in Al-Anbar, identify its core problems, investigate their causes and implications for local development, and explore potential future solutions, including the integration of renewable energy into the energy mix as a strategic option for achieving stability and sustainable development.

Study Area

The study focuses on Al-Anbar Governorate in western Iraq, which is one of the largest governorates in terms of area in the country. It shares borders with three countries: the Syrian Arab Republic, the Hashemite Kingdom of Jordan, and the Kingdom of Saudi Arabia. The governorate is characterized by desert terrain and extensive plains, in addition to the presence of the Euphrates River, which serves as the main water resource for the region. Its unique geographical location makes it a strategically important area for studying the electrical energy system, particularly given the climatic, geographical, and demographic challenges it faces.

Al-Anbar has a continental desert climate, with high temperatures in summer and relatively cold winters. The governorate also experiences high solar radiation levels throughout the year (515–537 $MW/m^2/day$), making it suitable for exploring solar energy applications. Moreover, the region is characterized by prevalent northwestern winds, with an annual average speed of 3.1 m/s, which is favorable for wind power

generation in selected sites such as Nukhaib, Al-Qa'im, and Haditha, Fig. (1).
The main population centers are distributed across the eastern, western, and central parts of the governorate, leading to uneven electricity demand and increased pressure on the distribution network. Additionally, vast uninhabited areas are available, suitable for establishing solar power plants and wind farms.

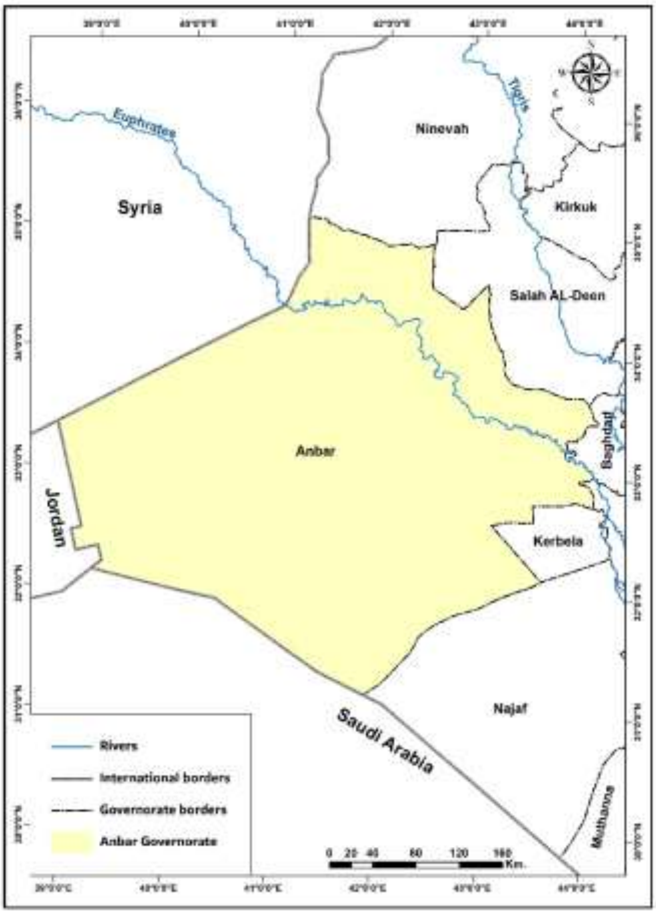


Figure (1): Iraq and the Location of Al-Anbar Governorate
Source: Ministry of Water Resources, General Directorate of Survey, Maps Production Department, Digital Unit, Administrative Map of Iraq, Scale (1:500,000), Baghdad, 2024.

Materials and Data

The study relied on a set of primary and secondary data collected and analyzed to assess the status and challenges of the electrical energy system, as detailed below:

1. Technical and Statistical Data of the Electrical Energy System:

- Data on faults and accidents in transmission and distribution networks and power generation stations for the year 2024 from the Ministry of Electricity, Directorate of Electricity Distribution – Al-Anbar, and Directorate of Power Transmission. This includes technical failures, energy losses, and supplied loads and deficits (MW).

- Data on electricity consumption by household appliances and daily usage patterns for 2024, including air conditioners, water heaters, electric heaters, and refrigerators, to estimate human consumption patterns and their impact on the system.

2. Population and Planning Data:

- Population numbers for the period 2020–2024 from the Ministry of Planning, Directorate of Statistics, to determine the expected electricity demand and deficit rates across different years.

3. Climatic and Renewable Energy Data:

- Monthly and annual solar radiation data for the period 1991–2023 from the Ministry of Transport, Iraqi General Authority of Meteorology and Seismology, Climate Department.

o Wind speed, direction, and frequency data for the same period to assess the potential for wind power generation.

4. **Maps and Locations:**

o Administrative map of Al-Anbar Governorate at a scale of 1:500,000 to identify optimal locations for establishing solar power plants and wind farms, considering proximity to substations, transmission networks, and available uninhabited land.

5. **Secondary Data and Electronic Sources:**

o Articles, reports, and online sources to illustrate international and local experiences in implementing solar and wind energy, including projects in the UK, Taiwan, Egypt, and Jordan.

o Scientific references to clarify the characteristics of solar radiation and wind, and to compare the potential of Al-Anbar Governorate with similar regions globally.

Results and Discussion

Challenges of the Electrical Energy System in Al-Anbar Governorate

The electrical energy system in Al-Anbar Governorate faces multiple challenges that directly or indirectly affect the stability of electricity supply. The indirect factors influencing load management and production include administrative shortcomings, future planning deficits, and bureaucratic obstacles that hinder the mitigation of electricity deficits across all components of the system. Direct factors contributing immediately to electricity shortages are primarily technical and security-related, while human-related consumption patterns also exacerbate the problems.

1. Administrative and Planning Challenges

The electricity system in many regions of Iraq, including Al-Anbar (the study area), suffers from various administrative and planning deficiencies that negatively impact production, transmission, and distribution efficiency. At the administrative level, the main challenges include insufficient human and financial resources. There is an uneven distribution of technical and administrative staff, resulting in reduced overall performance. In some areas, overcrowding of personnel further impedes proper operation. Administrative bureaucracy complicates procedures and delays the implementation of critical projects, leading to resource wastage and hindering the development of this essential sector. Additionally, a significant lack of coordination among institutions responsible for electricity has caused overlapping authorities and weak integration, preventing effective identification and resolution of technical and administrative issues and accumulation of faults.

From a planning perspective, the absence of long-term strategic vision is evident, with reliance on short-term, reactive measures rather than comprehensive plans that account for population growth, urban expansion, and future economic needs. For example, several diesel-powered generation stations were established in various districts; however, due to high operational costs and frequent malfunctions, these stations ceased to function effectively, failing to meet local electricity needs and becoming a burden on the system rather than a solution. Similarly, efforts to extend transmission lines to support the system and relieve load pressures are often delayed for years due to the need for official approvals from other authorities, resulting in project cancellations or reassignment to external beneficiaries.

Moreover, poor site selection for new stations, aging transmission networks, and overloading of the distribution network—exacerbated by the lack of modernization and expansion, and disregard for urban growth and population distribution—have significantly intensified network congestion and losses. Delays in implementing strategic projects further reflect shortcomings in planning due to administrative, financial, and security challenges. Chronic neglect of routine maintenance and rehabilitation has also led to severe deterioration of the electricity infrastructure, increasing rates of outages and system failures.

2. Technical and Security Challenges

The study area faces numerous challenges that directly affect the continuity and efficiency of electricity supply, primarily technical and security-related issues. Technical problems have become a major cause of electricity interruptions in recent years. One of the main challenges is the weak infrastructure of the electrical system, resulting from aging components at generation stations, substations, and transmission and distribution networks. Many facilities have not undergone maintenance, modernization, or expansion to relieve operational pressure over long periods.

The generation capacity is insufficient relative to the increasing electricity demand, forcing reliance on private generators to compensate for supply shortages. The network also suffers from substantial transmission losses. Table (1) and Figure (2) illustrate the monthly energy losses, indicating inefficiencies in transmission lines and the lack of modern monitoring systems to reduce technical failures. A shortage of specialized personnel and

inadequate equipment further hampers the system's ability to maintain a continuous and reliable electricity supply.
Additionally, the system experiences voltage fluctuations, which affect the performance of electrical devices and critical facilities. Most consumer meters remain conventional, prone to frequent malfunctions or absence in many locations, preventing effective consumption monitoring and detection of electricity theft. Consequently, total faults and incidents in the past year were very high, amounting to 1,474.8 MW across distribution branches, with an average monthly failure rate of 122.8 MW.

District	**Eastern Anbar**		**Western Anbar**		**Central Anbar**		**Total**	
	Distribution	Transmission	Distribution	Transmission	Distribution	Transmission	Distribution	Transmission
December	22.7	95.8	43.2	83.0	29.9	151.1	95.8	329.9
February	35.4	87.2	42.2	83.5	23.3	120.1	100.9	290.8
March	29.1	47.9	38.8	107.0	0.0	3.1	67.9	158.0
April	37.6	116.6	52.5	176.8	11.7	51.5	101.8	344.9
May	32.9	164.1	14.7	41.0	39.6	104.7	87.2	309.8
June	97.5	294.2	10.5	44.5	96.4	100.7	204.4	439.4
July	99.2	298.1	16.0	27.3	143.3	23.0	258.5	348.4
August	95.4	285.9	17.5	46.9	14.4	78.7	127.3	410.6
September	66.0	235.1	10.7	34.0	20.1	102.3	96.8	371.4
October	8.2	123.4	10.3	24.3	35.9	21.1	54.4	168.8
November	14.5	132.7	16.4	52.6	45.3	25.7	76.2	211.0
December	124.7	243.1	46.2	142.9	32.7	78.2	203.6	464.2
Total	**634.1**	**2124.1**	**319.0**	**863.8**	**492.6**	**860.2**		

Table (١): Power Losses due to Technical Failures and Accidents in the Electrical Energy System of Al-Anbar Governorate for the Year 2024 (MW)

Source: Prepared by the researcher based on:

1. Ministry of Electricity, Directorate of Electricity Distribution – Central Region, Al-Anbar Branch, Control Department, *Unpublished Data*, 2024.

2. Ministry of Electricity, Directorate of Power Transmission – Central Region, Al-Anbar Branch, Lines and Cables Department, *Unpublished Data*, 2024.

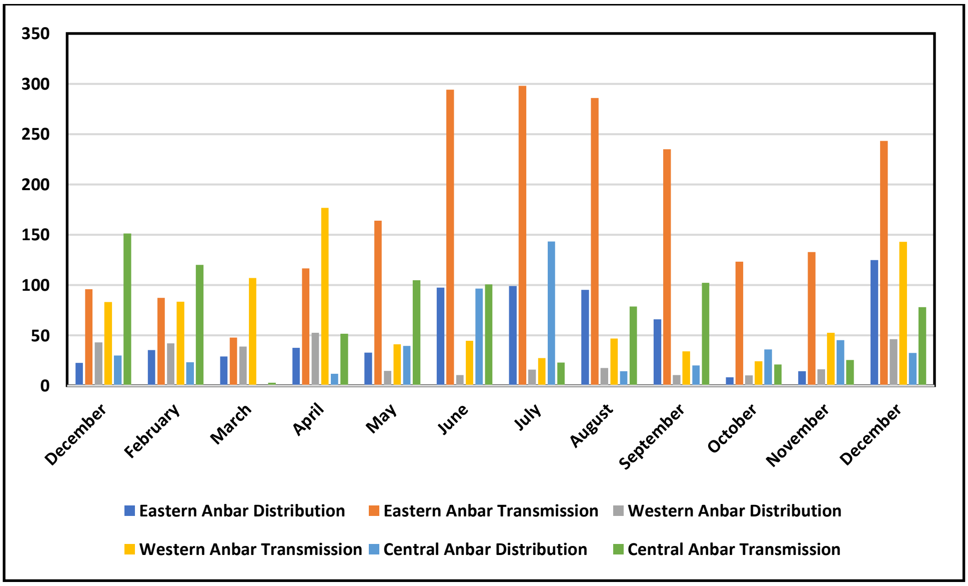


Figure (2): Power Losses due to Technical Failures and Accidents in the Electrical Energy System of Al-Anbar Governorate for the Year 2024 (MW)
Source: Prepared by the researcher based on Table (١).

Based on the above, several months recorded more than 400 faults and incidents, indicating periods of high stress on the network corresponding to peak electricity demand. Conversely, months with lower numbers of incidents coincide with reduced electricity demand, resulting in improved system performance. The eastern part of Al-Anbar experienced the highest incidence of faults and outages, while the western part recorded the lowest. Among the distribution branches, the central Al-Anbar branch had the lowest transmission losses at 780.1 MW, representing 20.7% of total faults and incidents. This reflects pressure on the central distribution network supplying both the eastern and western regions, as well as weak coordination among control centers and distribution units in the study area.

The overall high rate of faults points to chronic issues within the transmission and distribution networks, including insufficient routine maintenance, outdated infrastructure, weak investments, and the impact of political conflicts and environmental factors on system performance. In terms of transmission-related losses, the total energy lost due to faults and incidents in 2024 reached 3,847.2 MW across the transmission branches in the study area. The highest losses occurred in the eastern transmission network, amounting to 2,124 MW (56.4%), primarily due to weak network infrastructure, overlapping high-, medium-, and extra-high-voltage lines, population density, industrial and commercial load pressures, and occasional sabotage of transmission lines. In contrast, the western network recorded losses of 863.8 MW (22.9%), attributed to the extensive geographic spread of lines, long distances, challenging terrain and climatic conditions, and logistical difficulties in reaching and repairing fault points.

Regarding security challenges, Al-Anbar has been one of the most unstable governorates, subject to repeated attacks by terrorist and ISIS-affiliated groups targeting public infrastructure, particularly the electricity system. Transmission towers and lines have suffered repeated assaults, and the vast extent of the network makes full protection impossible. Security forces have implemented protective measures, including installing surveillance towers at key points and substations, and conducting regular patrols throughout the day. Furthermore, during periods of ISIS control, theft and sabotage of transformers and electrical cables at power stations caused prolonged service disruptions. Technical teams also face difficulties accessing remote areas or those experiencing security tensions, hindering regular maintenance and repair efforts, thereby impacting the reliability and continuity of electricity supply.

Figure (2): Some of the towers subjected to sabotage
Source: https://baghdadtoday.news/160735--.html

3. Electricity Consumption Challenges

Al-Anbar Governorate, like other Iraqi provinces, faces numerous challenges related to electricity consumption, reflecting significant economic, service-related, and social dimensions. Despite the large area of the governorate and the diversity of its economic activities, the electricity sector continues to suffer from chronic problems, including voltage fluctuations and high technical losses. Population growth, urban expansion, and elevated summer temperatures have increased pressure on the electricity network, particularly in areas with insufficient or deteriorating infrastructure, exacerbating investment challenges and making electricity delivery to rural and remote areas more difficult.

According to Table (2) and Figure (3), the supplied electricity over the past five years has varied depending on the production and transformation capacity provided by the Ministry of Electricity for each governorate and on population numbers. For instance, the highest electricity supply occurred in 2022, reaching 859 MW. Despite this level of supply, the electricity deficit in the same year amounted to 311 MW. This deficit is attributed to a rise in the population, which increased electricity demand, and the expansion of complex residential projects in the study area, further elevating the demand for electricity.

Conversely, the lowest electricity supply was recorded in 2020 at 526 MW, with a corresponding deficit of 100 MW. This was largely due to instability in the study area during that period, as many residents had not yet returned to the districts and subdistricts. Additionally, electricity projects and transmission lines in several areas of the study region had been destroyed during liberation operations from ISIS, further reducing supply capacity and contributing to the deficit.

No.	Year	Population	Average Required Load (MW)	Average Supplied Load (MW)	Average Deficit (MW)
1	2020	1,865,818	625	525	100
2	2021	1,914,165	1,277	593	684
3	2022	1,963,346	1,170	895	311
4	2023	2,013,300	1,186	761	425
5	2024	2,166,422	1,215	842	373

Table (2): Average Supplied Loads and Deficits According to the Population of Al-Anbar Governorate for the Period (2020–2024) (MW × 1000)

Source: Prepared by the researcher based on:

1. Ministry of Planning, Population Statistics Department, Directorate of Statistics – Al-Anbar Governorate, *Annual Statistics for the Years (2020–2024)*, Unpublished Data.
2. Ministry of Electricity, Directorate of Planning and Studies, Statistics and GIS Department, *Annual Statistical Report for the Years (2020–2024)*, Unpublished Data.

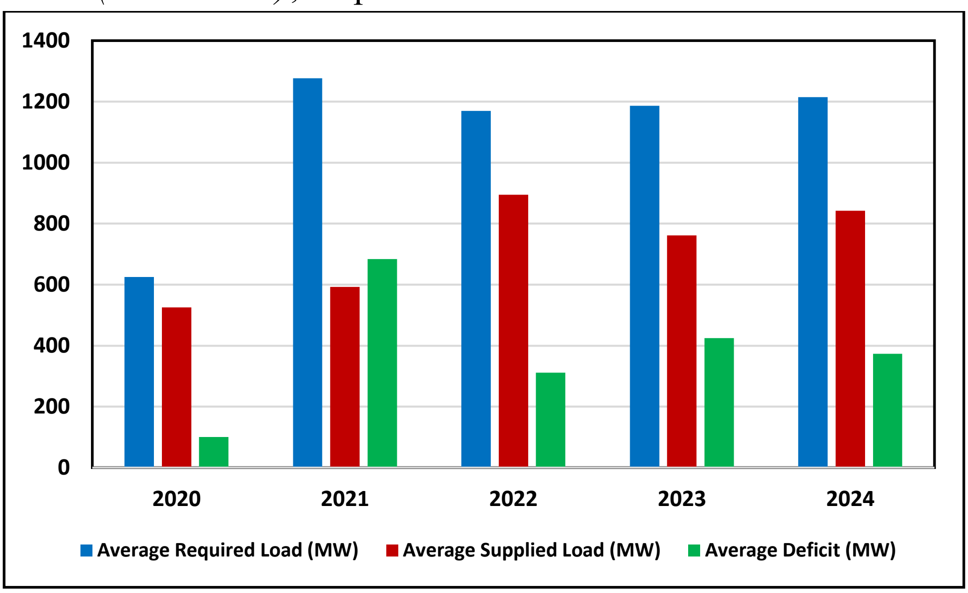


Figure (3): Loads, Supplied Energy, and Deficits in Al-Anbar Governorate for the Year 2024

Source: Prepared by the researcher based on Table (٢).

Misuse of Electricity by Residents

Improper electricity consumption by residents in the study area has exacerbated challenges within the electrical energy system. Electricity production requires substantial financial investments and large-scale projects to meet consumer demand through an integrated system encompassing generation, transmission, and distribution. In addition, operational costs such as fuel, maintenance, personnel salaries, and other expenditures place a significant burden on the state budget. However, these expenditures do not always generate sufficient returns to offset the costs incurred by the government. Table (3) illustrates the average operating capacity of essential household appliances for a typical medium-sized residential unit.

Device Type & Quantity	**Device Capacity (W)**	**Consumption in Summer**		**Consumption in Winter**	
		Watt-hour	MW	Watt-hour	MW
Freezer (1)	1×350	75,758,200	75.7	75,758,200	75.7
Refrigerator (1)	1×200	43,290,400	43.2	43,290,400	43.2
Lamps (6)	6×50	64,935,600	64.9	64,935,600	64.9
Air Cooler (1)	1×250	5,411,300	54.1	—	—
Air Conditioner (2 tons)	1×3500	757,582,000	757.5	—	—
Electric Heater (1)	1×1500	—	—	324,678,000	324.6
Electric Water Heater (1)	1×2500	—	—	541,130,000	541.1
Total	8,600	946,977,500	946.9	1,049,792,200	1,049.7

Table (3): Average Household Appliance Loads (Watt-hour per Residential Unit)

Source: Prepared by the researcher based on:

1. Ministry of Electricity, Directorate of Distribution – Central Region, Directorate of Electricity Distribution – Al-Anbar, Statistics and Data Department, *Unpublished Data*, 2024.
2. Ministry of Planning, Directorate of Statistics, Statistical Group for the Year 2024, *Population and Labor Force Statistics*, p. 52.
3. Household Consumption Calculation: Number of residential units in Al-Anbar Governorate (216,452) × Device Capacity ÷ 1,000,000 Watt (1 MW = 1,000,000 Watt).

Average Household Electricity Consumption and Daily Load Patterns

The average electricity consumption for a medium-sized household reached 8,600 W, equivalent to 8.6 kW. Among household appliances, the highest electricity consumers are air conditioners, water heaters, and electric heaters, with seasonal variations in demand. A 2-ton air conditioner consumes 3,500 W, an electric water heater consumes 2,500 W, and an electric heater consumes 1,500 W.

Electricity consumption varies significantly by season. Water heaters are generally unused during summer, while their consumption peaks in winter. Similarly, electric heaters are primarily used in winter, whereas air conditioners are mainly used in summer. Certain appliances, such as freezers, refrigerators, and lighting, operate year-round, maintaining continuous electricity consumption.

Regarding daily consumption patterns, Table (4) illustrates electricity use by hour. As shown in Table (4) and Figure (4), the lowest consumption occurs at 3:00 AM, with 555 MW, due to most residents sleeping, the closure of commercial markets, and the suspension of industrial and governmental activities. Conversely, peak consumption occurs at 10:00 PM, reflecting the high demand from commercial activity in markets and shops, as well as intensive household electricity use.

Hour	**Load (MW)**
1	578
2	563
3	555
4	570
5	585
6	645
7	660
8	690
9	694
10	701
11	713
12	720
13	713
14	713
15	713
16	713
17	713
18	705
19	728
20	750
21	728
22	698
23	690
24	668
Total (MWh)	**16,206**
Average (MW)	**675**

Table (4): Electricity Consumption During the 24 Hours of the Day in Al-Anbar Governorate on 15-04-2024

Source: Prepared by the researcher based on: Ministry of Electricity, Directorate of Electricity Distribution – Central Region, Al-Anbar Branch, National Control Department, *24-Hour Load Tables*.

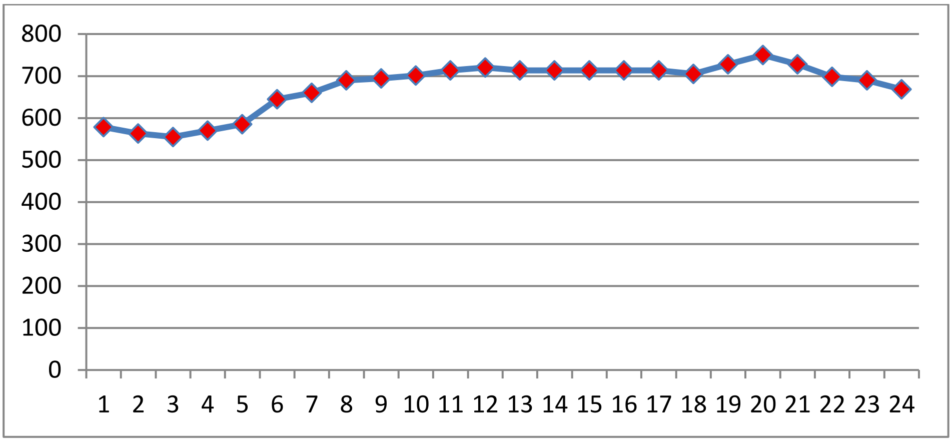


Figure (4): Electricity Consumption During the 24 Hours of the Day in Al-Anbar Governorate on 15-04-2024
Source: Prepared by the researcher based on Table (٤).

Electricity Solutions and Future Prospects
Despite the natural, climatic, and strategic location advantages of Al-Anbar Governorate, which borders Syria, Jordan, and Saudi Arabia, and has a large area suitable for supporting electricity production, the governorate suffers from a significant shortage in production and distribution, especially after the extensive destruction of infrastructure due to wars and armed conflicts. Therefore, practical solutions are required to develop the electricity sector, ensure sustainable energy supply, and reduce service fluctuations.

1. Developing the Current Electricity Sector
The current situation necessitates urgent measures to reduce the gap between production and consumption. The key steps can be summarized as follows:

1. Upgrading the Electricity Infrastructure

- Power Generation Stations: Most of them are out of service or operate at low capacity due to old age, destruction, or improper planning, such as the Fallujah Thermal Diesel Plant and Ramadi Gas Plant.
- Transmission Networks: They suffer from significant deterioration due to aging lines, climatic changes, and war damages.
- Local Production Dependence: Although the national grid covers part of the needs, frequent interruptions require establishing local power plants to meet demand sustainably.
- High Demand: The return of displaced people and economic activity increases the pressure on the system, necessitating urgent solutions.
- Lack of Strategic Planning for Renewable Energy: Limited government and private sector investments leave the future uncertain without clear solutions.

2. Mobile Power Stations

Many mobile stations were deployed after the destruction of primary plants. Since they are not integrated into electronic monitoring systems, reliance on them should be reduced and replaced with fixed plants that allow better load management and consumption control.

3. Capacitors and Reactors

Installing high-quality capacitors and reactors in all stations is essential to stabilize electrical current, especially in stations far from production sources, while considering the desert climate to prevent frequent failures.

4. Establishing New Power Plants

The governorate has only one hydroelectric plant with limited output due to variable water flow and low rainfall. Linking it to the national grid also restricts local coverage. It is essential to establish new 400 kV gas-based plants using local gas from the Akkaz field and convert existing diesel and oil-fired stations in Fallujah, Ramadi, Hit, and Haditha to gas, creating a surplus that can support the national grid.

5. Enhancing Private Sector Partnerships

Considering the large investment requirements, the government should open investment opportunities using BOT and PPP models, offering incentives to investors, particularly in clean energy, as applied successfully in countries like the UK, Taiwan, Egypt, and Jordan.

6. Improving Electricity Management

Installing smart meters, updating distribution and transmission networks, launching awareness campaigns to rationalize consumption, and imposing penalties for energy wastage are measures that reduce losses and improve network stability.

2. Future Prospects and Transition to Renewable Energy

Transitioning to renewable energy sources is a key opportunity for achieving sustainable development. Al-Anbar possesses abundant solar and wind energy potential, which requires a clear strategy involving government, local authorities, private sector partnerships, and international and regional support.

2.1 Solar Energy

Solar energy involves converting sunlight into electricity using photovoltaic cells and is one of the fastest-growing renewable energy sources. The sun provides continuous energy, with the Earth receiving approximately 57×10^6 calories per minute, equivalent to about one billion MW (Al-Mohammedi, 2003).

Solar energy is sustainable, easy to use, and environmentally friendly, unlike fossil fuels, which are polluting and depletable. Al-Anbar's geographic location provides high solar radiation due to long daylight hours, clear skies, and an optimal sun angle for most days of the year.

Table (5) and Figure (5, 6) illustrate the monthly solar radiation levels, showing that June recorded the highest solar intensity across key stations: Ramadi, Rutbah, Haditha, An-Nukhayb, and Ana. This offers excellent opportunities for continuous and sustainable electricity generation for all sectors in the governorate.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Ramadi	329.1	388.5	478.3	560.5	465.1	751.2	722.4	708.6	610.5	445.8	329.1	264.2	515.6
Rutba	349.6	394.3	501.6	609.8	670.3	774.5	773.1	722.5	606.3	462.5	349.6	279.2	537.1
Haditha	291.3	390.5	485.4	573.5	680.4	764.8	761.2	704.3	591.6	444.6	326.1	255.7	522.5
Nukhaib	298.8	394.1	504.3	589.9	674.3	770.4	770.1	723.5	606.4	459.2	351.3	276.4	534.9
Ana	215.4	300.2	403.7	480.5	538.8	619.5	609.7	587.3	480.2	346.6	258.1	209.6	420.8

Table (5): Electricity Consumption During the 24 Hours of the Day in Al-Anbar Governorate on 15-04-2024

Source: Prepared by the researcher based.

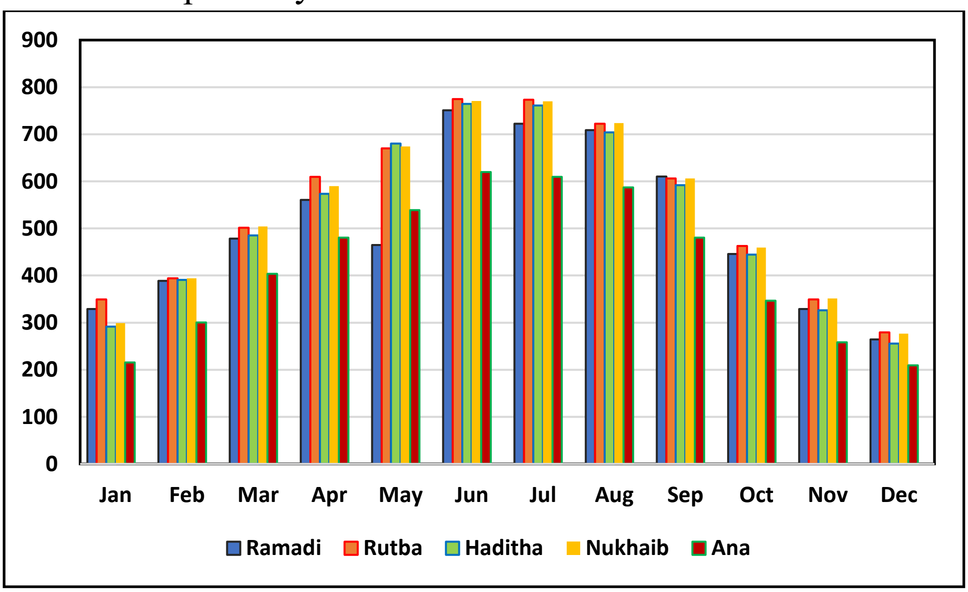


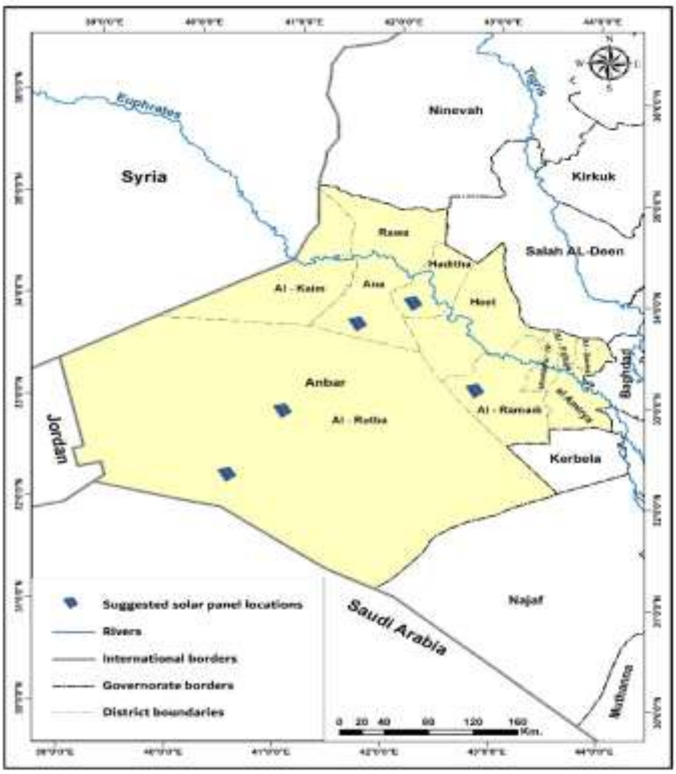
Figure (5): Annual and Monthly Average Solar Radiation in Al-Anbar Governorate (1991–2023)

Source: Prepared by the researcher based on Table (٥).

Figure (6): Solar Panels for Electricity Generation
Source: Internet, *hh://www.moodw3a.net*

Since solar panels require large areas for electricity production and these areas are available in the study region, which are mostly located outside urban centers with desert climates, these panels can be integrated with **agro-solar systems**. By planting crops in the shaded areas beneath the panels and using water that is periodically employed for cleaning the panels for irrigation, the energy generated is efficiently utilized without wasting water. Additionally, this approach helps stabilize desert soil encroaching toward urban areas and mitigates extreme climatic conditions experienced in the region.
However, solar energy has some drawbacks. It requires **substantial capital investment**, which is higher than traditional energy systems for many of its applications. When electricity

generated by solar panels is not immediately needed, storage solutions are required, necessitating specialized storage facilities, which further increase project costs. Moreover, policies to facilitate the use of solar energy are often limited, and there is a lack of coordination between national and local authorities, as well as inter-governorate agreements to maximize public benefit. Another challenge is the **difficulty of securing dedicated government financing** for solar projects. Although the state provides loans with interest to citizens for installing solar systems, high costs, elevated interest rates, short repayment periods, and other restrictive conditions have discouraged widespread adoption.



Figure(7): Locations of Solar Energy Systems Installation in Al-Anbar Governorate

2. Wind Energy

Variations in wind speed across seasons, months, and even within a single day provide opportunities for its use as a renewable energy source. Therefore, understanding the wind speed patterns throughout the year is essential to avoid risks and optimize energy production. Knowledge of all wind types and speeds in the study area is crucial for estimating potential energy output and determining the best sites for wind turbine installation (Ayash, 1991).

Wind energy is generated by converting the kinetic energy of moving air into electricity using wind turbines, which rotate generators to produce electrical power. The amount of electricity generated depends on wind speed, rotor diameter, and generator capacity (Al-Fahdawi, 2011).

Due to the global shift toward clean energy, industrialized countries such as **the United Kingdom** have established major wind power projects at the Thames estuary. The UK faces limited solar radiation, especially during long, sunless winter months, which motivated the use of wind energy to meet electricity demand. By 2020, these initiatives provided about five times the UK's electricity needs (Al-Huraib, 1995). Other countries have also successfully utilized wind energy for electricity generation.

There are two main types of wind turbines: **vertical-axis turbines** and **horizontal-axis turbines**. Both serve the same purpose—generating electricity—but are selected based on the terrain and site-specific conditions for wind farms. Each type has operational advantages, but the end result is the same: clean and sustainable electrical energy.

Figure (8): Electricity Generation from Wind Using Vertical-Axis Turbines

Source: Internet: https://saudipedia.com/article/11958

Accordingly, as observed in Table (6) and Figure (٩), the wind speeds in the study area are ideal for electricity generation and can be relied upon for establishing wind power plants in **Haditha, An-Nukhayb, and Ana**. The average wind speed in these locations exceeds **3 m/s**, which is above the minimum threshold required for electricity production.

Considering the prevailing wind direction in the study area, as indicated in Table (7) and Figure (٩, 10), it is predominantly **northwest**. The annual frequency of this wind direction reached **22.1%**, while the lowest recorded frequency was at **Rutbah station**, at **10.3%**.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Ramadi	329.1	388.5	478.3	560.5	465.1	751.2	722.4	708.6	610.5	445.8	329.1	264.2	515.6
Rutba	349.6	394.3	501.6	609.8	670.3	774.5	773.1	722.5	606.3	462.5	349.6	279.2	537.1
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Ana	215.4	300.2	403.7	480.5	538.8	619.5	609.7	587.3	480.2	346.6	258.1	209.6	420.8

Table (6): Monthly and Annual Average Wind Speeds (m/s) at the Study Area Stations for the Period (1991–2023)

Source: Prepared by the researcher based on: Ministry of Transport, Iraqi General Authority of Meteorology and Seismology, Climate Department, *Unpublished Data*, 2023.

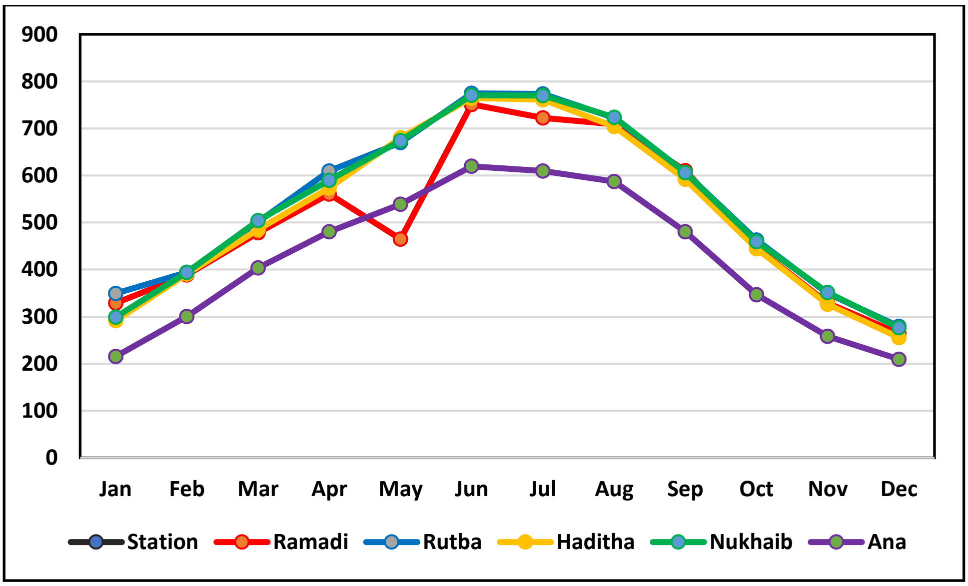

Figure (9): Monthly Average Wind Speeds (m/s) in the Study Area for the Period (1991–2023)

Source: Prepared by the researcher based on Table (6).

Wind Direction	Ramadi	Rutba	Haditha	Nukhaib	‘Ana	Al-Qa’im
Northeast	4.0	3.1	5.2	3.4	5.4	5.0
East	4.2	5.2	4.1	5.3	3.8	4.1
Southeast	3.2	5.1	3.2	5.7	3.3	3.9
South	8.3	8.3	8.1	8.5	8.1	7.7
Southwest	5.1	9.2	3.7	8.4	4.1	4.6
West	6.8	20.1	6.6	18.2	6.6	6.3
Northwest	21.7	12.3	22.1	15.2	21.9	22.1
North	18.6	17.9	19.2	17.6	18.6	20.3
Calm (No wind)	24.2	17.4	26.3	16.2	26.4	24.3

Table (7): Average Wind Direction and Frequency of Prevailing Winds in the Study Area for the Period (1991–2023)

Source: Prepared by the researcher based on: Ministry of Transport, Iraqi General Authority of Meteorology and Seismology, Climate Department, *Unpublished Data*, 2023.

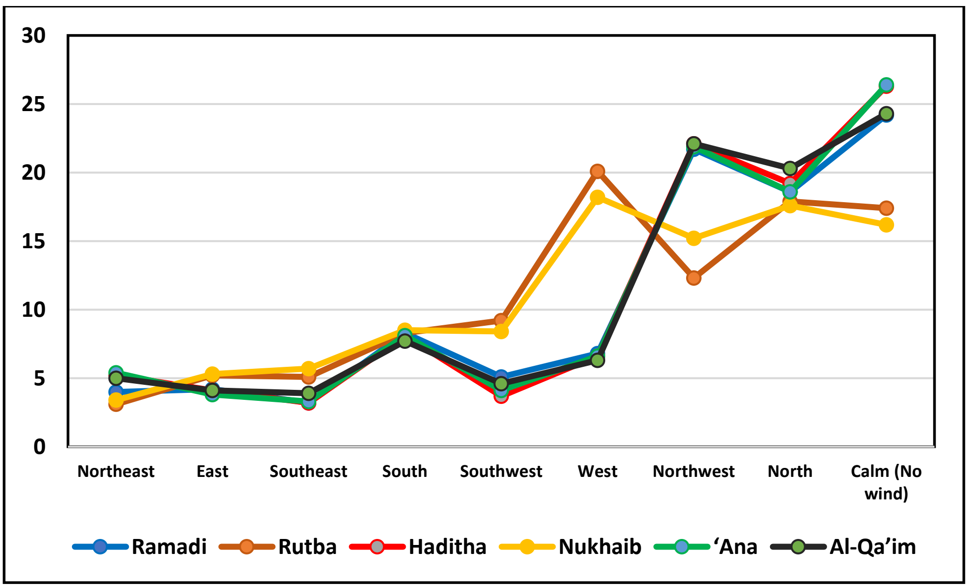

Figure (10): Average Wind Directions in the Study Area (1991–2023)

Source: Prepared by the researcher based on Table (7).

This is followed by **northern winds**, which recorded a frequency of **20.3%**, while the lowest wind frequency was observed at **Rutbah station**, at **17.9%**.

Based on the above, it is feasible to establish a **solar power plant complex** in the areas of **Ramadi, Rutbah, Haditha, An-Nukhayb, and Ana**, respectively, as these regions receive the highest solar irradiance, have optimal sun angles, longer daylight hours, relatively flat terrain, vast uninhabited areas, and proximity to substations and electricity transmission lines, making them suitable for the installation of solar panels.

Regarding **wind energy**, the best locations for establishing wind power farms, considering wind speed, direction, and frequency, are **Al-Qaim, An-Nukhayb, Haditha, and Ana**, fig. (11).

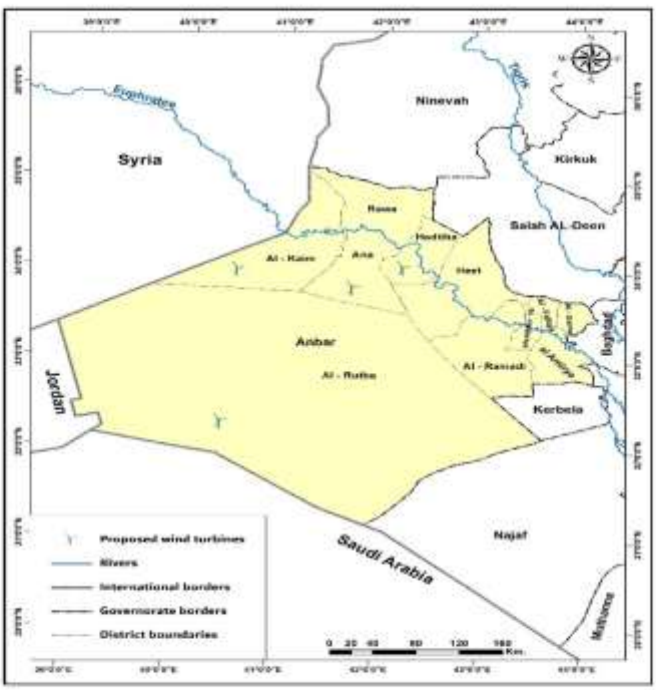

Figure (11); Selection of Sites for Wind and Solar Energy in Al-Anbar Governorate

Source: Prepared by the researcher based on data from the Ministry of Transport, General Authority of Meteorology and Seismology, Climate Department, Maps Department, Administrative Map of Al-Anbar, Scale (1:500,000).

Summary

Al-Anbar Governorate's electricity system faces a combination of structural, technical, administrative, security, and consumption-related challenges that undermine its stability and efficiency. Weak infrastructure, outdated generation stations, deteriorated transmission and distribution networks, and high technical losses, combined with administrative shortcomings such as poor planning, bureaucratic delays, and lack of coordination, have contributed to persistent electricity deficits, which reached 684 MW in 2021 and total technical and operational losses of 3,847.2 MW in 2024, with the highest losses recorded in eastern Anbar. Security issues, including repeated attacks on transmission lines and substations, alongside difficulties in maintaining remote areas, exacerbate these problems. In addition, rapid population growth, urban expansion, seasonal fluctuations in electricity demand, and non-rationalized household consumption increase the pressure on an already stressed system. Despite these challenges, Al-Anbar has significant potential for renewable energy integration. High solar radiation levels, averaging 537.1 W/m² per day in Rutba, and vast open lands make solar power a viable option, while favorable wind speeds, especially in areas such as Al-Qaim and An-Nukhayb, support the establishment of wind farms. To address current deficits and ensure sustainable energy supply, it is recommended to upgrade and modernize infrastructure, convert diesel plants to gas-based stations, deploy smart meters, improve energy management, and promote private sector investment

through BOT and PPP models. Implementing these measures, along with developing solar and wind energy projects, can significantly reduce losses, enhance network stability, and provide a reliable and sustainable electricity supply for the governorate.

Declarations

Ethical Approval and Compliance

Not applicable. This study does not involve human participants, their data, or biological materials.

Consent to Participate

Not applicable. This study does not involve human participants.

Consent for Publication

Not applicable. This study does not involve human participants, and no personal data is published.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Funding

No funding was received for conducting this study.

Competing Interests

The authors declare that they have no competing interests.

The study does not contain a clinical trial.

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