Вестник РУДН. Серия: Инженерные исследования
RUDN Journal of Engineering Research

2025;26(2):181–193

ISSN 2312-8143 (Print); ISSN 2312-8151 (Online)
journals.rudn.ru/engineering-researches

DOI: 10.22363/2312-8143-2025-26-2-181-193
EDN: MBKAHR

Research article / Научная статья

Development of an Energy Complex of Wind Farms and Thermal Power Plants in China

Qiujin Zhu, Oleg Yu. Sigitov✉

RUDN University, *Moscow, Russian Federation*
✉ OlegSigitov@gmail.com

Article history
Received: January 26, 2025
Revised: March 22, 2025
Accepted: March 28, 2025

Conflicts of interest
The authors declare that there is no conflict of interest.

Abstract. China is undergoing a transformation of its energy system to meet the goals of pollutant reduction and carbon neutrality. The integration of renewable energy sources into the existing energy system is a subject of considerable relevance. The initial phase of the study involved the development of a map showing potential sites for wind farms. Consequently, the locations exhibiting the highest and lowest levels of wind energy potential were identified. The second part of the study is based on an analysis of the current status of China's energy system and wind energy potential. It considers a model of an integrated energy complex combining wind farms and coal-fired thermal power plants. In order to develop such complex systems, it is necessary to consider the unstable operation modes of wind farms, in order to ensure that maximum energy consumption is covered. The findings of the study demonstrate that such a complex can play a significant role in optimizing the power structure, improving grid stability and reducing pollutant emissions, providing an effective solution for China's energy strategy.

Keywords: energy, electric power system, renewable energy sources, wind turbine, steam turbine, power balance, optimization

Authors' contribution
Zhu Q. — 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.

For citation
Zhu Q, Sigitov OYu. Development of an energy complex of wind farms and thermal power plants in China. *RUDN Journal of Engineering Research.* 2025;26(2):181–193. http://doi.org/10.22363/2312-8143-2025-26-2-181-193

Разработка энергетического комплекса из ветровых и тепловых электростанций в условиях Китая

Ц. Чжу, О.Ю. Сигитов✉

Российский университет дружбы народов, *Москва, Российская Федерация*

✉ OlegSigitov@gmail.com

История статьи

Поступила в редакцию: 26 января 2025 г.
Доработана: 22 марта 2025 г.
Принята к публикации: 28 марта 2025 г.

Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

Аннотация. Китай находится в процессе трансформации энергетической системы, направленной на достижение целей снижения выбросов загрязняющих веществ и углеродной нейтральности. Актуальной является проблема интеграции возобновляемых источников энергии в существующую энергетическую систему. В связи с этим в первой части исследования разработана карта с потенциально подходящими местами для размещения ветровых электростанций. В результате были определены места с наибольшим и наименьшим потенциалом ветровой энергии. На основе анализа текущего состояния энергетической системы Китая и потенциала ветровой энергии во второй части исследования рассмотрена модель интегрированного энергетического комплекса, сочетающего ветровые электростанции и угольные тепловые электростанции. Для разработки такого комплекса необходимо, чтобы максимальное энергопотребление покрывалось с учетом нестабильных режимов работы ветровых электростанций. Результаты исследования показывают, что такой комплекс может играть значительную роль в оптимизации структуры энергетики, повышении стабильности сети и снижении выбросов загрязняющих веществ, предоставляя эффективное решение для реализации энергетической стратегии Китая.

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

Вклад авторов

Чжу Ц. — сбор материалов, создание и обработка базы данных, разработка компьютерной программы; анализ данных, написание текста; *Сигитов О.Ю.* — постановка целей и задач исследования, научное руководство.

Для цитирования

Zhu Q., Sigitov O.Yu. Development of an energy complex of wind farms and thermal power plants in China // Вестник Российского университета дружбы народов. Серия: Инженерные исследования. 2025. Т. 26. № 2. С. 181–193. http://doi.org/10.22363/2312-8143-2025-26-2-181-193

Introduction

As the world's second-largest economy, China's energy consumption continues to increase, exacerbating the conflict between energy security and environmental sustainability. In 2023, China's total energy consumption exceeded 5.5 billion tons of standard coal, with fossil fuels, particularly coal, dominating the energy mix. However, the extensive use of coal has led to severe air pollution and green-house gas emissions.

To address climate change and achieve sustainable development goals, China has proposed the "carbon peaking and carbon neutrality" strategy, aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. This goal has accelerated the development of renewable energy in China with wind power owing to its environmental benefits and renewability and has become a key focus in China's energy transition.

The intermittency and instability of wind power make it difficult to solely undertake the base load power supply. Wind energy power generation fluctuates significantly owing to natural conditions, whereas the grid requires a high level of real-time supply and demand balance. This contradiction is particularly evident in regions with a high proportion of wind power.

Thermal power, especially coal-fired power, with its stable operation and strong peak-shaving capability, is an important means of compensating for fluctuations in wind power. By implementing flexibility retrofits to coal-fired units, power output can be more efficiently regulated, thus achieving complementary integration of wind and thermal power and providing reliability support to the grid.

Therefore, this study aims to explore how to effectively integrate wind farms and coal thermal power plants under Chinese conditions to:

1) improve the stability and flexibility of the energy systems;

2) optimize the energy structure and reduce carbon emissions;

3) provide a scientific basis and technical support for China's energy strategy.

1. Overview of China energy system structure

China's energy system is predominantly coal-based, but it also includes various forms of energy, such as wind, hydro, solar, and nuclear power. In recent years, the installed capacities of wind and solar power have increased significantly. As of 2023, China's total installed capacity for wind and photovoltaic power has reached 400 GW and 360 GW, respectively, accounting for approximately 40% of the global total and sustainability (Figure 1).

Below is brief information about various types of large power plants in the Chinese energy system.

Coal Thermal power plant. Tuoketuo Power Station is the largest coal-fired power plant in China and the world. The plant has a nameplate capacity of 6,720 MW. It consists of eight 600 MW units, two 300 MW units, and two 660 MW ultra-supercritical units. The power plant sources its coal from the Junggar Coalfield, which is approximately 50 km away. It meets its water requirements by pumping from the Yellow River, which is located 12 km away. Tuoketuo Power Station is one of the ten most carbon-emitting coal-fired power plants in the world. In 2018, it emitted approximately 29.46 million tons of carbon dioxide, with relative emissions estimated at 1.45 kg per kWh. The electricity generated at the plant is delivered to Beijing via 500-kV transmission lines. The plant includes ultra-supercritical units, which are more efficient and produce lower emissions than traditional coal-fired units. Tuoketuo Power Station plays a significant role in China's energy landscape, providing substantial power output while also facing challenges related to environmental impact and sustainability [1].

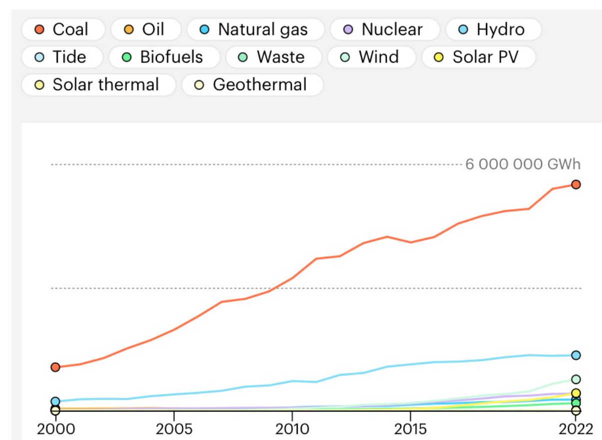

Figure 1. Evolution of electricity generation sources in China since 2000

Source: by EIA. Available from: https://www.iea.org/countries/china (accessed: 18.07.2024)

Oil power plants. China has several oil-fired power plants, although they are not as prominent as coal or hydroelectric plants. For example, Penny's Bay Power Station**,** Lantau Island, Hong Kong 300 MW, is primarily used as a peaking power plant, meaning that it operates during periods of high electricity demand. Shunde Power Station Shunde, Guangdong Province 278 MW, also serves as a peaking power plant, providing additional power during peak demand times. Wuhan Zhuankou Power Station Wuhan, Hubei Province 180 MW, is used for backup power and during periods of high demand. Coloane A Power Station Macau 271 MW, Companhia de Electricidade de Macau**,** This plant provides power to the Macau region and is used as a backup and peaking power plant.

These oil-fired power plants play a crucial role in providing backup power and meeting peak electricity demand, although their use is declining due to environmental concerns and the shift towards cleaner energy sources [2].

Natural gas power plants. China has several natural gas power plants, such as Guangdong Huizhou Natural Gas Power Plant, Huizhou, Guangdong Province (2.400 MW). It is one of the largest natural gas power plants in China and provides significant power to the Guangdong region. It uses advanced combined-cycle gas turbine technology to achieve high efficiency and lower emissions. Shanghai Caojing Natural Gas Power Plant (2.000 MW). This plant is a key part of Shanghai's energy infrastructure, utilizing natural gas to produce electricity with a reduced environmental impact compared to coal-fired plants. Beijing Jingneng Gas Power Plant (1.800 MW). This plant plays a crucial role in providing electricity to Beijing, particularly during peak demand periods. It is known for its high efficiency and low emissions. Tianjin Binhai Natural Gas Power Plant (1.500 MW), This plant supports the energy needs of the Tianjin region, contributing to the reduction of air pollution by using cleaner natural gas instead of coal. Zhejiang Ningbo Natural Gas Power Plant (1.200 MW) is part of Zhejiang's efforts to diversify its energy mix and reduce reliance on coal. It uses state-of-the-art technology to maximize efficiency and minimize emissions.

These natural gas power plants are part of China's broader strategy to reduce air pollution and greenhouse gas emissions by increasing the use of cleaner energy sources [3].

Nuclear power plants. China has several nuclear power plants, For example: Yangjiang Nuclear Power Plant Guangdong Province (6.000 MW). The Yangjiang Nuclear Power Plant is the largest in China, featuring six 1 GW CPR-1000 pressurized water reactors (PWRs). The plant is operated by the Yangjiang Nuclear Power Company, a sub-sidiary of the China General Nuclear Power Group (CGN). The first unit was commissioned in 2014, and the sixth unit became operational in 2019. Hongyanhe Nuclear Power Plant Liaoning Province (4.500 MW) consists of four 1 GW PWRs and two additional reactors under construction. It is operated by the Liaoning Hongyanhe Nuclear Power Company, a joint venture between CGN and China Power Investment Corporation. Qinshan Nuclear Power Plant Zhejiang Province (4.500 MW) is one of the oldest and largest nuclear power plants in China, with multiple reactors, including PWRs and heavy water reactors. It is operated by the China National Nuclear Corporation (CNNC). Tianwan Nuclear Power Plant Jiangsu Province (3.000 MW) features four 1 GW PWRs, with two additional reactors under construction. It is operated by the Jiangsu Nuclear Power Corporation, a subsidiary of the CNNC. Fuqing Nuclear Power Plant Fujian Province (6.000 MW) operates six PWRs, including two Hualong One reactors, which are China's indigenous third-generation nuclear reactors. It is operated by the Fujian Fuqing Nuclear Power Company, a subsidiary of CNNC [4].

The primary challenge for nuclear power plants is to manage radioactive waste and ensure safety. Although nuclear power is a low-carbon energy source, potential accidents and long-term storage of radioactive waste pose significant risks. Additionally, the high costs and long construction times of nuclear plants can be barriers to their development.

Hydro power plants. China has several hydro power plants, for example, Three Gorges Dam Hubei Province (22.500 MW). The Three Gorges Dam is the largest hydroelectric power station in the world, owing to its installed capacity. It spans the Yangtze River and was completed in 2008. The dam generates approximately 98.8 TWh of electricity annually.

The construction of the Three Gorges Dam has led to significant environmental and social issues, including the displacement of over 1.3 million people and the submergence of numerous archaeological and cultural sites. Additionally, the dam has altered the ecosystem of the Yangtze River, affecting fish populations and sediment flow.

Baihetan Dam Yunnan and Sichuan Provinces (16.000 MW). The Baihetan Dam is the second-largest hydroelectric power station in China. It spans the Jinsha River and was completed in 2021. The dam generates approximately 60.24 TWh of electricity annually.

Similar to the Three Gorges Dam, the Baihetan Dam has caused environmental concerns, including habitat disruption and changes in river flow patterns. Construction also required the relocation of local communities.

Xiluodu Dam Sichuan Province (13.860 MW), The Xiluodu Dam is the third-largest hydroelectric power station in China. It spans the Jinsha River and was completed in 2014. The dam generates approximately 55.2 TWh of electricity annually.

The construction of the Xiluodu Dam has led to environmental impacts, such as changes in river flow and sediment transport. Additionally, the project required the relocation of thousands of residents [5].

Wudongde Dam Yunnan and Sichuan Provinces (10.200 MW), The Wudongde Dam is the fourth-largest hydroelectric power station in China. It spans the Jinsha River and was completed in 2020.

The Wudongde Dam has caused environmental concerns, including habitat disruption and changes in river flow patterns. Construction also required the relocation of local communities.

Xiangjiaba Dam Sichuan Province (6.400 MW). The Xiangjiaba Dam is the fifth-largest hydroelectric power station in China. It spans the Jinsha River and was completed in 2012.

The construction of the Xiangjiaba Dam has led to environmental impacts such as changes in river flow and sediment transport. Additionally, the project required the relocation of thousands of residents.

These hydro power plants play a crucial role in China's energy landscape, providing substantial power output while also facing challenges related to environmental impact and sustainability.

Other power plant types. Power plants can be classified into various types based on their energy source. Some common types of power plants are as follows:

Solar Power Plants: These plants convert sunlight into electricity using photovoltaic (PV) panels or solar-thermal systems. Solar power plants are known for their low environmental impact and renewability. They are often used in regions with high solar insolation [6].

Wind Power Plants: Wind turbines convert the kinetic energy of wind into electricity. Wind power plants are clean and renewable energy sources with minimal environmental impact. They are commonly found in areas with consistent and strong wind.

Geothermal Power Plants: These plants use heat from Earth's interior to generate electricity. Geothermal power plants are highly efficient and have low environmental footprints. These are typically located in regions with significant geothermal activity.

Biomass Power Plants: Biomass power plants burn organic materials, such as wood, agricultural residues, and waste, to produce electricity. They are considered renewable and can help reduce waste; however, they emit carbon dioxide and other pollutants.

Tidal Power Plants: These plants harness energy from tidal movements to generate electricity. Although tidal power is predictable and renewable, the construction of tidal power plants can have a significant environmental impact on marine ecosystems [7].

Renewable energy sources. China is the world leader in electricity production from renewable energy sources, with significant contributions from hydro, solar, and wind power. The country aims to have 80% of its total energy mix from non-fossil fuel sources by 2060 and achieve a combined 1.200 GW solar and wind capacity by 20302. In 2023, China was on track to reach 1.371 GW of wind and solar power by 2025, five years before the target.

Overview of status and location of wind farms in China. The expansion of wind power in China is mainly concentrated in resource-rich areas, such as Inner Mongolia, Xinjiang, and the eastern coastal regions. Technological advancements have significantly reduced the cost of wind power, and the application of large wind turbines has further improved the power generation efficiency and stability. However, a high proportion of wind power integration into the grid poses a higher demand for grid dispatch and energy storage technologies.

For wind farm placement investigation, it is necessary to pay attention to different factors, such as energy demand, electricity grid in operation, possibilities of wind turbine component delivery, and wind power protection. Therefore, places near major cities with a radius of 400 km were chosen.

To calculate the wind power potential, attention was paid to changing various parameters such as: wind speed, air density, atmospheric pressure and temperature. This is because of the height of the modern wind turbine hub. (Blade length: Modern wind turbine blades can exceed 100 m. One of the longest blades currently in production is 108 m, which is used in the Haliade-X offshore wind turbine and can generate up to 14 megawatts (MW). Hub Heights: Onshore turbines now commonly feature hub heights of 100–160 meters, while offshore turbines can reach even greater heights. This design allows turbines to access stronger, steadier winds at higher altitudes, significantly improving energy yield [8].

As a result, it is necessary to recalculate the parameters (wind speed, air density, and atmospheric pressure) to the wind turbine height. There are various methods for calculating wind energy parameters depending on the external conditions[1] [9; 10].

The wind speed calculation at different heights was based on the following 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.

The air ensity changes also depend on height and are based on the following 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.

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

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

where h is height from the ground surface, m.

Thus, nine cities from China were selected, representing a diverse geography from the center, south, and north, with close distances of approximately 400 km: Inner Mongolia — Hohhot, Ningxia — Yinchuan, Tibet — Lhasa, Xinjiang — Urumqi, Yunnan — Kunming, Gansu-Dunhuang, Gansu — Lanzhou, Qinghai — Xining, and Xinjiang — Hami. The weather website was used to download the required data for 2023. For the calculations we use a wind turbine GE 3.4-137 with an installed capacity of 3.4 MW. The results for the average wind speed, air temperature, and wind flow power are presented in Figures 2–4.

Table 1 presents the average values of the wind energy parameters for Sanya in 2023. The map of the calculation results is presented in Figure 5. Wind power protentional $P(W)$ is the quantitative indicator that calculated as the sum of the average monthly wind flow power as follows:

$$P = \sum_{i=1}^{n} P_i = \sum_{i=1}^{n} \frac{1}{2}\rho_{ave} A V^3_{ave},$$

where n is the number of month during the year, ρ_{ave} is the average air density during the month kg/m^3, A is the cross section of wind turbine m^2, V is average wind speed during the month, m/s.

In the result we can see places with highest energy protentional (Inner Mongolia — Hohhot 831MW, Ningxia-Yinchuan 74MW, Tibet — Lhasa 195MW Xinjiang-Urumqi 183MW, Yunnan — Kunming 259MW, Gansu-Dunhuang 1497MW, Gansu — Lanzhou 479MW, Qinghai — Xining 478MW, Xinjiang — Hami 212MW).

[1] Sigitov OY, Radin YA. *Wind energy: a textbook.* 2024. ISBN 978-5-209-12118-3.

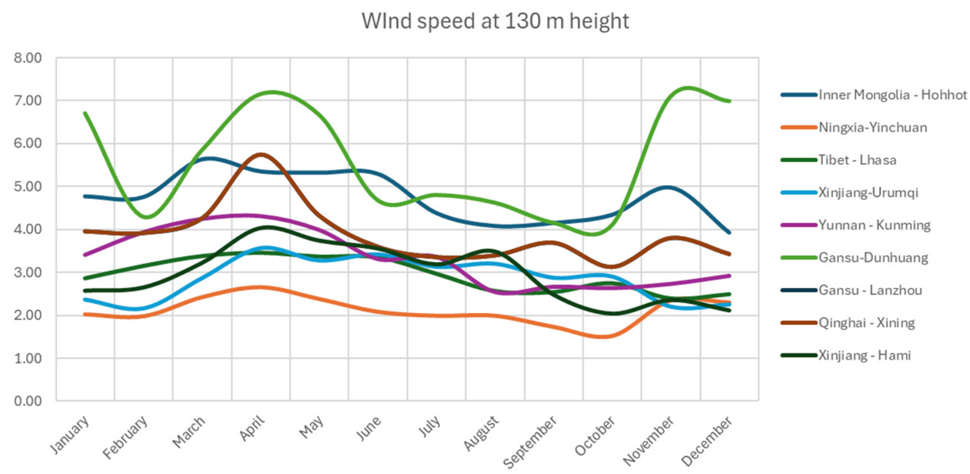

Figure 2. Average wind speed for nine cities of China
S o u r c e: by Zhu Qiujin

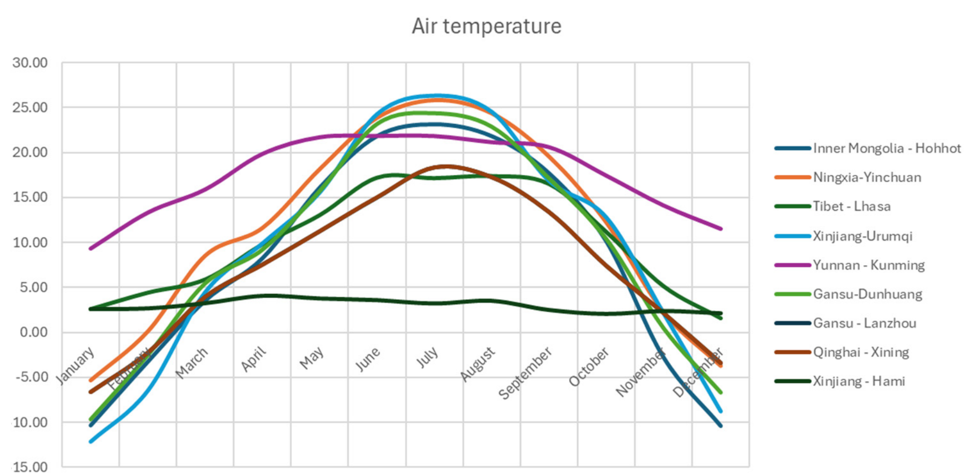

Figure 3. Average air temperature for nine cities of China
S o u r c e: by Zhu Qiujin

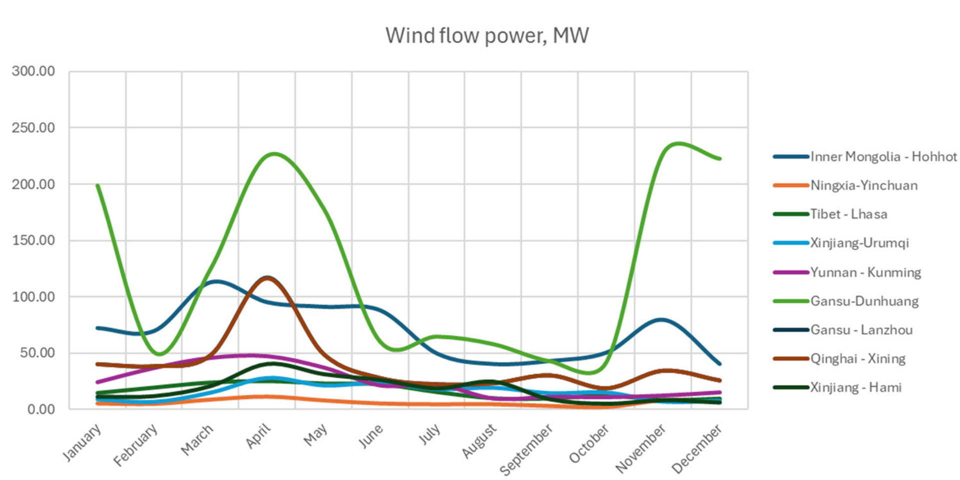

Figure 4. Average wind flow power for nine cities of China
S o u r c e: by Zhu Qiujin

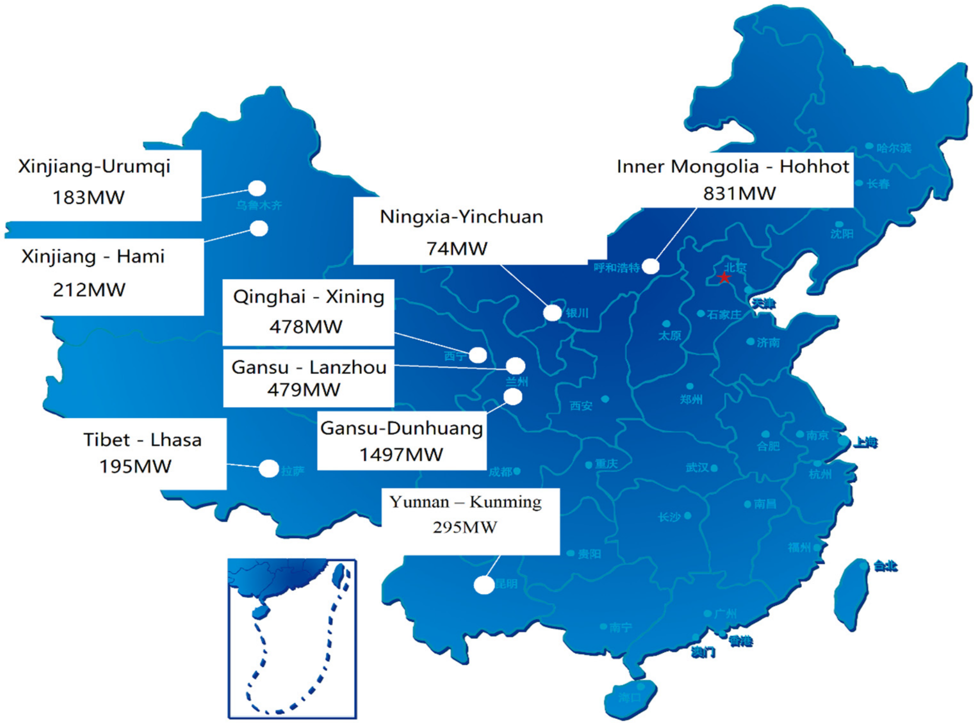

Figure 5. Map of wind power protentional in China
Source: by Zhu Qiujin for Collter. Available from: http://www.coliter.com/list/?language=1&classid=4 (accessed: 15.09.2024)

Table 1

Average values of wind energy parameters for Gansu-Dunhuang during the year

Parameters	January	February	March	April	May	June	July	August	September	October	November	December
V10, m/s	4.68	3.00	4.09	5.00	4.65	3.27	3.36	3.23	2.90	2.87	4.96	4.88
t, °C	-9.67	-2.50	5.46	9.22	15.74	23.18	24.38	22.88	17.14	10.41	0.48	-6.68
V130, m/s	6.70	4.30	5.85	7.15	6.67	4.68	4.81	4.63	4.16	4.11	7.10	6.99
ρ130, kg/m^3	1.32	1.28	1.25	1.23	1.20	1.17	1.17	1.17	1.20	1.23	1.27	1.30
P(W)	198.89	50.94	125.15	225.37	178.20	60.15	64.89	58.14	43.05	42.55	227.27	222.70

Source: by Zhu Qiujin

2. Results

2.1. Flexibility of Energy Systems

China's energy system is enhancing the flexibility of traditional power generation sources, namely, nuclear, hydro, and thermal (coal-fired) power, to accommodate the increasing share of renewable energy and ensure grid stability. A detailed examination of the flexibility of these conventional power generation sources is as follows in Table 2.

Nuclear power plants are designed for continuous, stable base-load operations, and have limited flexibility. Their long start-up times and low ramp rates render them unsuitable for rapid load adjustments.

Table 2

Comparison of the flexibility of conventional power generation sources

Parameter	Nuclear Power	Hydro Power	Thermal Power (Coal-Fired)
Minimum Load (% of rated capacity)	50–60%	0–30%	20–60%
Ramp Rate (% per minute)	1–3%	10–30%	2–6%
Start-Up Time	–	< 1 min	1-10 hour

S o u r c e: by Zhu Qiujin

Table 3

Comparison of operational parameters before and after flexibility retrofitting

Parameter	Before Retrofitting	After Retrofitting
Minimum Load (% of rated capacity)	50–60%	20–30%
Ramp Rate (% per minute)	1–3%	3–5%
Start-Up Time (hours)	4–10	< 2

S o u r c e: by Zhu Qiujin

Hydropower plants, particularly those with reservoir storage, offer high operational flexibility. They can start up quickly and adjust their output rapidly, making them ideal for load following and balancing intermittent renewable sources[2].

Traditionally, coal-fired power plants have exhibited moderate flexibility. However, through flexibility retrofitting, their operational parameters can be enhanced to better support grid demands.

To support the integration of renewable energy, China is implementing strategies to enhance the flexibility of its traditional power generation sources.

1. *Flexibility Retrofitting of Coal-Fired Plants.* Modifications are being made to reduce minimum load levels, increase ramp rates, and shorten start-up times, enabling coal-fired plants to respond more effectively to fluctuations in renewable energy generation [11].

2. *Optimizing Hydropower Utilization.* Efforts are underway to maximize the flexible operation of hydropower plants by leveraging their rapid response capabilities to balance supply and demand [12].

3. *Developing Ancillary Services.* The establishment of ancillary service markets encourages traditional power plants to provide flexible services, such as frequency regulation and reserve power, to support grid stability [13].

By enhancing the flexibility of traditional power generation sources, China aims to create a more resilient and adaptable energy system that can integrate higher proportions of renewable energy.

China is actively enhancing the flexibility of its coal-fired power plants to better integrate renewable energy sources and to ensure grid stability. This process, known as "flexibility retrofitting," enables coal power units to operate more dynamically, accommodating the variable nature of wind and solar power. There are several key Aspects of Flexibility Retrofitting (Table 3).

1. *Minimum Load Reduction.* Lowering the minimum operational load of coal-fired units allows them to decrease their output during periods of low demand, thereby facilitating greater integration of renewable energy. For instance, subcritical units can reduce their minimum load to 30% of the rated capacity, while supercritical units can achieve reductions to 20–25%.

2. *Ramp Rate Enhancement.* Improving ramp rates enables coal-fired units to adjust their output more rapidly in response to fluctuations in renewable energy generation. Typical ramp rates can be

[2] Innovation landscape brief: Flexibility in conventional power plants. *International Renewable Energy Agency.* Abu Dhabi, 2019. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Flexibility_in_CPPs_2019 (accessed: 10.12.2024).

increased from 1–3% per minute to 3–5% per minute through retrofitting.

3. *Start-Up Time Reduction.* Decreasing the time required for coal-fired units to start up from a cold state enhances their ability to provide backup power when the renewable sources are insufficient. Retrofitting can reduce start-up times from several hours to less than two hours.

It is necessary to note the negative factors of variable modes. Frequent load changes and low-load operations can increase the wear and tear on equipment, potentially reducing the lifespan of coal-fired units. Operating at lower loads may lead to decreased efficiency and higher specific fuel consumption, thereby impacting the economic viability of plants. In addition, low-load operations can affect the performance of emission control systems, potentially leading to increased pollutant emissions if not properly managed.

Despite these challenges, the flexibility retrofitting of coal-fired power plants is a crucial step for China to enhance grid flexibility and support the large-scale integration of renewable energy sources. Ongoing research and development aim to optimize these retrofitting processes and balance the operational flexibility with economic and environmental considerations.

2.2. Development of Energy Complex Consist of Wind Farms and Thermal Power Plant In China Condition

China is actively developing energy complexes that integrate wind farms with coal power plants to enhance energy security, improve grid stability, and support the integration of renewable energy sources. These hybrid systems leverage the advantages of both wind and coal power to create a more resilient and flexible energy infrastructure.

The key Features of Hybrid Energy Complexes are that wind farms provide renewable energy, while coal power plants offer reliable base-load power. This combination ensures a stable power supply, even when wind conditions are not favorable. Coal power plants can quickly ramp up or down to balance the variability of wind power and maintain the grid stability. Integrating wind power reduces the overall carbon footprint of the energy complex and contributes to China's climate goals [14].

One such example is the Gansu Wind Farm and Coal Power integration project. Gansu Wind Farm, one of the largest in the world, is integrated with nearby coal power plants to provide a stable and reliable power supply.

The Gansu Wind Farm, one of the largest wind farms in the world, has a nameplate capacity of 10.45 GW, with plans to expand to 20 GW [15]. This massive wind power installation was integrated with nearby coal power plants to provide a stable and reliable power supply.

In Shanxi Province, the hybrid energy complex combines wind farms with ultra-supercritical coal power plants. The installed capacity of new energy produced by wind and solar power in Shanxi Province reached 50.93 million kilowatts as of January 2024 [16].

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

This project demonstrates the feasibility and benefits of hybrid energy complexes. In Shanxi Province, a hybrid energy complex combines wind farms with ultra-supercritical coal power plants. This integration enhances the efficiency and flexibility of the power system.

Table 4 lists the operational parameters of Hybrid Energy Complexes. These sources provide comprehensive insights into the development of and challenges faced by Hybrid Energy Complexes in China. The development of hybrid energy complexes requires significant investments in infrastructure and technology. Managing the integration of wind and coal power requires advanced control systems and coordination. Although emissions are reduced, coal power plants still contribute to pollution and carbon emissions [17].

To calculate the energy complex, it is necessary to develop such an energy complex, including wind farms and thermal power plants, in which the maximum power consumption will be covered, taking into account the operating modes of the wind farm. The objective function in this case is presented as:

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

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

Table 4

Operational parameters of hybrid energy complexes

Parameter	Wind Farms	Coal Power Plants	Hybrid Energy Complexes
Capacity Factor	30–50%	60–80%	50–70%
Flexibility	Low	High	Decrease[1]
Emissions	Zero	High	Decrease

[1)] Flexibility is decreased in corresponding to requirements of energy system

S o u r c e: by Zhu Qiujin

Table 5

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
Coal Power Plant	ST 300 MW *K*-300-240	999	300	150	150	12	5 500
Coal Power Plant	SSG	999	600	180	420	30	6 000

S o u r c e: made by Zhu Qiujin

For this energy complex, we have the following 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:

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

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

Considering the above information regarding energy sources and their flexibility characteristics, Table 5 shows the input data for the objective function calculation.

Let us consider a case in which it is planned to create an energy complex of wind farms and thermal coalfired power plants. The following generating equipment is presented for consideration: one wind turbine (*L*-100) with a capacity of 2.5 MW and two coal-fired power units (*K*-300-240 and SSG) with capacities of 300 and 600 MW, respectively. In accordance with the objective function, constraint equations, and initial information on the maximum number of energy units, nominal capacity, low limit of power range available, power ramp, and lifetime cost, an optimal energy complex was obtained for a load with a capacity of 1500 MW. The energy complex includes the following components:

– a wind farm with an installed capacity of 600 MW, including 240 wind turbines;

– a thermal power plant, which includes two coal-fired power units (SSG) with a total installed capacity of 1,200 MW.

The total lifetime costs for such complex will amount to 12.960 million USD.

Accordingly, such energy complexes can be applied for the further development of China's energy system. They simultaneously provide technical feasibility, in terms of flexibility and economic efficiency.

Conclusion

The main classes and limitations that must be considered when constructing and optimizing schedules of classes are identified based on the application of a systems approach to the automated compilation of a schedule of classes for a multi-level university.

It is shown that the schedule of classes and metrics for assessing their quality should be considered as complex organizational and technical systems characterized by multi-factor integral criteria because of the specifics of the educational systems of a multi-level university, the subsystems of which are partially intersecting components of higher and secondary education.

The developed ontology allows one to construct a UML class diagram that implements the compilation and optimization of a schedule of classes using the example of specific conditions of a multi-level university. The operating algorithm and software tool developed on the basis of the constructed class diagram and using MySQL DBMS for storing the initial information ensure the construction of an effective schedule of classes for a multi-level university according to the integral criterion using penalty functions.

References

1. Grant D, Zelinka D, Mitova S. Reducing CO_2 emissions by targeting the world's hyper-polluting power plants. *Environmental Research Letters*. 2021;16:094022. https://doi.org/10.1088/1748-9326/ac13f1 EDN: DDXGGQ

2. Zhao Y, Zhang T, Sun L, Tong L, Wang L, Ding J, Ding Yu. Energy storage for black start services: A review. *International Journal of Minerals, Metallurgy and Materials.* 2022;29:691–704. https://doi.org/10.1007/s12613-022-2445-0 EDN: INOHVK

3. Ye L-C, Lin HX, Tukker A. Future scenarios of variable renewable energies and flexibility requirements for thermal power plants in China. *Energy*. 2019;167:708–714. https://doi.org/10.1016/j.energy.2018.10.174

4. Jie Y, Zhijie G, Yangjun Z, Bing L, Yan W. Analysis on the emission of tritium from Qinshan nuclear power base of China in recent ten years. *IOP Conference Series: Earth and Environmental Science*. 2019;227:052031. https://doi.org/10.1088/1755-1315/227/5/052031

5. Zhang X, Dong Z, Gupta H, Wu G, Li D. Impact of the Three Gorges Dam on the hydrology and ecology of the Yangtze river. *Water.* 2016;8(12):590–605. https://doi.org/10.3390/w8120590

6. Winter CJ, Sizmann RL, Vant-Hull LL. *Solar power plants: fundamentals, technology, systems, economics*. Berlin: Springer Publ.; 1991. https://doi.org/10.1007/978-3-642-61245-9 ISBN: 978-3-642-61245-9

7. Kangaji L, Orumwense E, Abo-Al-Ez K. Modelling and simulation of tidal energy generation system: A systematic literature review. *International Journal of Advanced Technology and Engineering Exploration.* 2022;9(92):1028–1055. https://doi.org/10.19101/IJATEE.2021.875704

8. Tumse S, Bilgili M, Yildirim A, Sahin B. Comparative analysis of global onshore and offshore wind energy characteristics and potentials. *Sustainability.* 2024;16(15):6614–6628. https://doi.org/10.3390/su16156614 EDN: SVFGCP

9. Cisneros-Saldana JI, Hosseinian S, Butenko S. Network-based optimization techniques for wind farm location decisions. *Frontiers of Engineering Management (FEM).* 2018;5(4):533–540. https://doi.org/10.15302/J-FEM-2018025

10. Rao KR. *Wind energy for power generation: Meeting the challenge of practical implementation*. 2019. https://doi.org/10.1007/978-3-319-75134-4

11. Liu J, Guo T, Wang Y, Li Y, Xu S. Multi-technical flexibility retrofit planning of thermal power units con-

sidering high penetration variable renewable energy: The case of China. *Sustainability.* 2020;12(9):3543–3558. https://doi.org/10.3390/su12093543 EDN: OTUXSN

12. Lewandowski M, Góralczyk A, Janicki W. Optimization algorithms for sustainable operation of multi-unit hydropower plants. *Sustainability*. 2024;16(24): 11093–11110. https://doi.org/10.3390/su162411093 EDN: REUZSD

13. Yi Z, Meng S, Abdolhosseinzadeh S. Optimal hydroelectric energy utilization with ATDOA: a case study of the Bumbuna Dam. *Water Supply.* 2024;24(10):3295–3313. https://doi.org/10.2166/ws.2024.069 EDN: YWOTLE

14. Zhou XC, Liu FC, Zheng JJ. Analyses on integration of wind power into Gansu Power Grid. *Advanced Materials Research*. 2012;608-609:569–572. https://doi.org/10.4028/www.scientific.net/AMR.608-609.569

15. Xiangjiaba D, Dai L, Dai H, Liu H, Wang Y, Guo J, Cai Z, Mi C. Development of an optimal model for the Xiluodu-Xiangjiaba cascade reservoir system considering the downstream environmental flow. *Sustainability.* 2020;12(3):966–980. https://doi.org/10.3390/su12030966 EDN: GVQRVJ

16. Ye B, Xie M, Yu Z, Lu Z, Yan D, Su B, Wang P, Jiang J.Technical and economic study of renewable-energy-powered system for a newly constructed city in China. *Energy Reports*. 2024;11:5069–5082. https://doi.org/10.1016/j.egyr.2024.04.059 EDN: LPVEHX

17. Grant D, Zelinka D, Mitova S. Reducing CO_2 emissions by targeting the world's hyper-polluting power plants. *Environmental Research Letters*. 2021;16(9):1–15. https://doi.org/10.1088/1748-9326/ac13f1 EDN: DDXGGQ

About the authors

Qiujin Zhu, Senior Lecturer of the Departament of Power Engineering, Academy of Engineering, RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation; ORCID: 0009-0005-8824-9306; e-mail: zhuqiujin1@gmail,com

Oleg Yu. Sigitov, Ph.D. in Technical Sciences, Senior Lecturer of the Department of Power Engineering, Academy of Engineering, RUDN University, 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation; eLIBRARY SPIN-code: 9915-2001, ORCID: 0009-0007-8541-4542; e-mail: OlegSigitov@gmail.com

Сведения об авторах

Чжу Цюцзинь, старший преподаватель кафедры энергетического машиностроения, инженерная академия, Российский университет дружбы народов, Российская Федерация, 117198, г. Москва, ул. Миклухо-Маклая, д. 6; ORCID: 0009-0005-8824-9306; e-mail: zhuqiujin1@gmail.com

Сигитов Олег Юрьевич, кандидат технических наук, старший преподаватель кафедры энергетического машиностроения, инженерная академия, Российский университет дружбы народов, Российская Федерация, 117198, г. Москва, ул. Миклухо-Маклая, д. 6; eLIBRARY SPIN-код: 9915-2001; ORCID: 0009-0007-8541-4542, e-mail: OlegSigitov@gmail.com