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The Energy Complex of Wind and Thermal Power Plants: Development in Iraq

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Conflicts of interest

The authors declare that there is no conflict of interest.

Abstract. The power system of Iraq aims to integrate all energy sources such as thermal power plants and renewable energy sources including wind energy. Wind speed data for 2022 in five locations were obtaied to calculate the wind energy potential of Iraq in the first part of the study. The selected locations were used to plot the graph of the regional distribution of average wind speed in Iraq. Four regions were identified according to the level of wind energy potential. Statistical analysis including wind flow power calculation was performed for each location. The second part of the study considered an energy complex including wind power plants and natural gas-fired thermal power plants. To develop such a complex, it is necessary that the maximum energy consumption is covered taking into account the unstable operating modes of wind power plants. The results show the technical feasibility in terms of flexibility and cost-effectiveness of such an energy complex.

Keywords: energy, electric power system, renewable energy sources, wind turbine, gas turbine, combined-cycle gas turbine, power balance, optimization

Authors' contribution

Osamah A. — collection of materials, creation and processing of a database, development of a computer program; data analysis, writing a text; *Sigitov O.Yu.* — setting goals and objectives of research, scientific guidance.

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Энергетический комплекс ветровых и тепловых электростанций: разработка в условиях Ирака

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Авторы заявляют об отсутствии конфликта интересов.

Аннотация. Электроэнергетическая система Ирака стремится обеспечить интеграцию всех источников энергии, таких как тепловые электростанции и возобновляемые источники энергии, включая энергию ветра. В первой части исследования для расчета ветроэнергетического потенциала Ирака применены данные о скорости ветра за 2022 г. в пяти населенных пунктах. Выбранные местоположения были использованы для построения графика регионального распределения средней скорости ветра в Ираке. Выделено четыре района по уровню ветроэнергетического потенциала. Для каждого населенного пункта проведен статистический анализ, включающий расчет мощности ветрового потока. Во второй части рассмотрен энергетический комплекс, включающий ветровые электростанции и тепловые электростанции на природном газе. Для разработки такого комплекса необходимо, чтобы максимальное энергопотребление покрывалось с учетом нестабильных режимов работы ветровых электростанций. Результаты подтверждают возможность практической реализации такого энергетического комплекса с точки зрения экономической эффективности.

Ключевые слова: энергетика, электроэнергетическая система, возобновляемые источники энергии, ветроэнергетические установки, парогазовые установки, газовая турбина, энергетический баланс, оптимизация

Вклад авторов

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Introduction

Energy System Structure of Middle East

The Middle East is central to the functioning of global energy markets. The region is home to five of the world's top 10 oil producers — Saudi Arabia, Iraq, the United Arab Emirates, Iran and Kuwait — and three of the top 20 gas producers. It accounted for more than four in ten barrels of global oil exports in 2022. Total energy supply in Middle East. According to the data recorded on the International Energy Agency (IEA), the total energy supplied in the Middle East reached with an increase in the supply process by 131%, with a global participation rate of 6% in 2022. Countries across the Middle East face significant energy and climate challenges. Domestic oil and gas demand could increase substantially, driven by economic expansion and population growth. Demand for cooling and desalinated water may also rise significantly as extreme weather conditions tied to climate change, such as heatwaves and droughts, are likely to become more frequent. Nearly 95% of the electricity generated in the Middle East comes from natural gas and oil — the highest share in the world, though countries in the region also have some of the world's best solar resources. As clean energy transitions reduce demand for fossil fuels globally, producer economies in the region will need to unlock new sources of revenue. As a result, a number of producers are developing plans to build out low-carbon energy industries — leveraging their energy expertise to diversify their economies and energy mixes at the same time.

Iraq, despite its vast hydrocarbon resources, faces a multifaceted energy crisis characterized by chronic electricity shortages, increasing energy demand, deteriorating infrastructure, and heightened environmental degradation. The reliance on fossil fuels not only jeopardizes energy security but also exacerbates public health issues and socioeconomic disparities across the nation. The country's energy landscape is marked by a precarious balance between energy supply and demand, with approximately 35% of the population experiencing unreliable access to electricity [1].

This inconsistent energy supply has significant repercussions for economic stability, social welfare, and overall quality of life. Moreover, the environmental implications of Iraq's fossil fuel dependency are dire. The country ranks among the most vulnerable to climate change, facing challenges such as increased desertification, water scarcity, and pollution-related health impacts. Current energy policies and government strategies have predominantly centered on oil and natural gas exploitation, neglecting the potential for diversification through renewable energy sources. Thus, the scope of this research is critical for assessing the barriers to, and avenues for, integrating renewable energy into Iraq's energy system [2].

1. Overview of Iraq Energy System Structure

There are three types of main stations operating in Al-Alaq of different sizes and distributed in different parts of Iraqi cities, some of which are old, some are new, and others have been modernized by adding new units, which are as follows:

Thermal power plants (oil). Iraq has 7 thermal stations to generate energy by heating water and converting it into steam, which is used to rotate steam turbines (with high speeds), which in turn rotate machines to generate electricity with different capacities. The stations are distributed among 6 Iraqi governorates. In the capital, Baghdad, there are two stations in Doura, with a capacity of 640 megawatts, and in southern Baghdad, with a capacity of 355 megawatts. As for Nineveh, it includes the North station, which is the largest thermal station in Iraq, with a capacity of 2,100 megawatts. Salah al-Din Governorate owns the Baiji thermal station with a capacity of 1,320 megawatts, while the Musayyib station, which has a capacity of 1,280 megawatts, is located in Babil Governorate, in Dhi Qar, the Nasiriyah station with a capacity of 800 megawatts, and in Basra, the Hartha station with a capacity of 400 megawatts, making this the total production[1].

Hydro power plants. Iraq produces electrical energy through 8 hydroelectric stations that use the energy contained in water complexes such as dams and waterfalls to rotate water turbines at low speeds, which in turn rotate machines to generate electricity with different capacities. Two hydroelectric power stations are located in Sulaymaniyah Governorate, namely the Darbandikhan Dam station with a capacity of 248 megawatts and the Dokan Dam station with a capacity of 400 megawatts. In Salah al-Din Governorate, there are two Al-Azim Dam stations with a capacity of 27 megawatts and the Samarra Dam station with a capacity of 84 megawatts. Nineveh Governorate includes the Mosul Dam station, which is the largest in Iraq, with a capacity of 1.52 gigawatts, and the second Mosul Dam station with a capacity of 62 megawatts. In Diyala Governorate, the Hamrin Dam station has a capacity of 50 megawatts, and in Anbar Governorate there is a modern dam station with a capacity of 660 megawatts. Thus, the total pro-duction of hydroelectric stations reaches 2,583 megawatts[2].

[1] Sigitov OY, Radin YA. *Wind Energy: A Textbook*. Moscow: RUDN; 2024. p. 1–138. ISBN 978-5-209-12118-3.

[2] Reliable Prognosis Website. *Weather for 59 locations in Iraq*. Available from: https://rp5.ru/Weather_in_Iraq (accessed: 11.12.2024).

Thermal power plants (natural gas). Iraq relies heavily on gas stations to generate electricity. Iraq has 26 gas stations that work by converting chemical fuel energy into thermal energy to heat gases that are fed into gas turbines, which convert that energy into kinetic energy first, which works to manage the gas turbine, and then into mechanical energy, which works to rotate the rotor in the generator that works with Magnetic field converts mechanical energy into electrical energy. The largest number of stations are located in Baghdad, with 11 gas stations: South Baghdad stations 1 and 2, with capacities of 246 and 400 megawatts, and Al-Dora stations 1 and 2, with capacities of 146 and 700 megawatts. It also includes Al-Taji stations 1 and 2, with capacities of 156 and 160 megawatts, in addition to the Al-Quds 1 stations. And 2 and 3, with capacities of 450 for each of 1 and 2, and a capacity of 500 for station 3. It also contains Al-Sadr station with a capacity of 160 megawatts and Al-Rasheed station 1 with a capacity of 94 megawatts, so the total production of Baghdad gas stations of electrical energy is 3 thousand and 462 megawatts. In Basra, there are 4 gas stations: the Rumaila station with a capacity of 1,460 megawatts, the Shatt al-Basra station with a capacity of 1,250 megawatts, the Zubair station, and the Najibiyah station with a production capacity of 500 megawatts each. Kirkuk Governorate contains two Mulla Abdullah stations with a production capacity of 222 megawatts and Taza with a capacity of 292 megawatts, while Dohuk Governorate includes the Dohuk station with a capacity of 500 megawatts, and in Erbil Governorate the Erbil station with a production capacity of 1,500 megawatts. In turn; Anbar Governorate includes the Anbar gas station with a production capacity of 1,646 megawatts, in Sulaymaniyah, the Sulaymaniyah station with a capacity of 1,500 megawatts, and in Najaf, the Najaf station with a capacity of 430 megawatts. In Diyala, the Mansouriya station has a production capacity of 728 megawatts in addition to the Karbala station, with a production capacity of 250 megawatts, bringing the total production of gas power stations to 14,550 megawatts [3].

Renewable energy sources. Renewable energy in Iraq is energy generated from natural resources such as sunlight, wind, water, rain, and geothermal heat, in addition to biomass energy. Iraq is not a leading country in this field despite the availability of suitable conditions. The heat of the sun, which some may find intense, is suitable for solar power generation. As for the winds, two types are common for Iraq in Summer. The south-east which may reach a speed of 80 kilometers per hour (50 miles per hour), and from mid-June until mid-September, the prevailing winds are north (from the north and northwest), and Iraq is rich in water resources owing to the Tigris and Euphrates rivers and water lakes. In 2006, as a result of the unstable conditions and continuous power outages, Iraq witnessed modest projects to exploit solar energy, and they became more clear and serious in late 2010, with the establishment of the "Renewable Energy Center," and the development of a program for the years 2012 and 2015, centered on production and distribution, and based on the establishment of stations, the production of solar heaters, and the lighting of public roads In 2022, the Renewable Energy Center was established in the Iraqi Ministry of Electricity to confront the process of transformation and reliance on clean energy, The following is a description of the most important types of renewable energy in Iraq [4].

Iraq is endowed with significant solar energy potential, receiving an average solar irradiation of 5–7 kWh/m²/day. A study by the U.S. Department of Energy indicates that Iraq could generate over 400 GW of solar energy, making it one of the best locations for solar power in the Middle East.

The wind energy potential in Iraq is also considerable, particularly in regions such as the northern Kurdistan region, where average wind speeds reach suitable levels for energy generation. According to research conducted by Global Wind Energy Council (GWEC), Iraq could harness up to 12 GW of wind energy.

Biomass potential in Iraq remains largely untapped, with agricultural waste and livestock manure providing possible sources for energy production.

The hydropower potential is limited due to the country's geographical features, but there are small-scale hydropower plants on the Tigris and Euphrates rivers [5].

Thus, Iraq energy system structure have basis generation by gas and coal thermal power plant. In addition there development hydro power plants and other renewable energy sources such as solar PV. Gas turbines constitute about 61% of installed generation capacity, steam 28%, diesel 3%, hydro 8%. Total electricity production from 2000 to 2022 shown in Figure 1.

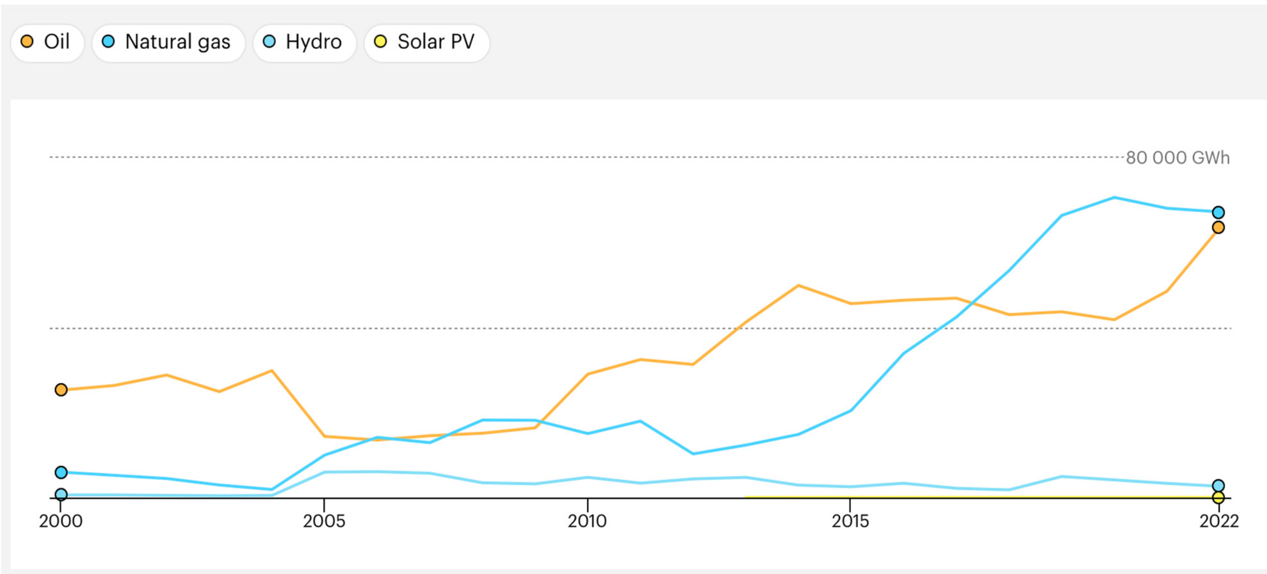

Figure 1. Evolution of electricity generation sources in Iraq since 2000

S o u r c e: by EIA. Available from: https://www.iea.org/countries/iraq (accessed: 15.09.2024)

2. Wind Farms Placement Investigation in Iraq Condition

For wind farms placement investigation, it is necessary to pay attention for different factors, such as: demand in energy, electricity grid in operation, possibilities of wind turbine component deliver and wind power protentional and others. For these reasons, places near major cities within a radius of 400 km have been chosen [6].

To calculate the wind power potential, attention was paid to changing various parameters such as: wind speed, air density, atmospheric pressure and temperature. It is due to modern wind turbine hub height. Modern wind turbine technology has advanced significantly over the past few decades, leading to larger and more efficient turbines designed to harness wind energy effectively. Here are some key points about wind turbine blade length and hub height.

Modern wind turbine blades can vary widely in length, typically ranging from about 40 meters (131 feet) to over 80 meters (262 feet) for onshore turbines. Offshore turbines can have blades exceeding 80 meters, with some of the largest reaching up to 100 meters (328 feet) or more. Longer blades capture more wind energy due to a larger swept area. This increases the turbine's capacity to generate electricity, especially in areas with lower wind speeds. Advances in materials and design, including the use of lighter and stronger composite materials, have allowed for the development of longer blades without significantly increasing weight [7].

The hub height of modern wind turbines usually ranges from about 80 meters (262 feet) to 150 meters (492 feet) for onshore turbines. Offshore turbines often have even greater hub heights, sometimes exceeding 200 meters (656 feet). The hub height is crucial as wind speed tends to increase with altitude. By placing turbines at higher elevations, they can access stronger and more consistent winds, leading to higher energy production. The optimal hub height can vary depending on local wind conditions, topography, and environmental considerations. Wind resource assessments are typically conducted to determine the best height for a specific location.

Thus, the trend in the industry is towards larger turbines, with both blade lengths and hub heights increasing to maximize efficiency and energy output. Innovations in floating wind turbine technology are allowing for the placement of turbines in deeper waters, further pushing the limits of hub heights and blade lengths. The increase in size is often coupled with improvements in turbine efficiency and capacity factors, allowing for more energy generation per unit installed capacity[1].

In the result, it is necessary to recalculate mentioned parameters (wind speed, air density, atmospheric pressure) to wind turbine height.

We calculate the wind parameters depending on the external climate conditions using the following mathematical equations [8].

Wind speed was calculated at different height in accordance to formula:

$$\frac{v(h_2)}{v(h_1)} = \left(\frac{h_2}{h_1}\right)^m,$$

where (h_2) is wind speed at WT altitude, m/s; (h_1) is wind speed at measurement altitude, m/s; h_2 is tower height, m; h_1 is wind speed measurement height (weather vane height), m; m is Hellman coefficient.

Air density changes was calculated in accor-dance to formula:

$$\rho = 3.4837\frac{p(h)}{T},$$

where ρ is air density, kg/m^3; $p(h)$ is air pressure at height h; kPa; T is air temperature, K; 3.4837 is specific gas constant of dry air.

Atmospheric pressure at altitude h can be determined using the barometric formula (the basic equation of atmospheric statics):

$$p(h) = p_0 e^{-mg}\frac{h-h_0}{RT},$$

where p_0 is air pressure at sea level, Pa; m is molar mass of gas, g/mol; g is gravity acceleration, m/s^3.

For calculations, the value of (h) up to a height of 5000 m can be determined from the approximating equation:

$$p(h) = 101.29 - 0.011837h + 4.793\times10^{-7}h^2,$$

where h is height from the ground surface, m.

Thus, 5 cities from Iraq were selected, representing a diverse geography from the center, south and north, with close distances not exceeding 400km. The weather website was relied upon to download the required data [4]. A set of mathematical functions were also used to obtain the required results. The map with calculation result presented in Figure 2.

Table 1 represents wind data, air density and power rates for the city of Saladin.

Table 1

Average values of wind energy parameters for Saladin during the year

Parameters	January	February	March	April	May	June	July	August	September	October	November	December
V^{10}, m/s	1.81	2.06	2.61	2.87	3.29	3.06	2.70	2.29	2.08	1.72	2.35	2.19
t, °C	12.1	13.3	19.3	23.6	29.7	35.0	38.4	39.2	34.9	27.9	20.0	14.8
V^{30}, m/s	2.6	3.0	3.7	4.1	4.7	4.4	3.9	3.3	3.0	2.5	3.4	3.1
P, W	118.71	191.26	543.05	874.69	1640.58	1547.64	1152.32	724.97	485.80	222.52	408.58	253.56

S o u r c e: by A. Osamah

[3] Reliable Prognosis Website. Weather for 59 locations in Iraq. Available from: https://rp5.ru/Weather_in_Iraq (accessed: 11.12.2024).

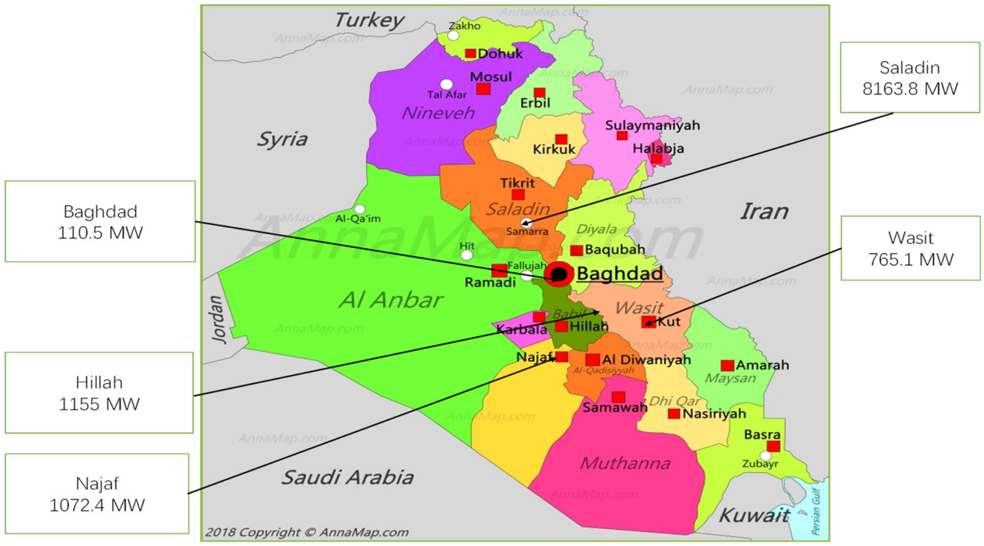

Figure 2. Map of wind power protentional in Iraq

S o u r c e: by A. Osamah for Iraq Map. Available from: https://annamap.com/iraq/ (accessed: 15.09.2024)

3. Flexibility of Energy Systems

Flexibility has become a common by-word for the energy transition. While everyone agrees that we need more flexibility in future power systems, views vary widely on how to achieve this, particularly to improve grid integration and make maximum use of solar and wind potential. To transform our energy system towards one dominated by renewable energy, flexibility has to be harnessed in all parts of the power system. Power system flexibility spans from more flexible generation to stronger transmission and distribution systems, more storage and more flexible demand. Production of heat and synthetic gas (e. g., hydrogen) from renewable electricity is also key for energy system decarbonization in the long term, and once in place it can be a significant additional To transform our energy system towards one dominated by renewable energy, flexibility has to be harnessed in all parts of the power system [9].

Flexibility of Nuclear Power. Nuclear plants are primarily designed to provide baseload power, operating continuously at or near full capacity, they are less flexible when it comes to rapid changes in output, due to thermal stress and safety considerations related to reactor operation, Modern designs, such as small modular reactors (SMRs), aim to improve flexibility for grid balancing, Continuous operation to meet base demand.

Flexibility of Hydro Power. Hydropower is one of the most flexible generation sources, capable of ramping up or down quickly to respond to demand. Pumped-storage hydropower enhances grid reliability by storing excess energy and releasing it during peak demand, Flexibility depends on water availability, reservoir size, and environmental regulations. Peak demand management and grid balancing.

Flexibility of Thermal Power (Coal or Gas). Traditional coal plants are designed for baseload operation and have slower ramp-up and ramp-down times due to the time needed to heat or cool the boiler. Modern coal plants with advanced technologies (e.g., ultra-supercritical boilers) offer improved flexibility but are still less responsive than gas plants. Baseload power with limited flexibility. Gas turbines and combined cycle gas plants (CCGTs) can ramp up and down quickly, making them suitable for managing variable loads. Gas plants are often used as peaking plants to meet sudden surges in demand. Peaking and backup power to complement variable renewables [10].

Flexible sources like hydro and gas are crucial for integrating variable renewables (e.g., wind and solar) into the grid. Nuclear and coal plants are less suitable for responding to short-term variability but can still complement renewables for providing consistent baseload power. Flexibility characteristics of different power generation sources show in Table 2.

Table 2

Comparison of the flexibility of different power generation sources

No.	Type	Quick start ramp rate, %/m	Load ramp up rate, %/m	Load ramp down rate, %/m
Generating plants (conventional)				
1	Gas turbine — simple cycle	22	22.1	21.0
2	Gas turbine combined-cycle power plant	4	2.2	5.0
3	Conventional hydro	6%/s	6%/s	6%/s
4	Nuclear power plants	5.0	1.5	3.0
Generating plants (renewable)				
5	Solar PV	1.0–5.0	0.4	0.4
6	Wind	1.0–10	1.0	1.0
Storage plants				
7	Pumped storage hydro power plant	6%/s	6%/s	6%/s

Source: by A. Osamah

4. Development of an Energy Complex of Wind and Thermal Power Plants in Iraqi Conditions

Iraq is actively developing power complexes that integrate wind farms with fossil fuel-fired power plants to enhance energy security, improve grid stability, and support the integration of renewable energy sources. These hybrid systems leverage the strengths of both wind and fossil fuels such as oil and gas to create a more flexible and resilient energy infrastructure. The key features of hybrid power complexes are that wind farms provide renewable energy, while fossil fuel-fired power plants provide reliable baseload power. This combination ensures a stable power supply even when wind conditions are not favorable. The fossil fuel-fired power plants can quickly ramp up or down to balance the variability of wind power, maintaining grid stability. At the same time, integrating wind power reduces the overall carbon footprint of the power complex, contributing to Iraq's desired climate goals [11].

These hybrid power complexes demonstrate the feasibility and benefits of integrating renewable energy sources with conventional power generation to enhance energy security, improve grid stability, and support Iraq's climate goals.

This project demonstrates the feasibility and benefits of hybrid power complexes. The hybrid power complex combines wind farms with supercritical coal-fired power plants. This integration enhances the efficiency and flexibility of the power system. Table 2 shows the operating parameters of hybrid power plants. These sources provide comprehensive insights into the development of hybrid power plants and the challenges they face in Iraq. Developing hybrid power plants requires significant investment in infrastructure and technology. Managing the integration of wind and fossil fuels requires advanced control and coordination systems [12]. However, while emissions are reduced, fossil fuel power plants still contribute to pollution and carbon emissions.

Operational Parameters of Hybrid Energy Complexes are shown in Table 3. Capacity Factor is the ratio of actual energy produced to the maximum possible output over a given time, Wind farms have lower capacity factors due to variable wind speeds. Coal plants and hybrid complexes have higher factors when supported by backup sources.

Table 3

Operational parameters of hybrid energy complexes

Parameters	Wind farms	Gas power plants	Hybrid energy complexes
Capacity Factor	25–50% (dependent on wind availability)	60–85%	40–80% (depends on renewable integration and backup)
Ramp Rate	Low to Moderate (limited by wind variability)	High (can adjust power output quickly)	High (depends on backup sources like)
Emissions	Zero (renewable energy source)	Medium (in comparison with coal TPP)	Low to Moderate (renewables reduce overall emissions)
Reliability	Moderate (dependent on weather conditions)	High (continuous base-load power supply)	High (combines reliability of fossil fuels with renewables)

Source: by A. Osamah

Ramp rate is the speed at which a power plant can increase or decrease its output, wind farms are slower due to natural wind constraints, while coal and hybrids (with advanced tech like batteries or gas turbines) can ramp up more quickly.

Emissions parameters show that wind farms are emission-free, coal plants emit significant pollutants, while hybrid complexes aim to minimize emissions by combining renewables and cleaner backup sources. Reliability parameters show that wind farms depend on weather, making them less reliable. Coal plants offer stable power but with environmental costs. Hybrid systems ensure reliability by balancing renewable and conventional energy [13].

5. Results

The final energy complex calculation requires wind and thermal power plants with the maximum power consumption coverage, the wind farm operation modes should be taken into account. The objective function in this case presented as:

$$z = \sum_{i=1}^{n} C_i N_i \rightarrow \min ,$$

where C_i is lifetime cost of the i-th generating unit, USD; N_i is amount of generation unit; n is amount of generation unit type (wind turbine (WT), gas turbine (GT), combined-cycle gas turbine (CCGT), steam turbine (ST)).

For this energy complex we have different constraints:

$$\begin{cases} \sum_{i=1}^{n} \frac{dP_i(t)}{dt} N_i \geq \frac{dP_{\text{wt}}(t)}{dt} N_i \\ \sum_{i=i}^{n} P_i^{\text{range}} N_i \geq \Delta P_{\text{wt}} N_i \\ P_i^{\text{nom}} N_i + P_{\text{wt}}^{b} N_i \geq P_{\text{load}} \\ N_i < N_{\max} \end{cases}$$

The constrains of wind farms:

$$\begin{cases} \frac{dP_{\text{wt}}(t)}{dt} N_i = \frac{0.1 P_{\text{wt}}^{\text{nom}}}{dt} N_i \\ \Delta P_{\text{wt}} = 0.9 P_{\text{wt}}^{\text{nom}} N_i \\ P_{\text{wt}}^{b} = 0.2 P_{\text{wt}}^{\text{nom}} N_i \end{cases}$$

where $\frac{dP_i(t)}{dt}$ is power ramp of i-th generation unit GT, CCGT, ST, MW/min; $\frac{dP_{\text{wt}}(t)}{dt}$ is maximum power ramp of WT, MW/min; P_i^{range} is available power range of GT, CCGT, ST, MW; ΔP_{wt} is maximum amplitude of WT power change, MW; P_i^{nom} is nominal capacity of GT, CCGT, ST, MW; P_{wt}^{b} is basis power of WT, MW; $P_{\text{wt}}^{\text{nom}}$ is nominal capacity of WT, MW.

Considering the above information about energy sources, the Table 4 shows input data for objective function calculation.

Table 4

Input data of energy complex

Power plant type	Energy unit type	Maximum amount of energy unit	Nominal capacity, MW	Low limit of power range, MW	Available power range, MW	Power ramp, MW/min	Lifetime cost, million USD
Wind Farm (WF)	L-100	999	2.5	0	0	0	4
CCPP	230 MW GT13E2 (1GT+1ST)	999	230	92	138	11.5	4000
GT	180 MW	999	180	72	108	21.6	6000

S o u r c e: by A. Osamah

Let's consider a case in which it is planned to create an energy complex of wind farms and thermal power plants. Wind turbine (L-100) with a capacity of 2.5 MW and two gas power units (combined cycle power plant GT13E2 (1GT+1ST) and gas turbine) with a capacity of 230 MW and 180 MW are presented as a choice of generating equipment. In accordance with the objective function, constraint equations, and initial information on the maximum amount of energy unit, nominal capacity, low limit of power range available power range, power ramp and lifetime cost, an optimal energy complex was obtained for load with capacity 800 MW. The energy complex includes:

– a wind farm with an installed capacity of 220 MW, including 88 wind turbines

– a combined cycle power plant, which includes 3 units (GT13E2 (1GT+1ST)) with a total installed capacity of 690 MW.

The total lifetime costs for such complex will amount to 12,352 million USD.

Accordingly, such energy complexes can provide their application in the further development of Iraq's energy system. They simultaneously provide technical feasibility in terms of flexibility and economic efficiency.

Conclusion

In conclusion, the development of an integrated energy complex combining wind farms and a thermal power plant in Iraq presents a significant opportunity to diversify and stabilize the country's energy supply. Given Iraq's abundant natural resources, both in terms of wind potential and fossil fuels, this hybrid approach offers several advantages. Wind energy, particularly in regions with favorable wind patterns, can contribute to reducing the dependence on non-renewable sources and mitigate the environmental impact of power generation. On the other hand, thermal power plants, fueled by Iraq's vast reserves of oil and natural gas, can provide reliable base-load power, especially during periods when wind generation is intermittent.

The integration of these two energy sources can enhance the overall reliability, efficiency, and sustainability of Iraq's energy infrastructure, addressing the country's growing demand for electricity while simultaneously fostering economic growth. Additionally, combining renewable and thermal sources allows for a more flexible and adaptive energy system, capable of balancing supply and demand fluctuations. However, to fully realize the potential of this energy complex, Iraq will need to overcome several challenges, including investments in infrastructure, technology transfer, and the development of local expertise.

Moreover, policy support and regulatory frameworks will be critical in fostering a conducive environment for such projects. Strategic planning that incorporates socio-economic considerations, environmental impacts, and long-term sustainability goals will be essential to ensuring that this hybrid energy complex not only meets Iraq's immediate energy needs but also contributes to global efforts to transition to cleaner and more sustainable energy systems.

Overall, the proposed energy complex in Iraq could serve as a model for other countries in the region, positioning Iraq as a leader in energy innovation and sustainability while improving its energy security and supporting socio-economic development.

References

1. Alshawaf M, Alhajeri NS. Renewable energy-driven desalination for sustainable water production in the Middle East. *International Journal of Sustainable Engineering*. 2024;17(1):668–78. https://doi.org/10.1080/19397038.2024.2394552 EDN: UPVMNZ

2. McGowan JG., Rogers AL, James F, Manwell JF. *Wind Energy Explained: Theory, Design and Application.* 2010. https://doi.org/10.1080/19397038.2024.2394552 ISBN 0-470-01500-4

3. Cochran J, Miller M, Zinaman O, Soonee SK. *Flexibility in 21st century power systems. ResearchGate.* 2014. Available from: https://www.nrel.gov/docs/fy14osti/61721.pdf (accessed: 11.12.2024).

4. Hassan Q, Al-Jiboory AK, Sameen AZ, Barakat M, Abdalrahman KYM, Algburi S. Transitioning to Sustainable Economic Resilience through Renewable Energy and Green Hydrogen: The case of Iraq. *Unconventional Resources*. 2024;5:100124. https://doi.org/10.1016/j.uncres.2024.100124

5. Algburi S, Rendal E, Jaber ZK, Fakhruldeen HF, Amjad A, Sapaev IB, et al. Evaluating the viability and potential of hybrid Solar-Wind renewable energy systems in relation to geographical and environmental factors. *Results in Engineering*. 2024:103473. https://doi.org/10.1016/j.rineng.2024.103473 EDN: EWCENM

6. Hassan Q, Algburi S, Al-Musawi TJ, Viktor P, Jaszczur M, Barakat M, Sameen AZ, Hussein AH. GIS-based multi-criteria analysis for solar, wind, and biomass energy potential: A case study of Iraq with implications for climate goals. *Results in Engineering.* 2024;22:102212. https://doi.org/10.1016/j.rineng.2024.102212 EDN: TPRMHI

7. Wu W, Prescott D, Remenyte-Prescott R, Saleh A, Ruano MC. An asset management modelling framework for wind turbine blades considering monitoring system reliability. *Reliability Engineering & System Safety*. 2024;252:110478. https://doi.org/10.1016/j.ress.2024.110478 EDN: EDETMW

8. Kale B, Buckingham S, Van Beeck J, Cuerva-Tejero A. Comparison of the wake characteristics and aerodynamic response of a wind turbine under varying atmospheric conditions using WRF-LES-GAD and WRF-LES-GAL wind turbine models. *Renewable Energy.* 2023;216:119051. https://doi.org/10.1016/j.renene.2023.119051 EDN: TWAQFW

9. Beiron J, Göransson L, Normann F, Johnsson F. Flexibility provision by combined heat and power plants — An evaluation of benefits from a plant and system perspective. *Energy Conversion and Management: X.* 2022;16:100318. https://doi.org/10.1016/j.ecmx.2022.100318 EDN: UWXGRW

10. Qasim MA, Yaqoob SJ, Bajaj M, Blazek V, Obed AA. Techno-Economic optimization of hybrid power systems for sustainable energy in remote communities of Iraq. *Results in Engineering*. 2025;25:104283. https://doi.org/10.1016/j.rineng.2025.104283

11. Nwagu CN, Ujah CO, Kallon DVV, Aigbodion VS. Integrating Solar and Wind Energy into the Electricity Grid for Improved Power Accessibility. *Unconventional Resources.* 2024;100129. https://doi.org/10.1016/j.uncres.2024.100129 EDN: AIDIQF

12. Aldarraji M, Vega-Márquez B, Pontes B, Mahmood B, Riquelme JC. Addressing energy challenges in Iraq: Forecasting power supply and demand using artificial intelligence models. *Heliyon.* 2024;10(4):e25821. https://doi.org/10.1016/j.heliyon.2024.e25821 EDN: YQKBLK

13. Qasim MA, Yaqoob SJ, Bajaj M, Blazek V, Obed AA. Techno-Economic optimization of hybrid power systems for sustainable energy in remote communities of Iraq. *Results in Engineering.* 2025;25:104283. https://doi.org/10.1016/j.rineng.2025.104283

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