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Prospects for using combined heat and power plants and boiler houses to balance the integrated energy system of Ukraine

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Abstract. The study analysed the current state of Ukraine's energy system, focusing on the shortage of manoeuvring capacities, large emissions of harmful substances into the atmosphere, and low energy efficiency of the key technological processes of existing generation facilities. These shortcomings also apply to heat energy producers, namely combined heat and power stations and industrial and municipal boiler houses. The existing energy system of Ukraine includes both types of producers, with a predominant type of energy (electricity or heat). The purpose of this study was to assess the prospects for introducing modern technologies to ensure the sustainability of electricity and heat production systems. The analytical methods used were those suitable for comparing gas turbine and combined cycle plants, as well as electricity and heat storage systems. The study reviewed various technologies that increase the manoeuvrability of systems for the production of these types of energy and reduce the generation of harmful substances by avoiding endothermic reactions in the combustion of solid, liquid, and gaseous fuels. Changes in the ratio of capacities of the main generating facilities built in the 1960s, deterioration of technological equipment, which has exhausted its technological life by 80-90%, indicate a lack of manoeuvring capacities and its aggravation as a result of destruction and damage caused by military aggression. The need to modernise coal-fired thermal power plants using modern combustion technologies in an environment enriched with oxygen (up to 30-40%) of atmospheric air was also emphasised. To improve the manoeuvrability of coal-fired units, it is necessary to bring their capacity to the level of 800-1000 MW, and to significantly reduce emissions of harmful substances, it is necessary to combine steam, gas, and combined cycle generation. The study explored the prospects for the development of highly manoeuvrable capacities through the reconstruction of existing combined heat and power plants and the conversion of municipal and industrial boilers into mini-cogeneration plants for their integration into the European energy market. The results can form the basis for the development of a state energy policy that will help increase the resilience and efficiency of Ukraine's energy system, reduce its dependence on electricity imports, meet environmental standards at both the national and European levels, and guarantee the country's energy security

Keywords: power generation facilities; steam turbine and combined cycle unit; air oxygen enrichment; endothermic reactions; environmental and energy safety

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Introduction

The energy security of the state is determined by the stability and manoeuvrability of generation facilities capable of producing the required amount of electricity and heat, considering their negative property, namely their low capacity for storage and accumulation. The Integrated Power System (IPS) of Ukraine is based mainly on the following generation facilities: thermal power plants (TPPs) using coal-fired units, nuclear power plants (NPPs), hydroelectric power plants and pumped hydroelectric energy storage (HPPs and PHESs). Furthermore, a certain niche is occupied by various units that use renewable energy sources (RES – solar, wind, etc.). Additionally, electricity is generated at combined heat and power plants (CHP, mini-CHP, boiler houses), which also provide heat to industrial enterprises and the household sector.

The ratio of capacities of these facilities at different points in time has shown various trends. Overall, the IPS of Ukraine is characterised by a shortage of manoeuvring capacities. This deficit has been exacerbated not only by the excessive enthusiasm for clean (green) energy, but also by the wider introduction of green tariffs. The phenomenon known as the 'green-coal' tariff paradox has led to the use of outdated coal-fired units to cover peak loads. This operating strategy, which involves frequent start-ups and shutdowns of these worn-out coal units, has led to increased emissions and increased risks of accidents in the electricity grid. And with the outbreak of full-scale military operations on the territory of Ukraine, the destruction caused by these negative impacts has increased dramatically.

A. Polyvianchuk *et al*. (2023) emphasised the significance of a phased approach to the modernisation of district heating systems (DHS), especially for countries with limited financial resources. They proposed a gradual integration of renewable energy sources, heat pumps, and individual substations, which proves that it is possible to considerably reduce both energy consumption and investment costs. This methodology is in line with the broader context of district heating system improvements, particularly in the transition to the 4^{th} and 5^{th} generations of DHSs.

B. Basok *et al*. (2022) comprehensively discussed the current challenges facing the Ukrainian combined heat and power sector. These challenges relate primarily to the retention of qualified personnel and the maintenance of technological heat and power equipment under martial law. A prominent aspect is the optimisation of equipment operation modes to minimise fuel consumption for heat and electricity generation, which ensures maximum efficiency. M.R. Chowdhury *et al*. (2021) discussed such issues on the example of the United States.

The study by O. Kyrylenko *et al*. (2022) provided an in-depth analysis of the functioning of electricity and heat supply systems in the context of the military aggression of the Russian Federation. This military conflict caused substantial economic losses to Ukraine's economy due to the destruction of numerous electricity and heat supply facilities, which simultaneously produced a significant share of electricity. Consequently, due to their economic, humanitarian, and geopolitical significance, energy infrastructure facilities have often been targeted by Russian aggression. These critical but vulnerable facilities need to be distributed across the country to ensure the reliable functioning of the economy and maintain a safe standard of living. Considering the state of heat and electricity generation during the first half of 2024, the findings of the study by M. Chernyavskyy *et al*. (2024) stressed the urgent need to transition to distributed generation systems. This recommendation can be further substantiated by the widespread use of protective separation methodologies in power grids, which are implemented as the principal approach to ensuring the safe and reliable operation of these engineering systems.

The energy sector of Ukraine includes a great number of facilities for generating electricity as the main end-use product (heated water and low-parameter water steam), as well as facilities for producing heat (CHP, mini-CHP, and boiler houses), for which the production of a certain amount of electricity is not the primary goal. These facilities must operate as a single organism, and therefore must be considered simultaneously, as they are intertwined in the generation of electricity (both centrally and in a distributed mode). For heat production, CHP, mini-CHP, and boiler houses should operate locally in their respective regions. This approach should improve the balancing potential to cover peak electricity loads while meeting the heating needs of all consumers.

Reducing CO2 emissions is also among the urgent tasks for the energy sector. V. Deshko & D. Karpenko (2018) emphasised that innovative approaches can be cost-effective in the context of a carbon tax, even considering the costs of producing oxygen and compressing CO2. V. Zdanovsky & M. Kulyk (2021) proposed to burn organic fuels (solid, liquid, gaseous) in an oxygen-enriched environment. Such an approach will not only increase the manoeuvrability of combined-cycle gas turbine plants, but also greatly reduce emissions of harmful substances such as nitrogen oxides, subject to the elimination of endothermic reactions during the combustion of organic fuels.

The purpose of this study was to assess the possibility of using heat and power plants and boiler houses to balance the integrated energy system, including the production of electricity and heat based on the introduction of existing modern advanced technologies.

Materials and Methods

Considering the complexity of the object of combined heat and power generation, to fulfil the purpose of this study, the method of analytical research of literature data, as well as the method of generalisation of available practical and calculated data of complex generation facilities were employed. Considering the fact that some energy facilities are subordinated to the Ministry of Fuel and Energy of Ukraine, while some heat and power generation facilities belong to the municipal sector, some scientific tasks were solved by the method of system analysis, as well as by the method of comparative analysis to compare different types of generation technologies. Furthermore, modelling and forecasting methods were used to assess the prospects and efficiency of introducing modern technologies, which helped to predict the impact of different scenarios of power system development on its stability. Economic analysis was used to assess the economic evaluation of the proposed technologies, which helped to estimate the costs of implementation and their economic feasibility. Environmental analysis was also a crucial element of the study, as it helped to assess the impact of innovative technologies on the level of emissions of harmful substances.

In preparing this article, the following steps were taken: studying the global experience of electricity and heat generation by the Ukrainian power system facilities, as well as heat and electricity generation by municipal heat and power enterprises; researching the efficiency of thermal power plants using gas turbine, combined cycle and cogeneration technologies; assessment of the suitability of combined heat and power plants and industrial and municipal boiler houses to improve the stability and balance of the power system; examination of the impact of technological, economic, and environmental constraints on the efficiency of small-scale energy facilities.

Through the analysis of publications in the field of sustainability and balancing of the power system based on the combination of cogeneration technologies and the use of the latest approaches to the processes of combustion of organic fuels, the study proposed results that can confirm the best technical and environmental performance. Considering the obtained findings on the key technological, economic indicators, and environmental assessments, the study provided a possible optimum choice of strategies for balancing the Ukrainian energy system, considering price constraints. The key indicators for achieving energy efficiency and system stability were also identified.

Results and Discussion

The analysis of the state of the IPS of Ukraine for the period up to 2015, the characteristics of the country's fuel base, and the prospects for the development of its energy sector after this period were detailed in the study (Khalatov, 2016). The conclusions of this fundamental research suggest that in the short term, it is necessary to focus on the use of innovative energy technologies, which should include:

- conversion of coal-fired units to circulating fluidised bed boilers (there are more than 600 of them in the world; at the same time, in Ukraine, there are a hundred times fewer);
- use of cogeneration technologies at existing CHP plants and conversion of large boiler houses into cogeneration mini-CHP plants;
- widespread use of gas turbine and combined cycle technologies for all modes of coverage – base, half-peak, and peak loads on domestically produced natural gas.

Industrial enterprises and critical infrastructure facilities require a considerable amount of thermal energy besides electricity to operate normally and to ensure the efficient functioning of their personnel and the household sector. The technological process of providing these consumers with thermal energy in the form of water steam or hot water is called heat generation, when electricity is also produced – cogeneration, and when the third type of energy is obtained – trigeneration (Klimenko *et al.*, 2011). An adjusted scheme of a cogeneration plant is presented in Figure 1.

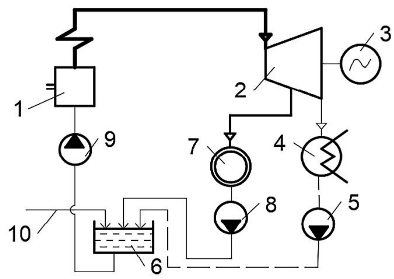

***Figure 1**. Simplified thermal scheme of a combined heat and power plant*

***Note:** 1 – boiler; 2 – turbine; 3 – electric generator; 4 – condenser; 5 – condenser pump; 6 – feed tank; 7 – heat consumers; 8 – network pump; 9 – feed pump; 10 – chemically clean water pipeline*

***Source:** developed by the authors of this study based on V. Klimenko et al. (2011)*

The water steam produced in boiler 1 is fed into steam turbine 2 and, in the final version, electric generator 3 produces a certain amount of electric energy, which is used both for the own needs of the heating system and for other consumers without conversion. The exhaust steam in the condenser 4 gives off a certain amount of heat used by the consumer and is sent by the condensing pump 5 to the feed tank 6, from where it is fed to the boiler unit by the feed pump 9. The heat energy, as the primary product from the intermediate extraction of the steam turbine 2, is used by group consumers in the form of steam or hot water and is fed by the feed pump 8 into the feed tank 6, where water losses are replenished with chemically treated water via the pipeline 10 to avoid corrosion of the primary process equipment. From the feed tank 6, the heated water is returned to the boiler unit 1. Depending on the needs of production consumers and public utility needs, the ratio of heat flows can vary within the relevant range.

Modern cogeneration units, for which heat production is predominant and electricity production is less significant, can be as follows: steam turbine units with a backpressure turbine and heat supply to consumers of all or part of the exhaust steam; steam turbine units with a condensing turbine with heat recovery; gas turbine units (GTUs) using the heat of combustion gases in a heat recovery boiler or directly in the technological process; diesel power units (DPUs) producing high-potential heat using flue gas heat and low-potential heat in the engine cooling circuit; combined cycle gas turbine units (CCGTUs) using heat from the exhaust gases of a gas turbine to produce heat, which is fully or partially directed to one or more steam turbines of the respective type.

There is a wide range of thermal power plants in Ukraine, the total number of which is much greater than the data presented in Table 1. Notably, information on individual plants located in the temporarily occupied territories (2024) is both limited and ambiguous, due to the complex territorial and political context. Nevertheless, thermal power plants across the country have historically provided heat to more than 25 cities in mainland Ukraine. However, even the largest and most modern of these facilities were designed and built between the 1960s and 1980s. During this period, there were substantial changes in both energy production technologies and demand for heat and electricity in the regions where these facilities are located. Table 1 presents the characteristics of the electric and thermal capacities of selected CHP plants in Ukraine for the period from 2014 to 2024.

***Table 1**. Characteristics of large CHP plants in Ukraine*

CHP plant name	Installed capacity		Year of commissioning	Fuel type
	electric, MW	heat, Gcal/year		
Kyiv CHP-5	700.0	974.0	1971-1976	Natural gas
Kyiv CHP-6	750.0	660.0	1982-1984, 2004	Natural gas
Kramatorsk	150.0	458.0	1936-1977	Natural gas/coal
Kremenchuk	255.0	671.0	1965-1969	Natural gas/fuel oil
Lviv	31.1	155.0	1930-1954	Natural gas
Myroniv	260.0	210.0	1953-1956	Natural gas/fuel oil
Mykolaiv	40.0	110.0	1949-1958	Natural gas/fuel oil
Odesa	68.0	205.0	1954-1984	Natural gas/fuel oil
Sevastopol	54.5	141.2	1937-1957	Natural gas
Siverskodonetsk	270.0	906.0	1956-1977	Coal/fuel oil
Simferopol	278.0	164.2	1958-1961	Natural gas
Kharkiv	62.0	293.0	1944-1970	Natural gas/fuel oil
Kharkiv CHP-5	470.0	700.0	1979-1990	Natural gas/fuel oil
Kherson	80.0	350.0	1956-1967	Natural gas/fuel oil
Kherson CHP-2	74.0	160.0	1952-1957	Natural gas/fuel oil
Cherkasy	200.0	648.0	1961-1969	Natural gas/fuel oil/coal
Chernihiv	210.0	409.0	1961-1974	Coal/fuel oil

***Source:** I. Volchyn et al. (2013)*

In Ukraine, the share of consumers served by district heating systems has increased substantially and stays quite high. This phenomenon is explained by the fact that, unlike in the European Union (EU), a considerable number of Ukrainian heat consumers are densely concentrated in multi-storey residential buildings. Furthermore, a large share of heat energy is consumed by industrial enterprises that do not have their respective boiler houses. In addition, long-distance heat transmission is generally less efficient. With this in mind, B. Basok *et al*. (2022) and O. Kyrylenko *et al*. (2022) concluded that attempts to restore the electricity and heat supply network to its pre-war state may not be feasible. They advocate instead for a comprehensive effort to integrate Ukraine's energy sector into the EU energy system (ENTSO-E), while respecting all relevant environmental standards.

In industrialised regions such as the United States, Japan, China, and the European Union, T. Papuha & O. Klymenchuk (2021) identified the growth in energy demand as a pivotal development trend. This trend requires procedural improvements, such as optimisation of energy management processes and development of innovative views on energy saving in production processes. European Union countries, together with other countries, have introduced various financing mechanisms and taxation schemes to mitigate the financial burden of introducing these innovative technologies. Energy saving policies emphasise increasing the share of renewable energy sources as a way to achieve their goals. The Energy Strategy until 2035 (Order of the Cabinet of Ministers..., 2023) should allow Ukraine to reach parity with developed countries.

Improving energy efficiency at Ukrainian enterprises is unattainable without a reliable energy management system and highly qualified specialists in the relevant fields. Combined heat and power plants, which are used for cogeneration of heat and electricity, play a major role in saving fuel in the energy system, which positively affects the efficiency of industrial production. The efficiency of fuel use at TPPs is assessed by the specific values of fuel consumption for the separate production of heat and electricity. These indicators are necessary for setting reasonable tariffs by specific heat and power producers, reflecting not only the efficiency of technological equipment, but also the broader economic activity of the energy company (Chepurnyi *et al*., 2011). A notable achievement in this area is the comparative analysis of combined heat and power systems of a steam turbine unit (STU-CHP) and a gas turbine unit (GTU-CHP), especially in scenarios involving equivalent electrical and thermal output.

The T-25-90 steam heat and power turbine serves as the basis for the STU-CHP system, demonstrating a total steam consumption of 130 t/h and a heating steam consumption of 90 t/h. In contrast, two configurations were investigated for the GTU-CHP system: one using a GTD-2500 gas turbine, which corresponds to the electrical capacity of an STU, and the other using two gas turbine units with a total thermal capacity equivalent to an STU. Experimental data from the study by M. Chepurnyi *et al*. (2011) substantiated the advantages of a combined heat and power scheme over separate heat and power generation. The use of STU-CHP systems can provide up to 40% savings in the use of conventional fuel, while the use of GTU-CHP systems considerably increases fuel economy. Still, when the electrical capacities of the STU-CHP and GTU-CHP are equivalent, the fuel savings show little change, with a slight decrease observed in the case of gas production.

L. Kesova & V. Khodakivskyi (2010) analysed Ukrainian CHP plants, covering about 250 units, most of which are small departmental industrial plants. The findings showed that most of these CHP plants are mainly fuelled by natural gas (76-80%), followed by fuel oil (15-18%), and hard coal (5-6%). However, the technical condition and extensive wear and tear of their process equipment is comparable to the problems faced in the heat and power sector. Therefore, to improve the economic and environmental performance of CHPs and large boiler houses operating in market conditions, it is essential to modernise and re-equip them with modern cost-effective technologies.

Considering the current stage of martial law (2024) and the subsequent post-conflict period, it is necessary to resume heat and power generation using mini-CHP systems. Additionally, STU and GTU boiler houses with a capacity of 25-50 MW should be considered. Therewith, the positive impact of technical re-equipment of small and mini-CHPs with advanced technologies may become more apparent after a long period of operation. Under martial law, the operation of CHPs to maintain heat loads in strict accordance with the schedules of heat consumers may somewhat limit their ability to balance the IPS of Ukraine (Zamulko & Dovgal, 2023). However, despite the inherent limitations of the existing fleet of coal-fired and natural gas-fired thermal power plants, there is still potential for their use in balancing the system. Analysing the current state of the IPS of Ukraine, considering the extent of damage caused to several TPPs, namely Burshtyn TPP, which has been using the stop-start methodology on its coal-fired unit for a long time to balance for long periods (up to 6 hours), shows that certain TPPs can still play a decisive role in ensuring reliable operation of the power system. However, this approach requires considerable state support, posing challenges against the backdrop of prevailing price constraints in the wholesale electricity market (WEM).

In 2019, Ukraine implemented one of its most complex and successful reforms by activating the WEM in July of that year. Notably, Ukraine implemented this reform in a much shorter time than other EU countries. By launching an energy market, Ukraine has demonstrated to both Europe and the international community its ability to quickly accomplish highly complex tasks (Zamulko & Dovgal, 2023). The WEM sector in Ukraine, as in other countries, is broadly segmented into generation, transmission, distribution, and consumption – each regulated by a separate regulatory and governance framework. The relevant government authorities set electricity tariffs, regulate the conditions of generation and transmission, and set quality standards for these segments.

In line with EU standards, trading in the new Ukrainian WEM takes place in several segments: the bilateral contract market (BCM), the day-ahead market (DAM), the intraday market (IDM), and the balancing market (BM). The introduction of price caps in the electricity market is a major challenge for all stakeholders – both public and private – due to the balance of economic requirements, environmental considerations and security of electricity supply. The factors that influence the introduction of price caps are multifaceted and context-specific and are based on concrete national energy policies. These factors are as follows:

- the dominant position of some companies in the WEM market, which can abuse their position and set low prices for the product, which can lead to challenges in ensuring the equilibrium between supply and demand in the WEM market;
- dependence on energy imports, which can lead to dependence on external suppliers and energy transportation costs, and such dependence leads to an increase in energy sector costs, which leads to an increase in electricity prices.

One of the mechanisms for introducing price restrictions on WEM is the regulation of energy supply tariffs. Such an approach allows the state to control electricity prices and maintain stability for consumers. This is usually achieved through state regulation of prices at the wholesale market level or through contractual agreements with energy companies. Alternative mechanisms include retail electricity trading, which allows consumers to choose the tariffs and suppliers that meet their needs and budgets. For this to be effective, there must be sufficient competition between electricity or heat suppliers. The state, through an authorised body, can regulate electricity prices by imposing excises and taxes on the electricity market.

The SWOT analysis considered in the study by A. Zamulko & M. Dovgal (2023) can serve as a fundamental tool for designing an optimisation model for the future development of CHPs. This model, considering the price constraints in the heat and electricity markets, will require CHP plants to find new ways to increase their competitive advantages, which will ensure optimum functioning of the process equipment. Competitive advantages may include the introduction of advanced technologies, the expansion of the renewable energy market, and the increase in the capacity of the CHP fleet.

CHPs and TPPs have many common positive and negative characteristics and are a full-fledged component of the IPS of Ukraine, which (the power system) is characterised by a lack of manoeuvring capacities in the production of electricity and heat due to the uneven schedule of their consumption. According to V. Zdanovsky & M. Kulyk (2021), a comprehensive analysis was performed, considering natural conditions, geographical location, available financial and economic opportunities, environmental constraints, and fiscal prospects. A balanced and sensible approach to such electricity and heat producers can help to synergistically integrate their positive attributes, thereby achieving an overall favourable outcome.

Since independence, Ukraine's electricity generation fleet, consisting mainly of thermal and nuclear power plants, has been designed to operate in the base-load segment of the electricity schedule. The need for flexible, manoeuvrable capacities has been exacerbated by the proliferation of renewable energy generation capacity due to the inherent challenges of storing and accumulating energy produced in the form of heat and electricity. Coal-fired TPP units can regulate the load within 30% of their rated capacity, but the capacities of HPPs and PHESs are insufficient to adequately address these challenges.

Demand for manoeuvrable power has increased, creating a potential threat of significant frequency fluctuations in the power grid, a phenomenon that is unacceptable and can trigger relay protection mechanisms, leading to system failures and localised power outages. This problem has become more acute with the onset of martial law and the subsequent destruction and seizure of coal-fired power plants, along with the disconnection of Zaporizhzhia Nuclear Power Plant (ZNPP), which consists of six power units of 1000 MW each, from the IPS. Risky but necessary measures have been taken to manage peak load scenarios under these stressful conditions. These measures include daily shutdowns of 200 and 300 MW units during the off-peak night period and operation of TPP and NPP units at capacities below the technical minimum. Notably, the operation of NPP units below the technical minimum is particularly dangerous.

At various TPPs, including the Burshtyn TPP, the problem was solved by shutting down coal-fired units at night and switching them back on in the morning. The frequency of these operations can reach up to 15 start-stop cycles per day on weekdays and Monday mornings. This means approximately 80 starts per week and around 320 starts per month. The annual additional starts of coal-fired power units required to regulate the electricity load schedule and maintain the standard grid frequency amount to approximately 3,800 starts per year. Consequently, coal-fired power units that were originally designed to operate within the baseload schedule are now often used within the semi-peak and sometimes even peak load schedule. This change leads to a 2 to 2.5-fold reduction in the number of operating hours and a reduction in the load on the power unit to 80% of its rated capacity, barely ensuring minimal profitability of the already heavily worn-out equipment.

According to practical estimates, each start-stop cycle is equivalent to a month of operation in terms of the level of wear of both the primary and auxiliary equipment of the power unit. The technological regulations, as well as the correction factor that accounts for equipment wear, indicate that each start-up consumes an extra 30 tonnes of fuel equivalent, which is on average equivalent to 1.3-1.5 tonnes of natural fuel, considering the calorific value. Thus, the direct fuel losses associated with the suboptimal use of coal-fired units as shunting power units amount to approximately 148.2-171.0 thsd tonnes per year. This amount of fuel could supply a 200 MW power unit for a little over a year. Considering the shortage of coal in Ukraine and the minimum price of UAH 600 per tonne, these losses amount to approximately UAH 90 million, or about USD 3 million. This calculation does not include other costs associated with replacing worn-out equipment and unscheduled or emergency repairs. To facilitate these launches, extra resources of critically scarce gas or fuel oil are required. As a result, the technical and economic performance of the equipment deteriorates substantially, leading to accelerated wear and tear of the power unit's equipment and an increase in the frequency of emergency repairs. For example, while in the late 1980s, the specific fuel consumption for electricity generated by TPPs was around 330-350 kgoe/kWh, as of 2024, it has increased by 30%.

The use of coal-fired TPPs to cover peak loads is typical for many power systems in countries with proven coal reserves and climatic conditions comparable to Ukraine's. These countries include the UK, Germany, Poland, Spain, and Kazakhstan. However, in these countries, coal-fired units have not reached the critical levels of wear and tear observed in Ukraine, and the capacity of individual units is much greater, which expands the range of power control. Notably, a modern 1000 MW coal-fired unit was built in Germany after the merger of its western and eastern regions, and two similar 800 MW units were built in Poland (Belchatów, Silesia).

In their work V. Zdanovsky & M. Kulyk (2021) propose the construction of one or two modern coal-fired units or large-capacity CCGTs (1000 MW) simultaneously with the decommissioning of technologically outdated and degraded coal-fired units. This strategy is aimed at aligning with the national emissions reduction plan. Despite the problems with gas supply, there is a need to accelerate the increase in domestic natural gas production. This increase in production will ensure the efficient operation of several combined-cycle gas turbine plants and gas turbine plants with a capacity of 150-200 MW in different regions. With simultaneous strict measures to reduce gas consumption, the additional use of gas for these relatively few STUs and GTUs would not be an excessive burden for the state but would provide considerable benefits in the short term. Furthermore, it is crucial to urgently complete the construction of a cascade of hydroelectric power plants (HPPs, PHESs) on the lower reaches of the Dniester, and to investigate the feasibility of creating a cascade of HPPs (mini-HPPs) on certain rivers in the Carpathian region. For this, combined-cycle power plants are particularly suitable (Energy Outlook, 2023; DiXi Group…, 2024), which can operate on solid fuel gasification products, including Ukrainian hard and low-grade coal. By applying advanced combustion technologies such as two- and three-stage combustion, cyclone pre-firing, and circulating fluidised bed (CFB) systems, compliance with environmental standards governing emissions of harmful substances into the atmosphere can be achieved.

As of April 2020, Ukrenergo's data indicate a constant mismatch between the maximum daytime load and the minimum nighttime drop, which stays at 5-6 GW, with an evening peak of 3-4 GW (Geletukha, 2020), and data indicate a shortage of manoeuvrable capacity of approximately 2 GW. The growing need for balancing energy sources places restrictions on renewables or nuclear power plants. Although the specific balancing periods may vary seasonally, their absolute duration (3 hours for the morning peak and 3 hours for the evening peak) is constant. The nighttime reduction in energy consumption and the corresponding reduction in renewable energy generation generally coincide in time. The challenge, however, lies in daily balancing, thus keeping the characteristic seasonal load profile in the grid constant (Kovetskyi & Kovetskaya, 2007; Klimenko *et al*., 2011).

To effectively manage the daily balancing of energy loads, it is imperative to have highly manoeuvrable capacities that can respond quickly within a typical timeframe of 15 minutes to 1 hour (Wachs & Engel, 2021; DiXi Group, 2023). These systems must be able to increase or decrease the load at the command of the dispatcher. Such requirements for the speed of response to load changes can be met by combined cycle or biomass or biogas CHP plants. As of 2020, approximately 180 MW of biomass and biogas capacities are operating in the Ukrainian power system. Forecasts according to the Order of the Cabinet of Ministers of Ukraine No. 605-r (2023) suggest that this capacity is expected to increase to 1.7-2 GW by 2035. For optimum performance in the peak load market, existing CHP plants should include slightly larger boiler units paired with powerful turbines, which contributes to the generation of more electricity. It is indicated that the tariff for the required amount of electricity should be approximately 0.273-0.279 EUR/kWh.

Another viable solution involves the deployment of gas turbine plants, specifically combined cycle plants. These steam plants are divided into steam-injected gas turbine (STIG) units and those that inject water or a steam-water mixture into the gas path (HAT and CHAT). In the STIG configuration, the steam produced in the waste heat boiler is injected into the high-pressure channel after the compressor, which enters the combustion chamber. In the Vodoley units, this disadvantage is mitigated by the introduction of a contact condenser that condenses the exhaust water vapour and returns the water back to the process. The unit includes an advanced gas turbine engine GTD DS-90 combined with a waste heat steam generator KUP-3100, a contact condenser KK-90, and a cooling system for water supplied to the contact condenser. Experimental tests demonstrated an efficiency range of 40-41%, while the level of nitrogen oxides NOx and carbon monoxide emissions did not exceed 50 mg/nm^3. In 1995, SE Research and Production Complex of Gas Turbine Construction Zorya-Mashproekt successfully commissioned a full-scale 25 MW Vodoley-25 contact gas and steam turbine unit in Ukraine. Further calculations performed by N. Dikyi *et al*. (2012) show that future Vodoley plants could potentially achieve a total efficiency of 55-57%. Furthermore, the gas turbine capacity can be increased by 30-60%, with fuel savings ranging within 20-25%. Therefore, there is considerable room for further improvement of this type of unit.

The efficiency of combustion of any organic fuel (solid, liquid, or gaseous) depends on a series of factors, the most significant of which is the presence of nitrogen in the air. Its reduction in the combustible fuel-air mixture not only leads to the production of fewer nitrogen oxides (second hazard class), but considering that this reaction is endothermic, the flue gas temperature increases, and fuel savings are possible. This allows not only increasing the level of environmental safety, but also reducing charges for emissions of harmful substances into the atmosphere. As a result of their analysis of existing technologies for enriching atmospheric air with oxygen, M. Kulyk *et al*. (2021) recommended focusing on membrane technologies that can easily ensure an oxygen concentration in the combustible mixture of 30-40%. Y. Chen *et al*. (2017) proposed a new gas and steam cycle (GSMC) using LNG/O2 (liquid natural gas/oxygen) as the working medium. This cycle integrates high efficiency power generation, energy storage, and CO2 sequestration. With a turbine inlet pressure of 40 MPa/800°C and a condensing temperature of 30°C, the output power efficiency reaches 49.2%, making it a promising solution for reducing emissions in the energy sector.

Notably, according to M. Kulyk *et al*. (2021), the combustion of 1 m^3 of natural gas requires 10.2 m^3 of oxidant at its normal concentration in the air, and at a concentration of 30%, the oxygen demand is 7.45 m^3; at an oxygen concentration of 40%, it is 5.36 m^3. The methodology recommended by the Ministry of Ecology and Natural Resources (Sectoral Guidance Document No. 34.02.305-2002, 2002) for calculating the total emissions of nitrogen oxides (NO_x and N_2O) using emission rates (k_{NOx} = 64.311 g/GJ and k_{N2O} = 0.1 g/GJ) is based on the following equation:

$$E_j = 10^{-6} \cdot k_j \cdot B_i \cdot Q_i^y, \quad (1)$$

where E_j is the gross emission of the jth pollutant for a certain period of time, t; k_j is the emission rate of the jth pollutant during the combustion of the ith fuel, g/GJ; B_i is the fuel consumption for the reporting period, t; Q_i^y is the lower heating value of the ith fuel, MJ/kg.

According to Equation (1), when using atmospheric air in the combustion process without enriching it with oxygen, and rounding the estimated calorific value of natural gas at the level of Q_r^i = 27.97 MJ/kg (GJ/t) to the value of 28 of the same dimension, the following nitrogen oxide emissions can be obtained: $E_{NOx} = 94.21$ t and $E_{N2O} = 0.1465$ t. And when natural gas is combusted in atmospheric air enriched with oxygen up to 40%, which is ensured by a certain set of membrane modules, the partial pressure of atmospheric nitrogen in the reaction mixture drops substantially. This greatly reduces the amount of raw materials required to produce nitrogen oxides, the most harmful toxic substances. The annual volume of natural gas was taken in the calculations to ensure the operation of the 25 MW Vodoley plant for 8,000 hours per year. Assuming that the emission rates in such a process will change by an insignificant amount, the share of harmful formations will decrease in proportion to the reduction of the oxidant, i.e., by 5.36 m^3/10.21 m^3 = 0.525 times. In this case, the gross emissions will be $E_{NOx} = 49.5$ t and $E_{N2O} = 0.077$ t. For environmental practitioners, such a considerable reduction in total emissions looks very reassuring.

According to studies and reports (Kulyk *et al.*, 2021; The National Commission..., 2021), it was found that to ensure the stable functioning of Ukraine's energy system, it is necessary to build highly manoeuvrable capacities and implement energy storage systems. Specifically, at least 1GW of highly manoeuvrable facilities with a quick start, capable of being fully activated within 15 minutes, and starting and stopping at least four times a day with a control range of at least 80% of the installed capacity, must be built. To maximise RES, it is necessary to increase the volume of highly manoeuvrable capacities to 2 GW. In addition, to stabilise the power system, it is necessary to introduce at least 0.5 GW of energy storage systems that will allow RES to be involved in balancing the power system and providing reserves. In the absence of RES involvement in balancing or NPP capacity constraints, the need for energy storage systems may increase to 2 GW.

By 2030, to implement the target scenario for the development of generating capacities, it is necessary to ensure a constant available operating capacity of at least 12 GW of TPPs. This can be achieved through the reconstruction of coal-fired TPPs and the implementation of emission reduction measures, or through the construction of new 1.2-1.5 GW of half-peak capacity. Based on the analysis, several key recommendations can be made to optimise the operation of combined heat and power plants and thermal power plants in the face of a shortage of manoeuvring capacities, considering environmental and economic aspects. The use of combined-cycle gas turbine plants can increase the efficiency of a power plant to 55-57% and reduce fuel consumption by utilising the heat of exhaust gases to produce steam. The introduction of gas turbines with steam injection (STIG) or water injection (HAT, CHAT) increases the manoeuvrability of the system and reduces emissions of harmful substances.

Enrichment of atmospheric air with oxygen up to 30-40% using membrane technologies reduces the volume of flue gases by almost half, which leads to a substantial reduction in emissions of nitrogen oxides (NOx) and nitrogen oxide (N2O). The use of natural gas in oxygen-enriched air can reduce annual gross NOx and N2O emissions by 47.5% and 47.3%, respectively. Considering the severe shortage of coal in Ukraine, it is necessary to increase domestic natural gas production and expand the use of biomass and biogas. This will help reduce dependence on imported energy resources and ensure stable operation of the energy system. The construction of new modern combined-cycle thermal power plants, reconstruction of boiler houses with their conversion into mini-CHPs, and completion of the construction of a cascade of pumped storage power plants on the Dniester River will help compensate for capacity losses and improve the manoeuvrability of the power system.

Thus, the key recommendations include the introduction of an energy management system, accelerating the development and deployment of combined cycle gas turbines (STUs) and gas turbine units (GTUs), and converting boiler houses into mini-CHPs to cover peak loads and balance the power system. The use of modern methods of oxygen enrichment for combustion, such as membrane technologies, will also help to improve fuel combustion efficiency and reduce harmful emissions. Table 2 summarises the systematic measures aimed at improving energy efficiency and grid stability.

***Table 2**. Summary of prospective measures to balance the IPS of Ukraine*

Measures	Means required to implement the measure	Implementation cost (high, medium, low)	Estimated timeframe for implementation of the measure, years	Startup duration, h
Implementation of an energy management system	Improvement of legislation, financial incentives for businesses and communities, implementation of a system for monitoring and managing energy resources	Low	3	–
Development of renewable energy storage	Installation of energy storage systems (batteries, tanks). At least 0.5 GW of energy storage systems	High	5-10	0.1-0.5
Modernisation of existing CHP and TPP plants	Equipment to improve efficiency and reduce emissions. Urgent reconstruction of TPP units or new construction of 1.2-1.5 GW of half-peak capacity. Ensuring a constantly available operating capacity of at least 12 GW of TPPs	High	3-7	hot – 80 min-2.5 h; cold – 3-6 h

Table 2. Continued

Measures	Means required to implement the measure	Implementation cost (high, medium, low)	Estimated timeframe for implementation of the measure, years	Startup duration, h
Implementation of highly manoeuvrable capacities	At least 1 GW of highly manoeuvrable capacities (gas turbine units, gas engine-based units) with a quick start (full activation from a stopped state – no more than 15 minutes, the ability to start and stop at least four times a day with a control range of at least 80% of the installed capacity). Integration of rapid response systems, process automation.	Medium	3-5	0.1-0.5
Use of combined cycle power plants	Efficiency increase up to 55-57% and reduction of fuel consumption due to utilisation of exhaust gas heat with steam production	High	3-7	0.25-2.5
Introduction of gas turbines with steam (STIG) or water injection (HAT, CHAT)	Installation of gas turbine units with steam or water injection to improve efficiency and fuel use. Automation of turbine control processes, modernisation of existing gas turbines.	High	4-8	0.15-1
Expand the use of biomass	Construction or modernisation of CHP plants for biomass combustion, introduction of biomass gasification technologies, development of biomass supply infrastructure, adaptation of existing boilers for biomass.	Medium	3-6	1-2
Construction of new modern CHP plants	Design and construction of new CHP plants with high efficiency and low emissions	High	5-10	0.15-1
Reconstruction and modernisation of boiler houses with conversion into mini-CHPs	Modernisation of existing boiler houses with the installation of cogeneration units, construction of mini-CHPs, ORC CHPs, introduction of combined heat and power technologies, and process automation.	Medium	3-5	0.15-1
Transition to distributed generation	Installation of small generation units (solar panels, wind turbines, micro-CHP), integration with existing grids, introduction of smart grids, financial incentives for investments in distributed generation	Medium	3-5	0.15-1
Involvement of industrial consumers in balancing the power system	Improvement of legislation and financial incentives for businesses to participate in balancing the energy system, installation of energy management systems, and creation of demand response programmes.	Low	2-4	–

Source: *developed by the authors*

The analysis of the data presented in Table 2 reveals substantial differences in the effectiveness, costs, and duration of various measures. For instance, measures involving the modernisation of existing CHP and TPPs, although costly, ensure considerable emission reductions and increase the efficiency of energy companies. On the other hand, the introduction of an energy management system is relatively inexpensive and quick to implement, making it an attractive measure for rapid energy efficiency improvements. The study findings also showed that measures with long implementation periods, such as the development of renewable energy storage, may require extra resources and planning, but their implementation is critical for the long-term stability and environmental sustainability of the energy system.

Conclusions

Having analysed the current state of Ukraine's unified energy system, it can be argued that the country is at a crucial stage in the development of its energy infrastructure. In the face of constant challenges, including military aggression and stringent environmental standards, Ukraine must adapt to new conditions and find effective solutions to ensure the stability of the energy system. The review of studies suggests that in the future, only STUs and GTUs will be able to compete with coal-fired power units in terms of regulatory capabilities and the minimum reasonable price of electricity supply when operating in a manoeuvrable mode. Reforming the electricity and heat supply system forms an integral part of this process. The transition to distributed generation, the introduction of innovative technologies such as cogeneration systems, gas turbine and steam turbine technologies are necessary steps to ensure the reliability and efficiency of the energy system. Modern combined heat and power plants and mini-CHPs can become vital elements for balancing the system, but their effectiveness depends on further modernisation and integration into the European energy network. A list of promising measures and areas that will help balance the IPS of Ukraine was identified as follows: implementation of an energy management system (this measure is characterised by low cost and short implementation time, which makes it a key step for promptly improving the efficiency of energy use); modernisation of existing CHPs, TPPs, and conversion of boiler houses into mini-CHPs (this measure contributes to a significant improvement in efficiency and reduction of emissions, which is important for ensuring environmental safety, increasing the manoeuvrability and reliability of energy supply); introduction of highly manoeuvrable capacities (this measure allows for flexibility and rapid response of the power system to changes in the energy load, which is critical for maintaining the stability of energy supply); development of renewable energy storage (the introduction of energy storage systems is strategically important for the balanced development of the power system, especially considering the growing share of renewable sources).

The authors of this study will continue to work in this area in their future research, specifically by exploring innovative technologies and solutions to improve Ukraine's energy system and industry. This will include assessing their impact on the environmental situation, economic aspects, as well as improving the reliability of the energy system, reducing the frequency of outages, and increasing its flexibility.

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Conflict of Interest

None.

References

[1] Basok, B., Dubovskyi, S., & Kudelya, P. (2022). Modern problems of CHP functioning in Ukraine. *Technical Electrodynamics*, 6, 52-57. doi: 10.15407/techned2022.06.052.

[2] Chen, Y., Zhu, Z., Wu, J., Yang, S., & Zhang, B. (2017). A novel LNG/O_2 combustion gas and steam mixture cycle with energy storage and CO_2 capture. *Energy*, 120, 128-137. doi: 10.1016/j.energy.2016.12.127.

[3] Chepurnyi, M., Tkachenko, S., & Pishenina, N. (2010). Performance indicators of energy installations for combined production of heat and electricity. *Scientific Papers of VNTU*, 1.

[4] Chernyavskyy, M., Dunayevska, N., Novoseltsev, O., & Eutukhova, T. (2024). Comparative assessment of electricity supply costs from different sources in baseload and regulated modes. *System Research in Energy*, 2(77), 4-15. doi: 10.15407/srenergy2024.02.004.

[5] Chowdhury, M.R., Jobayer, A.M., & Zhao, L. (2021). Potential of distributed energy resources for electric cooperatives in the United States. In *2021 IEEE/IAS 57th industrial and commercial power systems technical conference (I&CPS)* (pp. 1-9). Las Vegas: IEEE. doi: 10.1109/ICPS51807.2021.9416624.

[6] Deshko, V., & Karpenko, D. (2018). Technical-economic analysis of the creation of the thermal energy market in Ukraine. *Power Engineering: Economics, Technique, Ecology*, 2(52), 26-37. doi: 10.20535/1813-5420.2.2018.147336.

[7] Dikyi, N., Solomakha, A., & Suzdalskaya, E. (2012). Gas turbine unit "Vodoley" for combined production of electrical and thermal energy. *Energy Technologies and Resource Saving*, 3, 30-33.

[8] DiXi Group Summer Outlooks: Ukraine's own gas is enough, but electricity supply is expected to be in short supply. (2024). Retrieved from https://dixigroup.org/dixi-group-summer-outlooks-vlasnogo-gazu-dostatno-a-v-elektropostachanni-ochikuyetsya-deficzyt/.

[9] DiXi Group. (2023). *Development of distributed gas generation in Ukraine: Strategy and tactics*. Retrieved from https://dixigroup.org/wp-content/uploads/2023/11/alert_distributed-gas-generation_dixi_group-3.pdf.

[10] Energy Outlook. (2023). Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2023.pdf.

[11] Geletukha, G. (2020). Engagement of biomass CHP for power grid balancing in Ukraine. *Thermophysics and Thermal Power Engineering*, 42(3), 47-55. doi: 10.31472/ttpe.3.2020.5.

[12] Kiesova, L., & Khodakivskyi, V. (2010). Energy-saving technologies for small energy sector of Ukraine. *Power Engineering: Economics, Technique, Ecology*, 2, 36-42.

[13] Khalatov, A. (2016). Energy sector of Ukraine: Modern state and nearest prospects. *Herald of National Academy of Sciences of Ukraine*, 6, 53-61. doi: 10.15407/visn2016.06.053.

[14] Klimenko, V., Landau, Yu., & Sigal, I. (Eds.). (2011). *Energy: History, current state and future. Development of thermal and hydro energy*. Kyiv: Institute of Coal Energy Technologies.

[15] Kovetskyi, V., & Kovetskaya, M. (2007). Assessment of manoeuvring capabilities of power generating plants to ensure power quality. *Problems of the General Energy Sector*, 16, 47-53.

[16] Kulyk, M., Pavliuk, L., & Kozak, L. (2021). Improving environmental safety of gas turbine drives of gas pumping units. *Ecological Sciences*, 2(41), 16-23. doi: 10.32846/2306-9716/2022.eco.2-41.2.

[17] Kyrylenko, O., Sniezhkin,Yu., Basok, B., & Bazieiev, Ye. (2022). Energy sector of Ukraine: Possible scenarios for recovery and development. *Herald of National Academy of Sciences of Ukraine*, 9, 22-37. doi: 10.15407/visn2022.09.022.

[18] Order of the Cabinet of Ministers of Ukraine No. 605-r "On Approval of the Energy Strategy of Ukraine for the Period up to 2035 'Security, Energy Efficiency, Competitiveness'. (2023, April). Retrieved from https://zakon.rada.gov.ua/laws/show/605-2017-%D1%80#Text.

[19] Papuha, T., & Klymchuk, O. (2021). Foreign experience of energy saving: Prospects of its implementation at industrial enterprises of Ukraine. *Bulletin of Student Scientific Society*, 2(13), 245-249.

[20] Polyvianchuk, A., Semenenko, R., Kapustenko, P., Klemeš, J.J., & Arsenyeva, O. (2023). The efficiency of innovative technologies for transition to 4th generation of district heating systems in Ukraine. *Energy*, 263(D), article number 125876. doi: 10.1016/j.energy.2022.125876.

[21] Sectoral Guidance Document (GKD) No. 34.02.305-2002 "Emissions of Pollutants into the Atmosphere from Energy Installations". (2002, June). Retrieved from https://online.budstandart.com/ua/catalog/doc-page?id_doc=51507.

[22] The National Commission for State Regulation of Energy and Public Utilities approved the report on the assessment of compliance of generation in 2020. (2021). Retrieved from https://ua.energy/zagalni-novyny/nkrekp-zatverdyla-zvit-z-otsinky-vidpovidnosti-generatsiyi-u-2020-rotsi/.

[23] Volchyn, I., Dunaievska, N., Haponych, L., Chernniavskyi, M., Topal, O., & Zasiadko, Ya. (2013). *Prospects for implementing clean coal technologies in the energy sector of Ukraine*. Kyiv: HNOZIS.

[24] Wachs, E., & Engel, B. (2021). Land use for United States power generation: A critical review of existing metrics with suggestions for going forward. *Renewable and Sustainable Energy Reviews*, 143, article number 110911. doi: 10.1016/j.rser.2021.110911.

[25] Zamulko, A., & Dovgal, M. (2023). Analysis of prospects for the development of heat and power plants in Ukraine in the context of integration into the European space. *Proceedings of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine*, 66, 44-52. doi: 10.15407/publishing2023.66.044.

[26] Zdanovsky, V., & Kulyk, M. (2021). Selection of acceptable balancing of electricity production in Ukraine. In *Proceedings of the 5th international scientific and practical conference* (pp. 482-488). Kharkiv: Scientific Publishing Center "Sci-conf.com.ua".

Перспективи використання теплоелектроцентралей та котелень для балансування об'єднаної енергетичної системи України

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Анотація. Проведений аналіз сучасного стану енергетичної системи України, на основі чого звернена увага на дефіцит маневрових потужностей, великий обсяг викидів шкідливих речовин у атмосферне повітря, а також низьку енергоефективність основних технологічних процесів існуючих об'єктів генерації. Вказані недоліки характерні також і до виробників теплової енергії, а саме теплоелектроцентралей та промислових і комунальних котелень. Існуюча енергосистема України включає обидва типи виробників, в яких переважає якийсь вид енергії (електрична чи теплова). Метою статті була оцінка перспектив впровадження сучасних технологій для забезпечення стійкості систем з виробництва електричної та теплової енергії. Застосовані аналітичні методи, які підходять для порівняння газотурбінних та парогазових установок, систем акумулювання електричної та теплової енергії. Авторами проведений огляд різних технологій, які підвищують маневровість систем з виробництва вказаних видів енергії, а також знижують утворення шкідливих речовин за рахунок уникнення ендотермічних реакцій в процесі спалювання твердого, рідкого та газоподібного палива. Зміни у співвідношенні потужностей основних генеруючих об'єктів, побудованих у 60-ті роки 20-го століття, зношеності технологічного обладнання, яке на 80-90 % вичерпало свій технологічний ресурс, вказує на нестачу маневрових потужностей та її посилення в результаті руйнувань та знищення через військову агресію. Окремо підкреслена необхідність модернізації вугільних теплоелектростанцій з використанням сучасних технологій спалювання в середовищі, збагаченого киснем (до 30-40 %), атмосферного повітря. Для покращення маневровості вугільних блоків необхідно довести їх потужність до рівня 800-1000 МВт, а для суттєвого зниження викидів шкідливих речовин необхідно поєднання парової, газової та парогазової генерації. Розкрито перспективи розвитку високоманеврових потужностей шляхом реконструкції існуючих теплоелектроцентралей та переведення комунальних та промислових котелень у міні-теплоелектроцентралі для їх інтеграції в європейський енергетичний ринок. Результати можуть стати основою для формування державної енергетичної політики, яка сприятиме підвищенню стійкості та ефективності енергосистеми України, зменшенню її залежності від імпорту електричної енергії, дотриманню екологічних стандартів, як державного та європейського рівня та гарантуватиме енергетичну безпеку держави

Ключові слова: об'єкти генерації; паротурбінна та парогазова установка; збагачення киснем повітря; ендотермічні реакції; екологічна та енергетична безпека