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Technological possibilities of increasing the resilience of the power and district heating systems of Ukraine

Abstract. The decarbonization of the global economy has become a driving force behind the rapid development of wind and solar power plants. This process is also taking place in Ukraine, a signatory to the Paris Agreement aimed at reducing greenhouse gas emissions. The sharp increase in capacities of solar and wind power stations, due to the stochastic nature of their generation, has led to a number of systemic problems in the energy sector, including the significant excess of electricity generated by them. Given the insufficient flexibility of existing power systems and daily load variations, frequency regulation in the grid and power balance maintenance become significantly complicated, necessitating the refinement of existing methods and the application of new ones for their balancing. The purpose of this article is to identify the possibilities and assess the feasibility of the comprehensive application of Power-to-Heat technology along with electrical and thermal energy storage to enhance the resilience of power and heating systems, which also represents a scientific novelty. The conducted analysis and modeling have shown that the use of electric boilers as electric heat generators in Power-to-Heat technology provides much lower investment costs and greater maneuverable capacity compared to heat pumps. Heat pumps in Power-to-Heat technology are justifiably used in existing cooling systems, for example, in warehouses for storing chilled products, or when a large amount of thermal energy is required with minimal electricity consumption. By appropriately selecting the capacities of electric and thermal storage and the power of electric heat generators, it is possible to completely solve the problem of excess electricity from solar and wind power stations without imposing forced restrictions on their output power, thereby avoiding losses, which in the first half of 2021 in Ukraine amounted to no less than 17.2 million euro. This will also ensure the resilience and sustainability of energy systems,

reduce fuel consumption by district heating system boilers, leading to a decrease in greenhouse gas emissions. *Bibl. 63, Fig. 8, Tab. 2.*
Keywords: power system, district heating system, Power-to-Heat, electrical energy storage, thermal energy storage, electric boilers, heat pumps.

Introduction

The decarbonization of the global economy has driven the rapid development of wind (WPPs) and solar (SPPs) power plants. The stochastic nature of WPPs and SPPs generation caused a number of challenges for power systems. One of these challenges is the emergence of a significant electricity excess. This becomes especially noticeable as the share of these sources in the overall generation structure increases. The problem is exacerbated by insufficient power system flexibility and daily load changes. All this greatly complicates the frequency regulation in the grid and maintaining the balance of capacities [1]. These problems have arisen not only in the Integrated Power System (IPS) of Ukraine, but also in the power systems of many countries around the world, in some of which it has led to catastrophic consequences. An example is South Australia, where wind and solar energy provides more than 40 % of electricity generation. The blackout that took place there in 2016 [2] showed that to increase the resilience of power systems with a significant level of renewable energy sources in their structure, the requirements for meteorological forecasts and means of balancing the correspondence between the generated power and the load are sharply increasing.

One of the possible ways to utilize this excess electricity and ensure the sustainability of power systems is to use Power-to-Heat (PtH) technology [3]. PtH technology converts electrical energy into thermal energy with the help of electric heat generators (EHGs), which is transferred to the district heating system (DHS), where it is consumed and/or accumulated.

Studies using PtH technology elements are known. For example, in the article [1] it was studied the application of battery energy storage systems for use in frequency and power regulators in power systems. In [4–6], technical and economic studies were carried out on the application of EHGs as consumer regulators for power systems. There are also studies on the application of various types of electric [7, 8] and thermal energy storage [9], which have been widely used in practice in many countries. In the paper [10] it was analyzed the impact of structural changes on the decarbonization of district heating in Ukraine.

The authors were not aware of any previous works in which the research had been conducted PtH technology application electric and thermal energy storage systems to increase the sustainability and renewability of power and heat supply systems, which is the subject of this paper.

The purpose of the study is to determine and evaluate the possibility and feasibility of integrated application of PtH technology together with electric and thermal energy storage systems to increase the resilience of energy systems.

Power-to-Heat applications

The term Power-to-Heat [11] was first used when the need arose to utilize excess electricity generated by solar and wind power plants. PtH technologies convert electric energy to heat using electric heat generators, which can be electric boilers, heat pumps, and hydrodynamic heaters. Unlike traditional electric heating systems with nighttime thermal energy storage that fully covers the needs of consumers, PtH systems are hybrid, they also have traditional heat generators that use fossil fuels [11]. In general, PtH is understood as a large-scale centralized conversion of electric energy into heat in a multivalent energy complex that converts fuel into electricity and heat with high efficiency. An example is municipal utilities that operate district heating systems and additionally install electric heaters at their CHP plants and thus use PtH technology [12].

The amount of excess electric energy from renewable energy sources (RESs) can be significant, for example, in the Inner Mongolia region of China, curtailment wind farms accounted for 9 % of total production in 2014, and more than 30 % in 2012 [11]. When there is an excess of electricity in the power system, EHGs are switched on to convert this excess into thermal energy, while traditional heat generators reduce their capacity or accumulate this energy. To increase the flexibility and reliability of such a hybrid heat supply system, thermal storage and electric batteries energy storage are applied [11], which allow the utilization of cheap excess electricity for EHGs, store it and supply it to consumers when demand increases.

PtH technology is developing rapidly. It has already been implemented in Canada, China, Japan, the United States, and the EU countries — Denmark, Germany, Sweden, Switzerland, and the United Kingdom [11].

The advantage of this technology is that it can reduce the amount of generation restrictions from SPPs and WPPs, slightly increase electricity prices from them during hours of minimum demand, saving fuel in the production of thermal energy, and, accordingly, reduce greenhouse gas emissions. Denmark and Germany, which have a high percentage of RESs in their electricity supply, have seen an increase in the number of PtH projects over the past few years, with investments in district heating systems and industry. For example, in Aarhus (Denmark), an 80 MW electric boiler and a 2 MW heat pump were installed in an existing CHP plant to meet the needs of district heating consumers. The electric boiler and heat pump use excess electricity from the WPP, the maximum production of which occurs in the winter months (coinciding with the maximum demand for heat) [11]. A retrospective of the growth of the installed capacity of PtH technology in Denmark is shown in Fig. 1 [13].

The data shown in the figure indicate the predominant use of electric boilers in PtH technology compared to heat pumps, due to the high investment costs of the latter.

Another example of the implementation of PtH technology is the Flensburg city, located in northern Germany near the border with Denmark, where 98 % of residents are connected to the district heating system, which is one of the largest in Germany. In January 2013, a 30 MW electric boiler was commissioned in this city, which uses excess electricity

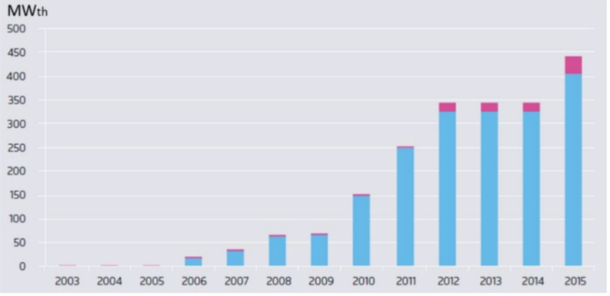

Figure 1. Installed capacity of Power-to-Heat technology in Denmark (electric boilers are marked in blue and heat pumps in red).

(at a low price) from wind farms to heat district heating water to 100 °C [13].

Currently, electrode boilers/electric heaters with a total capacity of more than 800 MW have already been installed throughout Germany, which, in combination with CHP and DHS, form highly efficient hybrid systems. In Europe, PtH technology has great potential for combining energy supply sectors and forming super-systems for converting electricity and heat in the future [12]. In countries with a very limited level of district heating, PtH technology can be used in industry [14].

The application of PtH technology in developed European countries is motivated by a number of legislative acts to limit the use of fossil fuels. For example, in Germany and Norway, new buildings are prohibited from installing heating boilers that use petroleum products. In the Netherlands, new buildings are not allowed to be connected to gas networks. As an incentive, the city of Lemgo (Germany), allows electric boilers to participate in the energy market for ancillary services [11].

The use of electricity from SPPs and WPPs for heating purposes, together with thermal accumulators, contribute to the decarbonization of the heat supply sector and increase the flexibility of energy systems [15].

In Ukraine, there is also a problem with the negative impact of SPPs and WPPs on the stability of the power system due to the stochastic mode of their generation and low flexibility of the power system. In 2021, the installed capacity of SPPs increased by 16 % and that of WPPs by 38 % compared to 2020, reaching 1529 MW and 6226 MW, respectively. At the same time, in 2021, the production of electricity by SPPs increased by 11 % compared to 2020, and by WPPs — by 20 %. This indicates a possible forced limitation of SPP and WPP generation in 2021, which is confirmed by the fact that the installed capacity utilization factor (ICUF) of SPP and WPP in 2021 were lower than in 2020 (11 % and 31 % vs. 12.3 % and 33 %, respectively).

The schedules of dispatchable power limits for SPPs and WPPs, which were applied in 2020 and 2021, based on the data of NPC Ukrenergo [16], are shown in Fig. 2.

As can be seen from Fig. 2, in 2021, the total monthly capacity curtailments of SPPs and WPPs increased sharply compared to 2020, which is explained by the corresponding increase in their installed capacities, while the maneuvering capacities

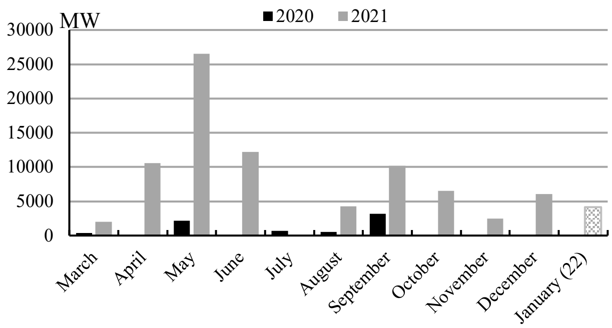

Figure 2. Total monthly generation capacity curtailments for SPPs and WPPs.

of the power system or flexibility remained unchanged. In 2022, the capacity curtailments of SPPs and WPPs began in January (see Fig. 2). That is, the IPS of Ukraine lacked sufficient maneuvering capabilities, and therefore, in the conditions of a power excess and exhausted unloading reserves, decisions were made to limit the generation of SPPs and WPPs to ensure the operational security of the power system. At the same time, the state paid the owners of SPPs and WPPs for the shortfall in the respective amount of electricity and incurred losses. According to the available information provided in [16], the amount of electricity not received from SPPs and WPPs for March, April, August, October, November and December 2021 was calculated, which amounted to about 217,000 MWh. The losses incurred by the state during this period amounted to about 17.2 million euro.

Given the fact that DHS are widespread in Ukraine [17, 18], they supply about 52 % of thermal energy (excluding industry). Therefore, the introduction of PtH technology, which consumes excess electricity from RESs, converting it into heat for the needs of consumers and thermal storage of DHS, is also relevant for Ukraine, which is also emphasized in the publication [19].

The main technological elements of the PtH technology are EHGs, electric and thermal energy storage devices. Electric and thermal energy storage devices have been repeatedly analyzed and their application considered (for example, in [8, 9, 20–38]). Less attention has been paid to electric heat generators, so only they will be analyzed further.

Electric heat generators

The main element of the PtH technology is an electric heat generator, which converts electrical energy to heat and determines the main technical and economic indicators of this technology. Currently, there are three types of EHGs: electric boilers, electrically driven heat pumps, and hydrodynamic heaters. Hydrodynamic heaters are produced with low power of about 15–45 kW [39], so they will not be analyzed.

Electric boilers

Compared to other types of boilers, electric boilers are safer and more environmentally friendly due to the absence of fuel combustion. They are easy to install and maintain (no storage facilities for fuel and its waste are needed), do not have a chimney, and have a fairly high efficiency (about 95–98 %) [40]. They are used both for heating systems and in industry. Depending on the method of heating the heat carrier, there are three types of electric boilers: tube heating element, electrode, and induction. All three types of electric boilers are characterized by ease of maintenance and control, require a minimum of preventive maintenance, and do not require highly qualified personnel for installation and maintenance. However, induction boilers are bulkier and more expensive than other types of electric boilers, and accordingly, they are not manufactured for high power. Therefore, induction boilers will not be considered.

A common disadvantage of all types of electric boilers is their highest operating costs compared to other types of heat generators (gas, solid fuel, heat pumps) [41], which are due to the very expensive energy resource – electricity. The only possibility to increase the efficiency and feasibility of implementation electric boilers is to use them during a excess of energy in the power system, or during a “nighttime dip” in the power system’s electric load, when the price of electricity is much lower. Thus, electric boilers can and should be used in PtH technology to consume excess electricity in the power system and to control its electrical load. At the same time, their main disadvantage becomes their advantage – the heat supply companies where they will be installed will receive cheap thermal energy and additionally a fee for providing ancillary services to power systems.

In electric tube boilers, the heating function is performed by tubular heating elements that heat the heat carrier. On the Ukrainian market, there are available tube boilers made in Ukraine (AVPE)

[42] and Finland (FIL-SPL) [43]. These boilers operate from a three-phase 380-volt grid and have a stepwise power control, with an efficiency of about 0.98.

Using the National Commission for State Regulation of Energy and Public Utilities of Ukraine (NERCEP) methodology for calculation the cost of non-standard connection services [44], the rates of payment for non-standard connection to the electricity grid were calculated for 24 large settlements (mainly regional centers) in Ukraine. For further calculations, their average value was used, which for the second category of consumers is: for networks with a voltage of 380 V — 88.8 euro/kW, and for a voltage of more than 6000 V — 78.9 euro/kW of installed electric capacity of the electric heat generating technology. Taking this into account, the total specific investment costs for implementation were calculated by the expression:

$$C^{ic} = C^{bc} + C^{gc}, \qquad (1)$$

where C^{ic} — specific cost of implementing an electric boiler, euro/kW; C^{bc} — specific cost of the boiler, euro/kW; C^{gc} — specific cost of connection to the grid, euro/kW.

The calculation results for boilers of different capacities are shown in Fig. 3.

As for the operating costs, according to the manufacturer of domestic AVPE boilers, the main cost element is heating elements. They are produced in 15 kW units, and according to the manufacturer, the cost of one module is 57 doll. The service life of these units is 3–5 years. To calculate the operating costs, let's consider a 1200 kW AVPE boiler. It has 80 units that will exhaust their lifespan in 5 years. The cost of replacing them will be: 80 units × 57 doll. = 4560 doll., 1 day of work of 3 mechanics and 2 electricians — 89 doll.,

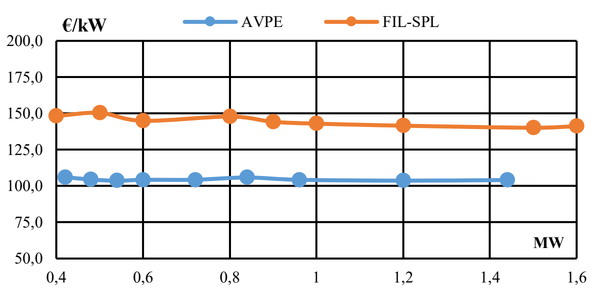

Figure 3. Specific investment costs for the implementation of heating boilers.

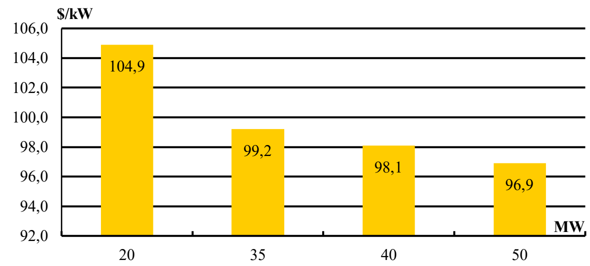

Figure 4. Specific investment costs for the implementation of electrode boilers.

total operating costs — 4649 doll. The average annual operating costs will be 930 doll./year or 0.775 doll./kW per year (0.680 euro/kW). According to the boiler supplier FIL-SPL, the average annual operating costs of a 1.2 MW boiler are 884 doll. or 0.737 doll./kW per year (0.646 euro/kW).

In electrode boilers, the elements for heating are the electrodes themselves, and the heat carrier (water), which has resistance, is heated by the electric current passing through it. Water molecules are split under the influence of current into positively and negatively charged parts (ions) that move between the electrodes [40]. These are high-voltage boilers (6–30 kV), which are produced for high power (over 50 MW) and are most commonly used in PtH technology. Some of the best powerful electrode boilers are manufactured by the Swedish company Zander & Ingestrцm. The company produces electrode boilers in the power range of 16–60 MW, supply voltage 6–20 kV, power control range 0–100 % [45]. The cost of a 50 MW boiler is about 900 thousand euro [46]. Using formula (1) and the data given in [46], we calculated the specific investment costs for the implementation of these electrode boilers. The calculation results are shown in Fig. 4.

The specific operating costs for electrode boilers are assumed to be 0.495 euro/kW per year.

Heat pumps

Heat pumps (HPs) have a number of undeniable advantages over other heat generation technologies, provided that low-potential heat sources are available and there are heat consumers in the places of their location. As shown in [47], in densely built-up settlements, heat pumps that use low-potential heat are the most suitable for Ukrainian DHSs: ambient air, ventilation emissions from buildings, flue gases from powerful boiler houses and CHP plants, sewage, seas and rivers, soil and groundwater, and technological processes. In [48] it is shown that the total thermal potential of the above sources in Ukraine is 4.97 GW, which allows the use of heat pump units in DHSs with a total capacity of about 7.5 GW.

Available powerful industrial HPs cover a wide range of operating temperatures. Heat carrier supply temperatures of up to 80 °C can be achieved with standard compression HPs. High-temperature HPs reach temperatures of up to 100 °C. Ultra-high-temperature HPs provide a supply temperature of up to 165 °C. The maximum heat supply temperatures and heating capacities of 26 industrial HPs from 15 manufacturers are illustrated in Fig. 5 [49].

Heat pumps are considered large (powerful) if their capacity is more than 100 kW. HPs are mass-produced in the range from few units to several tens of megawatts (50 MW) of thermal capacity. An analysis of the literature [50–53] and a number of investment proposals allowed us to determine the specific investment costs for heat pumps that are most commonly used in cities [53]. The assumption was made that due to cheaper materials and labor in Ukraine, the specific investment costs for the implementation of heat pump installations will be 15–20 % lower (Table 1) than those given in [53].

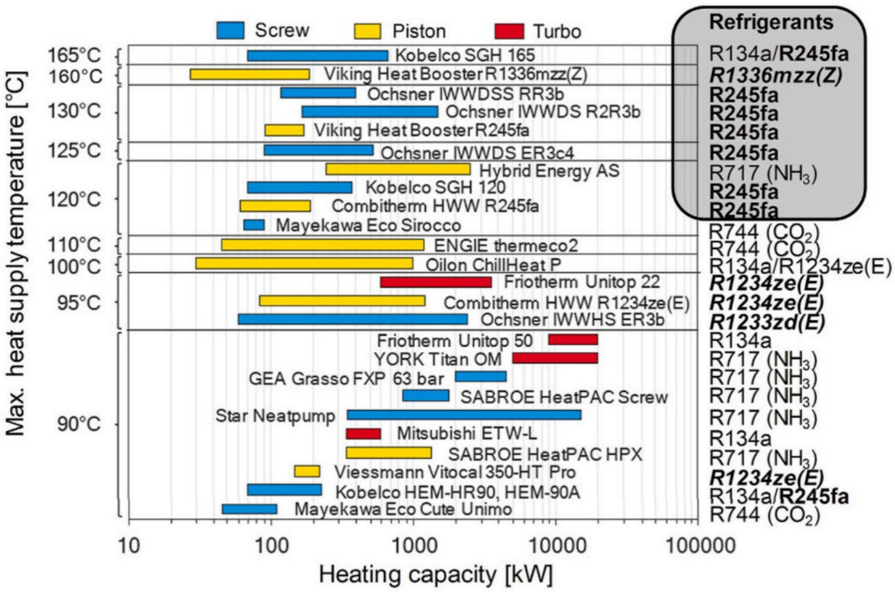

Figure 5. Commercially available industrial HPs that provide temperatures above 90 °C (compressor types: blue — screw compressor; yellow — reciprocating compressor; red — turbocharger) [49].

Table 1. Technical and economic indicators of heat pumps for use in Power-to-Heat technology

Low-potential heat source	Thermal capacity of unit, MW	Electric load, MW	Conversion rate	Specific project costs, euro/kW
Air, ventilation emissions	1.0	0.286	3.5	750
Waste gases from thermal power plants and boiler houses	1.0	0.25	4	443
Waste water	1.0	0.25	4	1023
Waste heat from industrial processes	2.2	0.55	4	704
Soil and groundwater	1.0	0.286	3.5	983

Note. Operating costs are usually assumed to be 1–2 % of the total project costs.

A simplified structural diagram of the use of PtH technology in the power system (PS) and DHS is shown in Fig. 6.

The algorithm of the supersystem shown in Fig. 6 may be as follows. When excess power from WPPs and SPPs occurs and the regulating reserve for unloading is exhausted, the power system accumulates electric energy with the possibility of further discharging it in peak zones. When the electric storage systems are full, the excess electricity is consumed by PtH technology ETGs, which convert it into thermal energy. To maintain the heat balance in accordance with expression (3), boiler houses and CHP plants reduce heat production, thereby reducing natural gas consumption and, accordingly, greenhouse gas emissions. It is easy to show that when converting every 10 MWh of excess electricity with PtH technology, 8.43 Gcal of thermal energy will be produced and natural gas consumption by DHS boilers will be reduced by about 1100 m^3, which will lead to a reduction in greenhouse gas emissions by 2.04 tons. If it is not possible to fully consume the thermal energy generated by the EHG, its excess is accumulated in the main heating networks and accumulator tanks for operational needs. When they are full, the rest of the heat energy is accumulated in seasonal heat storages. By selecting the appropriate capacities of electric and thermal accumulators and capacities of EHGs, the problem of excess electricity from WPPs and SPPs can be completely solved without resorting to forced curtailment of their output.

In addition to the use of excess electricity, PtH technology can use cheap excess electricity during the nighttime dip in the electric load, where EHGs can be used as consumer-regulators [5, 54]. By consuming this electricity, EHGs will also produce cheap thermal energy, which can be consumed and/or stored in thermal storage (especially during the non-heating period). The stored thermal energy can be used in the DHS during peak loads of the power system, providing a service of load reduction by disconnecting the EHGs. In addition to cheap thermal energy, heat generating companies can earn additional profit by providing services to regulate the load of the power system (participation in the ancillary services market).

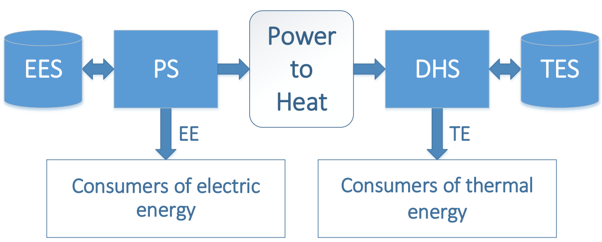

Figure 6. Scheme of using Power-to-Heat technology: EES – electric energy storage, TES – thermal energy storage, TE – thermal energy, EE – electric energy.

In a generalized form, in the first approximation, the balance of electric power of the PS is described by the expression:

$$P_t^{DS} + P_t^{VS} \pm P_t^{RS} \pm P_t^{ES} \pm P_t^{F} - Z_t^{L} - Z_t^{EHG} = 0\,, \qquad (2)$$

where t is time; P_t^{DS} is the power of dispatchable sources (TPPs, CHPs, NPPs, HPPs); P_t^{VS} is the power of variable sources (WPPs, SPPs); P_t^{RS} is the power of regulating sources (TPPs, PHPPs); P_t^{ES} is the power of electric energy storage systems; P_t^{F} is the power of electricity flow; Z_t^{L} is the power of electric load; Z_t^{EHG} is the power of electric heat generators (electric boilers, heat pumps).

The balance of thermal power of the DHS can be represented by the following expression:

$$q_t^{B} + q_t^{CHP} - q_t^{L} + q_t^{EHG} \pm q_t^{TS} = 0\,, \qquad (3)$$

where q_t^{B} is the capacity of boilers; q_t^{CHP} is the capacity of CHP; q_t^{L} is the capacity of heat load; q_t^{EHG} is the capacity of electric heat generators; q_t^{TS} is the capacity of thermal storage.

In the balance equation of the existing power systems, there are no P_t^{ES} and Z_t^{EHG} components, and in the DHS no q_t^{EHG} and q_t^{TS}. Therefore, the sustainability of power systems is ensured if:

$$P_t^{RS} \geq \Delta Z_t^{L} + \Delta P_t^{CS}\,, \qquad (4)$$

where ΔZ_t^{L} is the change in the electric load of the power system; ΔP_t^{CS} is the change in the capacity of WPPs and SPPs.

If condition (4) is not met and the maneuvering reserve is exhausted, the power system dispatcher is forced to change the capacities of TPPs and, if necessary, to shut down 200 MW and 300 MW TPP units. If all the reserves are exhausted, the power of WPPs and SPPs is forced to be limited to ensure the balance.

The resilience of existing power systems is ensured by starting up additional TPP units (or shutting down operating ones) and/or changing the power flow capacity between power systems.

There are no problems with ensuring the stability of the existing DHSs at all (if fuel is available).

In the new structure, the sustainability of the power system is ensured under the following conditions:

$$P_t^{RS} \pm P_t^{ES} + Z_t^{EHG} = \Delta Z_t^{L} + \Delta P_t^{CS} . \quad (5)$$

As can be seen from expression (5), additional components of P_t^{ES} and Z_t^{EHG} can provide wider opportunities to maintain the balance of power and sustainability of power systems (P_t^{ES} is actually an additional source that can either generate or consume electricity in the event of a sharp decrease in load or total generation capacity). A broader application of electrical storage in energy systems is discussed in [21, 29].

The feasibility of using PtH technology will be determined by a comparative techno-economic analysis. The weighted average tariff for thermal energy generation for 2021, which was calculated on the basis of the data given in [55], was taken as a criterion, and the Marginal Levelized Price of Energy (MLPOE) [56] was compared with it.

Unlike LCOE, this indicator, in addition to costs, takes into account all potential revenues from the introduction of a particular technology. In fact, MLPOE is the minimum weighted average break-even price of thermal energy produced by PtH technology, which is determined by the formula:

$$MLPOE_k = LCOE_k + LCOP_k , \quad (6)$$

where $MLPOE_k$ is the marginal levelized price of heat energy of the k-th technology implemented at the enterprise; $LCOE_k$ is the levelized cost of heat energy of the individual k-th heat generating technology; $LCOP_k$ is the levelized cost profit of the heat generating enterprise from the implementation of the k-th heat generating technology.

The expression for calculating the levelized cost of heat energy for the k-th type of heat generating technology can be written in the form:

$$LCOE_k = \frac{IC_k + \sum_{t=1}^{T_r}\left[\left(C_{kt}^{moe} + C_{kt}^{fer} + C_{kt}^{ghe} + \sum_j C_{jkt}^{pe} + C_{kt}^{ip} + C_{kt}^{dc}\right)(1+r)^{-t}\right]}{\sum_{t=1}^{T_r} Q_{kt}(1+r)^{-t}} \quad (7)$$

where IC_k are the investment costs; t is the period of project operation (year); T_r is the operational lifespan of the k-th type of heat-generating technology (years); C_{kt}^{moe} are the cost of maintenance and operation for period t; C_{kt}^{fer} are the cost of fuel and energy resources for period t; C_{kt}^{ghe} is the payment for greenhouse gas (GHG) emissions for period t; C_{jkt}^{pe} is the payment for emissions of the j-th pollutant for period t; C_{kt}^{ip} are the interest payments on the loan for period t; C_{kt}^{dc} are the funds allocated for the decommissioning of the technology at the end of period t; Q_{kt} is the amount of heat produced for period t; r is the discount rate.

The levelized benefits of the heat generating enterprise from the implementation of the k-th heat generating technology are determined based on the expression:

$$LCOP_k = \frac{\sum_{t=1}^{T_r}\left[\left(P_{kt}^{as} + P_{kt}^{rng} + P_{kt}^{ghe} + P_{kt}^{pe} + P_{kt}^{ob}\right)(1+r)^{-t}\right]}{\sum_{t=1}^{T_r} Q_{kt}(1+r)^{-t}} , \quad (8)$$

where P_{kt}^{as} are the benefits from the provision of ancillary services when implementing the k-th type of electric heat or cogeneration technology; P_{kt}^{rng} are the profit from reducing natural gas (fuel) consumption when implementing the k-th type of heat generating technology; P_{kt}^{ghe}, P_{kt}^{pe} are the benefits from reducing greenhouse gas and pollutant emissions due to reduced fossil fuel consumption, respectively; P_{kt}^{ob} are other benefits (sale of electricity by cogeneration units, provision of cooling services when using heat pumps, reduction of maintenance and operation costs, etc.) As a limiting factor, the simple payback period of investments (Pb) was chosen.

Let's assume that in 2021, the curtailment of WPPs and SPPs amounted to 15 % (1394.3 thousand MWh) of their total electricity production, which amounted to 9295.3 thousand MWh.

In 2020, according to the data provided in [57], standalone boiler houses, TPPs, CHPs, NPPs, heating network enterprises, other enterprises, organizations, institutions with boiler houses, heating networks, individual boilers, and other heat supply sources supplied 88954.1 thousand Gcal, including DHS – 46256.1 thousand Gcal or 53795.8 thousand MWh (52 % of the total supply). Let's assume that in 2021, DHSs supplied the same amount of heat energy as in 2020. During the heating season, Ukrainian DHSs supplied about

46264.4 thousand MWh of heat energy. Therefore, there will be no problem with the conversion of 1394.3 thousand MWh of excess electricity into heat (1366.4 thousand MWh) and its consumption during the heating season. The existing heat generators that consume fossil fuels will simply reduce their own heat production. We will make a similar estimate for the non-heating period. In recent years, there have been significant changes in the field of centralized hot water supply. The availability of relatively cheap electric water heaters (boilers) on the Ukrainian market and unreasonable pricing policies for natural gas and electricity have led to massive decentralization processes.

For example, in Zaporizhzhia, the heat supply company lost about 75 % of its hot water customers. In a number of cities (Mykolaiv, Kherson, Odesa, Bila Tserkva), CHP plants are shut down due to the lack of hot water consumers during the non-heating season. Based on the above, it was assumed that the average heat load of hot water supply systems in the non-heating period of 2021 was 2100 MW, and heat production amounted to 7378.6 thousand MWh (6434.4 thousand Gcal), which is about 14 % of the total annual heat supply. Comparing the heat production of the DHS in the non-heating period with the amount of heat energy from the PtH technology (1366.4 thousand MWh), we can conclude that all of it can be consumed without the use of seasonal batteries. If operational accumulation is necessary, the DHS main heating networks can be used, the total capacity of which is 30155 MWh in the non-heating period [35]. Therefore, the MLPOE of PtH technology was calculated only for the costs of an electric heat generator, taking into account the full costs of its connection to electricity and heat networks, as well as the benefits of reducing payments by saving natural gas and reducing greenhouse gas and pollutant emissions.

Initial data for the calculation: weighted average tariff for thermal energy generation — 2205 UAH/Gcal; project life cycle — 20 years; own funds — 15 %, borrowed funds — 85 %; unforeseen expenses — 10 %; discount rate calculated as the weighted average of the cost of equity and borrowed capital — 6.6 %; repayment period of borrowed funds — 5 years.

In the calculations, the range of electricity prices was chosen based on their weighted average value in different market segments [58, 59], tariffs for transmission, distribution, and dispatch control [60–63], and the cost of supply as of 2023.

<u>Use of electric boilers in PtH technology:</u> electric boiler capacity — 20 MW; efficiency — 0.98; specific design costs — according to Fig. 4 (104.9 euro/kW); total investment costs — 2307.8 thousand euro; specific operating costs — 0.495 euro/kW per year; installed capacity utilization factor (variable) — 10, 20, 30, 40 %; cost of excess electricity (variable) — 35, 40, 45, 50, 55, 60, 65, 70 euro/MWh; cost of electricity during nighttime dip in the electric load profile — 55, 60, 65, 70, 75, 80 euro/MWh.

<u>Use of HP in the PtH technology:</u> heat output of HP — 1 MW; sources of low-potential heat: ventilation emissions (air), flue gases of boilers and CHP plants, wastewater; conversion factor (COP) of HP — 3.5 (for ventilation emissions), 4.0 (for flue gases and wastewater); annual installed capacity utilization rate — 60 % (normal operation of most HP); specific design costs — according to Table 1, specific operating costs — 2 % of total project costs; overhaul costs — 30 % of total project costs.

The results of calculations of the use of a 20 MW electric boiler showed that the total investment costs amount to 2307.8 thousand euro, and the maneuvering capacity is 20.4 MW. Accordingly, the specific investment cost per unit of maneuvering capacity is 113.1 euro/kW (2,307,800/20,400). The MLPOE of thermal energy at different values of the ICUF and prices for excess electricity are shown in Fig. 7.

As can be seen from Fig. 7, the field of feasibility of using PtH technology at different ICUFs and the cost of excess electricity is limited by the heat tariff line. The higher the ICUF, the

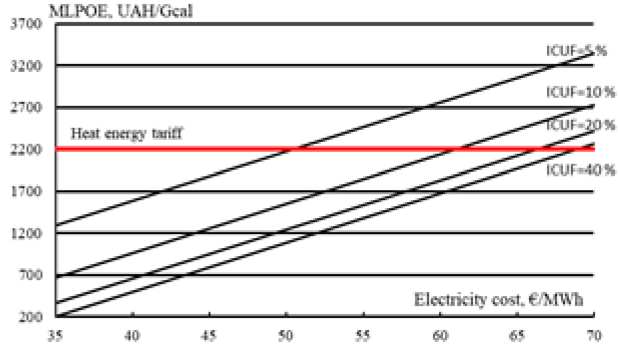

Figure 7. MLPOE for Power-to-Heat technology with a capacity of 20 MW.

higher the price of electricity can be purchased. Even with an ICUF of 5 %, the technology will not be unprofitable if the cost of excess electricity is no more than 50 euro/MWh, and with an ICUF of 40 % — 69 euro/MWh.

When using PtH technology during the “nighttime dip” in the electric load profile (ELP), the electric boiler will operate 2920 hours per year (ICUF = 33.3 %). When calculating the MLPOE indicators, in addition to the profits mentioned above, the profit from providing ancillary services to the power system was also considered (9.48 euro/MWh was taken). The calculation results are shown in Fig. 8.

As can be seen from Fig. 8, it is advisable to use the PtH technology not only in the presence of excess electricity, but also during the nighttime dip in the ELP. In this case, break-even of thermal energy is ensured at higher electricity prices (about 82 euro/MWh), and an acceptable payback period is ensured at an electricity cost of 75 euro/MWh.

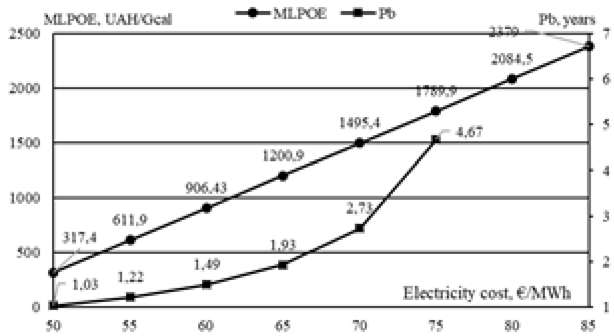

Figure 8. MLPOE for Power-to-Heat technology when used during the nighttime dip in the electric load profile.

The results of calculations of the use of HPs in PtH technology showed that the total investment costs for HPs using low-potential energy of flue gases from boiler houses and CHPs are 487.3 thousand euro, ventilation emissions and air — 825 thousand euro, wastewater — 1125.3 thousand euro. The maneuvering capacity is 0.29 MW for HPs using ventilation emissions and air, and 0.25 MW for the rest. Accordingly, the specific investment costs per unit of maneuvering capacity for the HPs that use flue gases are 1680.3 euro/kW, ventilation emissions and air — 3300 euro/kW, and wastewater — 4501.2 euro/kW. The MLPOE and Pb indicators are shown in Table 2.

As can be seen from Table 2, the MLPOE in the entire accepted range of electricity prices and for all considered sources of low-potential heat is much lower than the weighted average heat tariff (2205 UAH/Gcal). The payback period is acceptable only when HP use flue gases and ventilation emissions and air as sources of low-potential heat.

Comparing the results of calculations when using electric boilers and heat pumps in PtH technology, it should be noted that electric boilers should be used to obtain the maximum maneuverable power, and heat pumps should be used to obtain the maximum amount of heat energy produced.

Due to the fact that the investment costs for the implementation of HP are significant, it is advisable to use existing heat pump cooling systems,

Table 2. MLPOE and Pb values when using HP in Power-to-Heat technology

Electricity cost, euro/MWh	Low-potential heat source					
	Flue gases		Ventilation emissions, air		Waste water	
	Indicators					
	MLPOE, UAH/Gcal	Pb, years	MLPOE, UAH/Gcal	Pb, years	MLPOE, UAH/Gcal	Pb, years
95	25.5	2.0	500.6	4.3	898.3	7.7
100	97.6	2.1	583.1	4.5	970.4	8.1
105	169.7	2.13	665.5	4.8	1042.6	8.6
110	241.9	2.21	747.9	5.1	1114.7	9.2
115	314	2.3	830.4	5.4	1186.8	9.9
120	386.1	2.39	912.8	5.7	1258.9	10.6
125	458.2	2.49	995.2	6.1	1331.1	11.5
130	530.4	2.6	1077.7	6.5	1403.2	12.6

for example, warehouses for storing chilled products. A similar idea was proposed by a group of scientists from research organizations and universities in the Netherlands, Denmark, Spain, and Bulgaria in the Night Wind project, aimed at creating a pan-European system for storing energy generated by wind power plants [63]. The idea is that when there is an excess of electricity in the grid, refrigerators consume more electricity and lower the temperature of the food stored in them by several degrees. When the electrical load is high, the refrigerators are disconnected from the grid until the temperature rises to a predetermined value.

Conclusions

The analysis has shown that one of the most effective technological methods of increasing the resilience of energy systems in the world is the use of Power-to-Heat technology, electric and thermal storages.

The use of electric heat generators of the Power-to-Heat technology, electric and thermal energy storages can significantly increase the sustainability and renewability of the electric and thermal energy systems of Ukraine. By properly selecting the capacity of electric and thermal storages and the capacity of electric heat generators, it is possible to completely solve the problem of excess electricity from solar and wind power plants without introducing a forced limitation of their capacity, thereby avoiding losses, which in half of 2021 in Ukraine amounted to at least 17.2 million euros.

Conversion of every 10 MWh of excess electricity by Power-to-Heat technology into heat will reduce natural gas consumption by district heating boilers by about 1100 m^3, which will lead to a reduction in greenhouse gas emissions by 2.04 tons.

The use of electric boilers as electric heat generators in Power-to-Heat technology provides much lower investment costs and greater maneuverability compared to heat pumps. It is advisable to use heat pumps in Power-to-Heat technology in existing cooling systems, such as warehouses for storing chilled products, or when it is necessary to obtain a large amount of thermal energy with low consumption of electric energy.

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Технологічні можливості підвищення резильєнтності систем електро- та централізованого теплопостачання України

Анотація. Енергетична інфраструктура України переживає період значних трансформацій, зумовлених як зростанням частки відновлюваних джерел енергії, так і взятих Україною екологічних зобов'язань. Різке збільшення потужностей сонячних та вітрових електростанцій через стохастичний характер їх роботи обумовило низку проблем із забезпечення резильєнтності (стійкості та відновлюваності) енергосистем, що вимагає вдосконалення методів та засобів їх балансування. Метою статті є визначення можливості та оцінка доцільності комплексного застосування технології Power-to-Heat разом з акумуляторами електричної та теплової енергії для підвищення резильєнтності електроенергетичних та теплоенергетичних систем, що також є науковою новизною. Поставлені цілі досягнуті методом порівняльного техніко-економічного аналізу та здійсненням моделювання використання технології Power-to-Heat в централізованому теплопостачанні. Виконаний аналіз та моделювання показали, що, вибираючи належним чином ємності електричних та теплових акумуляторів, а також потужності електричних теплогенераторів, можна повністю вирішити проблему надлишкової електроенергії від сонячних та вітрових електростанцій без введення примусового обмеження їх потужності, тим самим уникнути збитків, які за І половину 2021 року в України становили не менш 17,2 млн євро. *Бібл. 63, рис. 8, табл. 2.*

Ключові слова: енергосистема, система централізованого теплопостачання, Power-to-Heat, накопичувачі електроенергії, теплові акумулятори, електричні котли, теплові насоси.

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