https://heatpumpingtechnologies.org/annex47/wp-content/uploads/sites/54/2019/07/heat-roadmap-europe.pdf

31. Bach B., Werling J., Ommen T.S., Mьnster M., Morales Gonzбlez, J.M., & Elmegaard B. Integration of large-scale heat pumps in the district heating systems of Greater Copenhagen. *Energy*. 2016. Vol. 107. pp. 321–334. DOI: 10.1016/j.energy.2016.04.029.

32. Waste-to-Energy Plant Sysav Malmц, enhancing the overall Energy Efficiency with 2 Unitop® 28C heat pump units. — https://www.friotherm.com/wp-content/uploads/2017/11/sysave006_uk.pdf

33. Large scale heat pumps in Europe. 2020. Vol. 2. — https://www.ehpa.org/wp-content/uploads/2022/11/Large-heat-pumps-in-Europe-and-industrial-uses_2020.pdf

34. Wolf S., Blesl M. Model-based quantification of the contribution of industrial heat pumps to the European climate change mitigation strategy. *Proceedings of the ECEEE Industrial Efficiency Conference 2016*. Berlin, 12–14.09.2016. Stockholm, 2016. 4-061-16_Wolf.pdf

35. A Renovation Wave for Europe — greening our buildings, creating jobs, improving lives. COM (2020) 662 final. Ur-lex.europa.eu/resource.html?uri=cellar:0638aa1d-0f02-11eb-bc07-01aa75ed71a1.0003.02/DOC_1&format=PDF

36. Market data. EHPA. — https://www.ehpa.org/market-data/

37. The Future of Heat Pumps, 2022. — https://www.iea.org/reports/the-future-of-heat-pumps

Received May 9, 2023

UDC 620.92
DOI: 10.33070/etars.2.2023.03

Derii V.O., *Candidate of Technical Sciences, ORCID: 0000-0002-5689-4897,*
Teslenko O.I., *Candidate of Technical Sciences, ORCID: 0000-0002-3772-5991,*
Sokolovska I.S., *Candidate of Technical Sciences, ORCID: 0000-0003-1959-9837*
General Energy Institute of the National Academy of Sciences of Ukraine, Kyiv
172, Antonovycha Str., 03150 Kyiv, Ukraine, e-mail: info@ienergy.kiev.ua

Methodical approach to estimating the potential of thermal energy production by heat pump plants in case of their implementation in regional district heating systems

The results of the estimation of the annual potential for thermal energy production using heat pumps (HPs) in district heating systems (DHS) for the regions of Ukraine and the country as a whole are given. This study is relevant due to the high level of DHS development in Ukraine, which reaches 52 %. Today, the outdated equipment of DHSs in Ukraine needs significant technological modernization. Also, in the near future, it will be necessary to restore DHSs destroyed as a result of the total destruction of the civil infrastructure by the russian aggressor. The post-war reconstruction of Ukrainian cities has a unique chance to radically update DHSs using renewable energy sources and innovative technologies, including HPs. The authors propose a new methodical approach for the regional determination of the forecast implementation scope of HPs in DHSs. Using this approach, the economically available energy potential of thermal energy production by HPs in DHSs from various low-potential heat sources (LPHS) was determined, both for the regions of Ukraine and for the country as a whole. As of 2020, this energy potential for DHSs of Ukraine is 62.601 million Gcal/year (262.1 PJ/year): 22.2 % is provided by natural LPHS (heat of air (2.2 %), river water (16.9 %), ground and groundwater (3.1 %)) and 77.8 % is provided by anthropogenic LPHS (heat of ventilation emissions of buildings connected to the DHS (43.0%), sewage water (9.7 %), flue gases from boilers and combined heat power plants (14.3 %), cooling water of technological processes (10.8 %)). The calculated energy potentials for the thermal energy production by HPs from various LPHSs for DHSs of 24 regions of Ukraine are presented also. Information from scientific publications, regulatory documents, annual reports of the State Statistical Service of Ukraine and other government agencies used as the initial data for calculations. Approved methods of heat engineering calculations, methods of statistical and calculation-comparative analysis using Microsoft Excel computer software used to calculate and visualize the results. Methodical recommendations for determining the priority and locations for the implementation of HPs in regional DHSs of Ukraine, which developed by the authors of the article, are presented. *Bibl. 48, Fig. 2, Tab. 4.*

Keywords: district heating systems, heat pumps, low-potential heat sources.

Introduction

District heating systems are one of the effective and promising means for providing thermal energy to consumers. In Ukraine, the level of centralization of heating systems is quite high, although the demand for thermal energy from DHSs has been gradually decreasing since the mid-90s of the last century: from 146.6 million Gcal in 1997 to 49.8 million Gcal in 2015. Today, the main technical equipment of the DHSs of Ukraine needs significant modernization due to insufficient funding during the last 30 years [1], and it will also be necessary to build new DHSs in the areas where hostilities are currently taking place due to the total destruction of the civilian infrastructure. The post-war reconstruction of destroyed cities with their heating systems and new construction will result in densification of the existing buildings, which will cause an increase in the heat load density of the DHSs. As a result, their efficiency will improve and the level of competitiveness will increase. This will be a unique chance to radically update them with the use of renewable energy sources (RES) and innovative technologies, including heat pump plant (HPP). At the same time, the cost of thermal energy for the consumers of the DHSs will significantly decrease.

As shown by previous studies carried out by the authors [2], heat pumps are one of the heat-generating technologies that should be used in DHSs of Ukraine. The operation of heat pumps in the mode of daily regulation of the electrical load in energy systems is also economically beneficial.

The expediency of implementation HPP, which using different types of low-potential heat sources (LPHS), in the DHSs is the subject of many studies in the world [3–13], in particular, thermal atlases have been created that describe the current needs in heat and the potential for the development of centralized heat supply in such countries as Germany, Great Britain, Denmark [14]. In Ukraine, the problem of implementing HPP was also studied [15–21].

According to the European project "Heat Roadmap Europe", in the future, up to 25 % of the energy from heat pumps (HP) may feed to the DHSs. It is assumed that thermal and electrical systems with low temperatures of supply and return water will be integrated in the 4th generation DHSs, and they will also interact with district cooling systems [22]. These problems are discussed also in detail in [14, 23].

Currently, the 5th generation DHSs are already being developed, which will be integrated and smart controlled and will apply innovative technologies using various types of renewable and secondary energy sources, in particular LPHS, thermal and electric storage systems, etc. [24–26].

Today, HPPs are used in DHSs in many countries. For example [9, 27–29], in Germany, in the town of Bergheim, the heat of sump water from the mining pit is used by two HPs of 293 kW each in the first DHS and one HP of 865 kW in the second DHS. In Finland, the return line of the DHS is the heat source for the HP of 158 kW in the town and municipality of Mänttä-Vilppula, and waste heat from the data center is used for the HP of 3.6 MW in the city of Mäntsälä. In Denmark, waste heat from the local paper factory is used for the HP of 5.3 MW in the town of Skjern, and from a food industry enterprise in Lille-Skensved for the HP of 7–4 MW (winter/summer). In Norway, seawater heat is used for the 13.2 MW HP in the municipality of Drammen and two HP with the total heating capacity of 16 MW in Forne-bu/Rolfsbukta. In Lausanne (Switzerland) the heat source for the HP of 4.5 MW is the water of Lake Leman. In Budapest (Hungary) sewage energy is used for two HPs (heating capacity is 1.69 MW, cooling capacity is 1.748 MW) in heating system of district with more than 100,000 habitants. In Milan (Italy) the underground water is a heat source for two HPs of 850 kW each, and at the same time, the excessively high level of groundwater is reduced. In Great Britain, in London, 500 houses in the Islington district use waste heat from the subway (Bunhill 2 network) for district heating.

Basic material

As you can see from the given examples, it is possible to use HPPs of different types in the DHSs, depending on the available LPHS. LPHSs can be of natural or anthropogenic origin. LPHS of natural origin is external air, surface waters of reservoirs (rivers, seas, lakes), underground waters, ground and rocks of the upper layer of the Earth, and solar energy; LPHS of anthropogenic origin is discharge (waste) water, air from heating and ventilation systems, flue gases, heated air and heated water or other liquids of cooling systems of technological processes, etc.

In European countries, large HPs use seven main types of LPHS [30, 31], the features of which are given in the table 1. Generalized characteristics of heat pump technologies that use the mentioned above LPHSs are given in [31].

The use of LPHSs of anthropogenic origin for the operation of HPPs makes it possible to solve two tasks at the same time: reducing the negative impact on the environment and improving the energy efficiency of heat and cold production. This approach corresponds to the EU Strategy 2020 [32], which provides for the development of low-temperature DHSs, connecting local demand with RES and LPHS of anthropogenic origin, as well as with electricity and gas networks.

In [33], it is shown that it is advisable to use the heat of LPHS of both anthropogenic and natural origin for the DHSs of Ukraine. An estimate of the thermal potential of the above-mentioned sources for the HPPs of the DHSs is given in [34].

A new methodical approach was developed to estimate the potential of thermal energy production by HPPs in regional DHSs, which differs from the existing ones in that it takes into account the coverage of the region by DHSs and the possibilities of HPPs to access LPHS. According to this approach, a calculation model (formula (1)) was created. This model enables to determine the current and forecast economically achievable output of thermal energy $Q(\tau)$ by HPPs in DHSs for cities of the country:

$$Q(\tau)=\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{j=1}^{J}\frac{SPF_{0jnm}(\tau)}{SPF_{0jnm}(\tau)-1}k_{nm}^{cav}(\tau)\cdot \cdot k_{nm}^{ac}(\tau)\cdot k_{j}^{tr}\cdot\varphi_{jnm}^{p}, \quad (1)$$

where n = 1,…, N is the sequence number and the total number of regions in the country; m = 1,…, M is the sequence number and the total number of cities with district heating systems in the region n; j = 1,…, J is the sequence number and total number of LPHS types; $SPF_{0jnm}(\tau)$ is the (average annual) seasonal performance factor of energy trans formation in the city m, region n, LPHS of type j

Table 1. Heat sources used for HPPs in European countries and their features [30]

Type of Heat Source	Capacity, MW	Percentage of Total Capacity, %	Number of Units	Average Capacity Per Unit, MW	Temperature Range, °C	Temperature	Stability/ Security	Proximity to Urban Areas
Sewage water	891	56	54	17	10–20	H	H	H
Ambient water	390	24	34	11	2–15	M	H	H
Industrial waste heat	129	8	28	5	12–46	H	L	M
Geothermal heat	97	4	19	5	9–55	H	H	L
Flue gas	40	2	7	6	34–60	H	M	M
District cooling	30	< 2	4	7	0–9	L	M	H
Solar heat storage	4	< 1	3	1	10–35	H	H	M
Total	1580	–	149	–	0–60	–	–	–

Note: H — high, M — medium, L — low.

in year τ; $k_{nm}^{cav}(\tau)$ is the coverage coefficient by DHS for the region in the year τ; $k_{nm}^{ac}(\tau)$ is the access ratio in the city m of the region n to LPHS of the type j in the year τ; k_j^{tr} is the conversion factor of the HPP heat exchanger from LPHS of the type j; φ_{jnm}^{p} is the economically feasible energy potential of LPHS of the type j in the city m of the region n in the year τ, Gcal/year.

It should be given some explanations about the estimated average seasonal performance factor SPF_0. Thus, Article 10 of the Law of Ukraine "On Alternative Energy Sources" [35] contains the general conditions for classifying heat pumps as renewable energy equipment: "Aerothermal, geothermal, and hydrothermal energy obtained with heat pumps should be considered as obtained from renewable sources, provided that the final energy output significantly exceeds the consumption of primary energy, which is necessary to drive heat pumps". The Directive (EU) 2018/2001 [36] establishes the criterion for classifying HPP as renewable energy equipment — it is the minimum acceptable value of SPF_0, which is equal to:

$$SPF_0 = 1.15/\eta, \tag{2}$$

where η is the efficiency factor of the energy system for electricity production, which means the "the ratio between total gross production of electricity and the primary energy consumption for the production of electricity and shall be calculated as an EU average based on Eurostat data" (Directive (EU) 2018/2001, ANNEX VII [36]). Calculations of the electrical efficiency of the energy system of Ukraine according to the Eurostat methodology given in [37] and in accordance with the data of the State Statistics Service of Ukraine regarding the energy balance of the country for 2010 [38] provide the SPF_0 of 3.2 [39].

Based on the mentioned above and taking into account the information given in [40] and [41], the value of SPF_0 was calculated for different LPHSs, and assumptions were made regarding the access factors for LPHSs and transfer coefficients of HPPs heat exchangers. The results are shown in the table 2.

The coverage coefficient (k_{nm}^{cav}) by DHS for the region was determined according to [42].

Economically feasible potentials of LPHS are calculated as follows.

Table 2. The estimated average efficiency factor of HPP and coefficients for calculations

Heat Pump Plant	SPF_0	k^{ac}	k^{tr}
Air — Water*	3.5	0.5	0.6
Ventilation emissions — Water*	3.5	0.5	0.6
Flue gas — Water	4.5	1	0.7
Process heat — Water	4.2	0.3	0.7
Sewage water — Water	3.8	0.7	0.5
Rivers, reservoirs — Water	3.3	0.02	0.75
Ground and groundwater — Water	3.5	0.3	0.7

Note. * It is assumed that HPPs air-water and HPPs ventilation emissions-water will operate together during the heating period, therefore the air will be diluted by ventilation emissions of buildings and its temperature will rise. In the non-heating period, ventilation emissions will not be used, but only air.

The amount of heat Q_{nm}^{DHS} discharged to the outside by the ventilation systems of the apartments connected to the DHS in the city m of the region n during the heating period can be determined by the following formula [34]:

$$Q_{nm}^{DHS} = k \cdot V_{nm}^{DHS} \cdot \rho \cdot C \cdot (t_{\kappa}^{av} - t_{nm}^{hp}) \times \times \tau_{nm} \cdot n \cdot 24 \cdot 10^{-6} \tag{3}$$

where k is the proportionality factor, 0.2388; V_{nm}^{DHS} is the volume of apartments connected to the DHS, m³; ρ is the air density (reference data), 1.204 kg/m³; C is the mass heat capacity of air (reference data), 1.007 kJ/(kg·K); t_{κ}^{av} is the average temperature of air indoors, 18 °C is accepted; t_{nm}^{hp} is the average ambient air temperature in the city m of the region n during the heating period; τ_{nm} is the duration of the heating period in the city m of the region n, days; n is the rate of air circulation in apartments, once per hour; 24 is the number of hours in a day.

The thermal energy potential of air was determined by the formula [34]:

$$\varphi_p^e = \frac{\varphi_p^t}{\varphi_c^t} \cdot \varphi_c^e, \tag{4}$$

where φ_p^e is the economically feasible air potential in the region n; φ_p^t is the technically achievable air potential in the region n; φ_c^t, φ_c^e is the technically achievable and economically feasible air potentials in the country, respectively [43, 44].

The available thermal energy potential of river water E_m^a (GJ/year) is calculated according to the formula [34]:

$$E_m^a = C_w \cdot p \cdot \Delta t \cdot W_r , \qquad (5)$$

where C_w is the specific heat capacity of water, 4190 J /(kg·°C) at 15 °C; p is the water density, 998 kg/m³ at 15 °C; Δt is the change of the river water temperature in the heat pump condenser, 2 °C is accepted; W_r is the annual flow (volume) of river water, km³/year.

The potential of waste heat of boiler houses and combined heat power plants (CHPPs) is

$$Q_{\tau nm}^{fg} = \frac{\delta}{100} \cdot Q_{\tau nm}^{CHP,B} , \qquad (6)$$

where $Q_{\tau nm}^{fg}$ is the waste heat potential of flue gases of boilers and CHPPs; δ is the weight-average loss of thermal energy with flue gases, 8.6 %; $Q_{\tau nm}^{CHP,B}$ is the thermal energy output of boilers and CHPPs in the year τ.

The economically feasible potential of waste water, ground and groundwater, and thermal secondary energy resources in industry was determined according to [21, 45, 46], respectively.

The economically feasible potential of seas is limited only by the presence near the DHS, accessibility, technical and financial capabilities of the heat supply company.

Information on the production of product types in the regions is presented by the State Statistical Service of Ukraine as confidential, therefore the potential of thermal secondary energy resources (TSER) was determined for the country as a whole. The total annual energy potential of TSER will be 32,075.8 thousand GJ, or 7,660.8 thousand Gcal. The access factor is taken as 0.3, and the heat exchanger conversion factor is 0.7, $SPF_0 = 4.2$. Then the amount of thermal energy produced by HPP in DHS will be 6756.8 thousand Gcal/year.

Using this model, the above-mentioned potential was calculated for Ukraine as a whole (Fig. 1) and at the level of its regions (Fig. 2) for 2020.

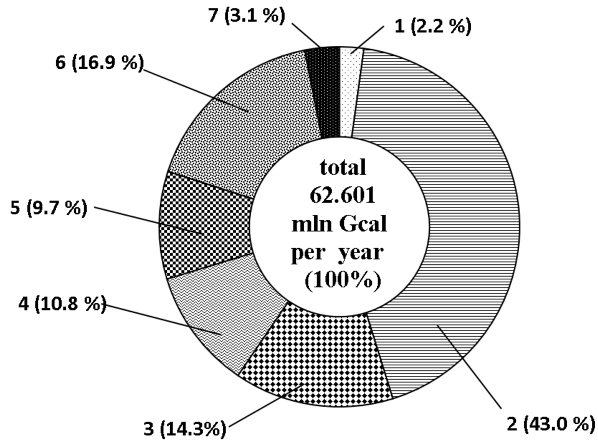

Figure 1. The total energy potential of thermal energy production of HPPs in DHSs of Ukraine and distribution by its components: 1 — Air — Water; 2 — Ventilation emissions — Water; 3 — Flue gas — Water; 4 — Process heat — Water; 5 — Sewage water — Water; 6 — Rivers, reservoirs — Water; 7 — Ground and groundwater — Water.

Fig. 1 shows that, as of 2020, the total potential of thermal energy production by HPP in DHS of Ukraine may reach 62.601 million Gcal/year, which is equivalent to 8.9 million tons of standard coal per year. The distribution of the energy potential of thermal energy production from LPHSs of various origins is: from natural LPHSs — 13.894 million Gcal/year (22.2 %), from anthropogenic LPHSs — 48.707 million Gcal/year (77.8 %). Natural LPHSs are the heat of air (1.367 million Gcal/year or 2.2 %), river water (10.599 million Gcal/year or 16.9 %), and ground and groundwater (1.931 million Gcal/year or 3.1 %); anthropogenic LPHSs are the heat of ventilation emissions of buildings connected to DHSs (26.938 million Gcal/year or 43.0 %), sewage water (6.053 million Gcal/year or 9.7 %), flue gases of boiler houses and CHPs (8.959 million Gcal/year or 14.3 %), and cooling water for technological processes (6.757 million Gcal/year or 10.8 %). For comparison: in 2020, the total thermal energy output of all heating systems of Ukraine (autonomous, decentralized, moderately centralized, and centralized) was 88.954 million Gcal [47], in particular, 46.256 million Gcal (52 %) from DHSs.

The considered 24 regions of Ukraine are characterized by the disproportionality of LPHSs: in regions with large cities and developed heavy and chemical industry, the potential of anthropogenic

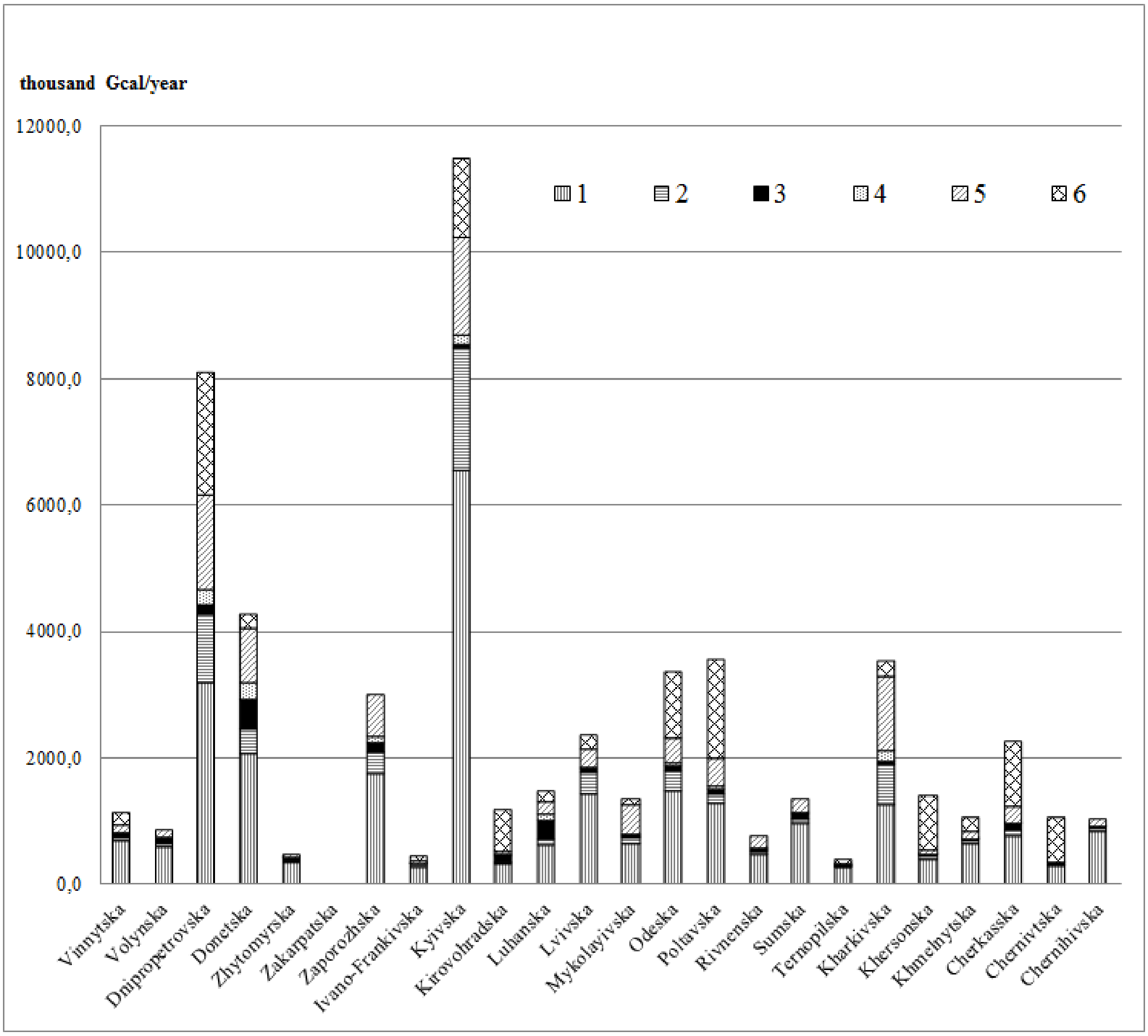

Figure 2. The potential of thermal energy production by HPPs in regional DHSs: 1 — Heat of ventilation emissions; 2 — Heat of ground and groundwater; 3 — Heat of flue gas; 4 — Heat of sewage; 5 — Heat of air; 6 — Heat of rivers.

LPHS is greater than in regions with agrarian industry (Fig. 2).

Undoubtedly, it will be impossible to fully realize such thermal potential in the DHSs because of the following reasons:

— in the process of DHSs development, in addition to HPPs, other thermal energy generation technologies will be used — solar collectors, CHPPs, biofuel boilers, electric boilers. Accordingly, these technologies will compete with each other, and it is not a fact that HPPs will occupy the entire thermal energy market;

— processes of decentralization will continue, especially in the field of hot water supply due to mass installation of individual water heaters (boilers);

— the efficiency of production, transportation, and consumption of thermal energy will increase;

— the population of Ukraine will decrease;

— global climate change (warming) will occur.

As a result of these and other reasons, as it is shown in [2], the demand for thermal energy of the DHSs will steadily fall and will reach the level of 35 million Gcal / year in 2050 (28 % less than in 2020), and thermal energy production will be 38.8 million Gcal / year. At the same time, the share of HPPs will be about 38.7 % (about 15 million Gcal) [48]. In fact, this is the predictive potential that will be used.

As a result of the financial analysis of the projects of the use of HPPs in the DHSs with various LPHSs, a profitability index was determined and used as a measure for their ranking. The profitability index was calculated by the formula:

$$PI_i = \frac{NPV_i}{IC_i}, \tag{7}$$

where PI_i is the profitability index of the project i, NPV_i, IC_i are the net present value and initial cost of the project j, respectively.

The ranking results are given in the table 3.

Of course, it is advisable to implement projects with the best financial indicators in the first place. According to the table 3, they are HPPs, which use waste heat of boiler houses and CHPPs, technological processes, and ventilation systems as LPHS. An additional advantage of these LPHSs is that they are anthropogenic. It is also advisable to include projects for the implementation of HPPs, which use the heat of sewage water, in the list of priority implementation, despite the fact that they are less effective than projects with natural LPHS (heat of the sea and rivers). This is due to their convenient location (in every quarter of the city), high heat and temperature potential, heat flow stability, accessibility, and a decrease in their impact on the environment. The priority of implementing HPPs, which use low-potential heat from sources of anthropogenic origin, is also explained by the direct proximity to the DHS, greater specific heat capacity and relatively greater temperature potential (15 °C to 45 °C). Whereas sources of natural origin have a lower temperature potential (5 °C to 20 °C, and for outdoor air in winter and below −10 °C). Open reservoirs are not always located within the settlements with DHS, and the air and topsoil have a low specific heat capacity, which requires the use of significant volumes of air and land areas to extract the necessary heat capacity from these sources.

The use of the LPHSs discussed above for the mass implementation of HPPs in the DHSs will enables make their projects typical and carry out wholesale purchases of equipment, which will reduce investment costs. The use of natural LPHS (heat of the sea, rivers, ground and groundwater) will be limited and has a single character.

An ideal place for HPP location is a place close to LPHS and DHS networks. CHPPs meet these criteria. CHPPs, according to their purpose, should operate according to the heat schedule. When the heat output of CHPP changes, its electric output proportionally changes, and this can be used to provide auxiliary (system) services to power systems. To do this, HPP should be installed on the CHPP territory. When the heat output of CHPP changes, the heat balance in the DHS will be maintained by the HPP and, if necessary, by gas boilers.

Table 3. Profitability index of using HPPs with different LPHS

Low-potential heat source	Capacity of HPP, MW	PI
Waste heat of boiler houses and CHPPs	1.0	5.6
Waste heat of boiler houses and CHPPs	2.2	5.0
Waste heat of technological processes	2.2	4.5
Heat of sea	8.016	3.3
Ventilation emissions, air	0.1	2.8
Ventilation emissions, air	1.0	3.0
Heat of rivers	1.0	2.7
Sewage water	1.0	1.5
Sewage water	14.7	2.6
Ground and groundwater	1.0	1.3

HPPs can also be implemented in district and quarterly boiler houses. In this case, it is attractive that:

— the majority of boiler houses are located in the center of heat loads;

— there are no problems with heat accumulators, because main heat networks can be used as them;

— near the boiler houses, as a rule, sewer collectors are located, which can be used as LPHS for HPP;

— according to statistical data, boiler houses have a significant excess of installed capacity, and, accordingly, boiler units. Therefore, there are no problems with the HPP placement, they can be placed on the sites of dismantled outmoded and worn-out boilers;

— an increase in the electrical load of boiler houses in the case of HPP introduction is not problematic.

In addition to the LPHSs mentioned above, the heat of cooling and condensation of steam of flue gases from boilers and the outside air can be used as a LPHS for HPPs.

HPPs can be located on the roofs of residential, public, and administrative buildings, which are connected to the DHS. Ventilation emissions of these buildings and ambient air can be used as LPHS.

Another variant of HPPs implementation is in heat distribution systems. This option provides for the installation of HPPs in central heating points, heat distribution stations (heat substation). During the heating period, the technology can be used for heating and/or hot water supply. The heat produced by the HPPs can replace the energy produced by the boilers in the boiler house or be accumulated in the main return line. The heat of sewage, the collectors of which are located in every residential area of large cities, and air (if there are no others nearby) can be used as LPHS.

Taking into account the significant unevenness of hot water consumption, the use of this technology in the non-heating period is possible only if a heat accumulator is installed in the heat substation, or a branch of the main network connected to the heat substation is used as an accumulator.

The technology of using HPPs in heat distribution systems can be used to increase the heat load of the existing DHS (in case of new consumers). Let's consider it on the example of Kharkiv CHPP-5. According to the project, it was supposed to supply heat to the city through three main pipelines, but only two of them were built. Therefore, part of the installed heat capacities turned out to be actually "closed" due to the insufficient transmission capacity of the existing heating networks. As a way out of this situation, there is installation of HPP, which will obtain heat from the return lines of existing networks, on the consumer side in the heat distribution systems. In this case, the heat carrier flow rate will not change, and its temperature in the return lines will decrease that indicates the release of additional heat. Thus, funds for the laying of additional pipelines will be saved. HPP installed in heat distribution systems can be used to control the load of energy systems. The algorithm of operation is as follows. At low load in the power system (night-time valley), HPPs operate with maximum productivity, and at high load — with minimum productivity, up to their complete shutdown. In this case, the heat balance in the DHS of the residential area is provided with the heat of the main pipelines. In this technology, both electric heaters and HPP can be used. LPHS for HPP can be sewage, the collectors of which are located in each residential area of large cities. The places of possible location of HPP in DHS are summarized in the table 4.

Table 4. Locations of HPPs in the DHS

Locations of HPPs in the DHS	Available LPHS
Roofs of residential, public, and administrative buildings, which are connected to the DHS	Ventilation emissions of buildings, air
Heat distribution systems (heat substation)	Sewage, air, ground and groundwater, energy of the return line of CHPP (in case of additional heat load)
Boiler houses and CHPPs	Flue gases, sewage, process water, air, ground and groundwater
Separately located HPPs	Rivers and lakes, sea water, ground and groundwater, sewage, air, waste heat of industrial enterprises

Conclusions

A new methodical approach is proposed for the regional determination of the forecast implementation scope of heat pump technologies in the DHSs. During the period of post-war renewal of Ukraine, this approach enables to estimate the economically available energy potential of HPPs in the case of using different LPHS in each region, taking into account the consequences of Russia's military invasion of Ukraine. This methodical approach takes into account the regional features of the use of heat pump technologies with different types of LPHS and their changes over time for perspective forecasting: seasonal (average annual) calculated coefficient of energy transformation from the LPHS, coverage of the DHS region; access to LPHS; heat transfer efficiency of the HPP heat exchanger from the LPHS; economically feasible energy potential of the LPHS.

The total achievable potential of heat production by HPPs in the regional DHSs of Ukraine was calculated: 62,601 thousand Gcal/year, which is almost twice the annual release of these DHSs in 2020.

The post-war reconstruction of destroyed cities with their heating systems and new housing construction will result in densification of the existing buildings, which will cause an increase in the heat load density of the DHSs. As a result, DHS's efficiency will improve and their level of competitiveness will increase. This will be a unique chance to radically update DHSs using RES and innovative technologies, including HPPs. At the same time, the cost of thermal energy for the consumers of the DHSs will significantly decrease.

References

1. [Decentralized heating in Ukraine: potential and ways of implementation]. — URL: https://www.minregion.gov.ua/wp-content/uploads/2017/03/Detsentralizovane-opalennya.-Potentsial-ta-shlyahi-vprovadzhennya.pdf (Last accessed: 12.12.2022). (Ukr.)

2. Derii V.O. (2021). [Trends in the development of the district heating systems of Ukraine]. *Problemi zagalnoi energetiki.* No. 1. pp. 52–59. doi: 10.15407/pge2021.01.052. (Ukr.)

3. Lund H., Möller B., Mathiesen B.V., Dyrelund A. (2010). The role of district heating in future renewable energy systems. *Energy*. Vol. 35, Iss. 3, pp. 1381–1390. doi: 10.1016/j.energy.2009.11.023.

4. Pelda J., Holler S. (2019). Spatial distribution of the theoretical potential of waste heat from sewage: A statistical approach. *Energy*. Vol. 180, pp. 751–762. doi: 10.1016/j.energy.2019.05.133.

5. Dénarié A., Muscherà M., Calderoni M., Motta M. (2019). Industrial excess heat recovery in district heating: Data assessment methodology and application to a real case study in Milano, Italy. *Energy*. Vol. 166, pp. 170–182. doi: 10.1016/j.energy.2018.09.153.

6. Sayegh M.A., Jadwiszczak P., Axcel B.P., Niemierka E., Bry´s K., Jouhara H. (2018). Heat pump placement, connection and operational modes in European district heating. *Energy & Buildings*. Vol. 166, pp. 122–144. doi: 10.1016/j.enbuild.2018.02.006.

7. Barla M., Donna A.D., Perino A. (2016). Application of energy tunnels to an urban environment. *Geothermics*. Vol. 61, pp. 104–113. doi: 10.1016/j.geothermics.2016.01.014.

8. Ninikas K., Hytiris N., Emmanuel R., Aaen B., Younger P.L. (2016). Heat recovery from air in underground transport tunnels. Renew. *Energy*. Vol. 96, pp. 843–849. doi: 10.1016/j.renene.2016.05.015.

9. Lagoeiro H., Revesz A., Davies G., Maidment G., Curry D., Faulks G., Murawa M. (2019). Opportunities for Integrating Underground Railways into Low Carbon Urban Energy Networks: A Review. *Applied Sciences*. Vol. 9, 3332. doi: 10.3390/app9163332.

10. Harvey L.D.D. (2015). A Handbook on Low-Energy Buildings and District-Energy Systems. Fundamentals, Techniques and Examples. Earthscan by Routledge. 720 p.

11. The international network for district energy, promoting sustainable heating and cooling in Europe and beyond. *Euroheat & Power*. — https://www.euroheat.org/knowledge-hub/district-energy-explained.html (Last accessed: 12.12.2022).

12. King M. (2018). Community Energy: Planning, Development & Delivery. Guidebook. International District Energy Association (IDEA). 57 p. — URL: https://www.heatnetworksupport.scot/wp-content/uploads/2015/12/CommunityEnergyPlanningDevelepmentAndDelivery.pdf (Last accessed: 12.12.2022).

13. District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy, UN Environment. UNEP DTIE. Energy Branch. 71 p. — URL: https://www.unep.org/resources/report/district-energy-cities-unlocking-potential-energy-efficiency-and-renewable-energy (Last accessed: 12.12.2022).

14. Möller B., Wiechers E., Persson U., Grundahl L., Connolly D. (2018). Heat Roadmap Europe: Identifying local heat demand and supply areas with a European thermal atlas. *Energy*. Vol. 158, pp. 281–292. doi: 10.1016/j.energy.2018.06.025.

15. Karp I.M., Nikitin E.E., Pyanykh K.E. (2021). [State and ways of development of district heating systems in Ukraine]. Kyiv: Naukova dumka. 264 p. (Ukr.)

16. Nikitin Y., Komkov I. (2022). [An integrated approach to the development of plans for transformation of electrical and heat supply systems]. *Energotekhnologii ta resursozberezhennya*, No. 2, pp. 4–16. doi: 10.33070/etars.2.2022.01. (Ukr.)

17. Nikitin Y., Dutka O. (2020). Technical and economic efficiency of combined district heating with local heat source for district hot water. *Energotekhnologii i resursosberezhenie*, No. 1, pp. 34–40. doi: 10.33070/etars.1.2020.4. (Ukr.)

18. Snezhkin Y.F., Bileka B.D. (2020). Use of Combined Cogeneration–Thermal Pumping Plants for Municipal Heat Power Engineering and Heat Technologies. *Journal of Engineering Physics and Thermophysics.* Vol. 93, pp. 376–383. doi: 10.1007/s10891-020-02131-6.

19. Basok B.I., Dubovskiy S.V., Kudelya P.P. (2022). [Modern problems of CHP functioning in Ukraine]. *Tehnicheskaya termodinamika*. No. 6. pp. 52–57. doi: 10.15407/techned2022.06.052. (Ukr.)

20. Snezhkin Yu.F. (2017). [Energy-efficient heat pump technologies: state and prospects of their implementation in Ukraine]. *Industrial Heat Engineering*. Vol. 39, No. 2. pp. 18–24. (Ukr.)

21. [Energy Efficiency and Renewable Energy Sources]. Ed. A.K.Shidlovsky. (2007). Kyiv : Ukrainian Encyclopedic Knowledge. 560 p. (Ukr.)

22. Celsius Initiative. Heat pumps in district heating systems. — URL: https://celsiuscity.eu/heat-pumps-in-district-heating-systems (Last accessed: 16.12.2022).

23. Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F., Mathiesen B.V. (2014). 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy*. Vol. 68, pp. 1–11. doi: 10.1016/j.energy.2014.

02.089.

24. Revesz A., Jones P., Dunham C., Davies G., Marques C., Matabuena R., Scott J., Maidment G. (2020). Developing novel 5th generation district energy networks. *Energy*. Vol. 201, 117389. doi: 10.1016/j.energy.2020.117389.

25. Buffa S., Cozzini M., D'Antoni M., Baratieri M., Fedrizzi R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*. Vol. 104, pp. 504–522. doi: 10.1016/j.rser.2018.12.059.

26. Wirtz M., Heleno M., Moreira A., Schreiber T., Mьller D. (2023). 5th generation district heating and cooling network planning: A Dantzig–Wolfe decomposition approach. *Energy Conversion and Management*. Vol. 276, 116593. doi: 10.1016/j.enconman.2022.116593.

27. Large scale heat pumps in Europe. — URL: https://planenergi.eu/activities/district-heating/heat-pumps (Last accessed: 12.12.2022).

28. Large scale heat pumps in Europe. — URL: http://dry-f.eu/News-Events/News/ArtMID/422/ArticleID/57/Large-scale-heat-pumps-in-Europe-2nd-edition (Last accessed: 12.12.2022).

29. Bunhill Heat and Power Islington. — URL: https://heatpumpingtechnologies.org/annex47/wp-content/uploads/sites/54/2019/07/bunhill-heat-and-power.pdf (Last accessed: 16.12.2022).

30. David A., Mathiesen B.V., Averfalk H., Werner S., Lund H. (2017). Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. *Energies*. 10. P. 578. doi: 10.3390/en10040578.

31. Gaur A.S., Fitiwia D.Z., Curtisa J. (2019). Heat Pumps and Their Role in Decarbonising Heating Sector: A Comprehensive Review. *Working Paper*. No. 627. — URL: http://aei.pitt.edu/102238/1/WP627_0.pdf (Last accessed: 16.12.2022).

32. Powering a climate-neutral economy: An EU Strategy for Energy System Integration. Brussels, 08.07.2020. COM(2020) 299 final. 22 p.

33. Derii V.O., Sokolovska I.S., Teslenko O.I. (2022). [Overview of low grade heat sources for heat pump plants in district heating systems]. *Problemi zagalnoi energetiki*. Iss. 1–2. pp. 30–41. doi: 10.15407/pge2022.01-02.030. (Ukr.)

34. Derii V., Sokolovska I., Teslenko O. (2022). [Estimation of the potential of low grade heat sources for heat pump plants in district heating systems]. *System Research in Energy*. Iss. 1. pp. 4–18. doi: 10.15407/srenergy2022.01.004. (Ukr.)

35. [Law of Ukraine "On Alternative Energy Sources"]. *Official website of the Verkhovna Rada of Ukraine*. — URL: https://zakon.rada.gov.ua/laws/show/555-15#Text (Last accessed: 12.12.2022). (Ukr.)

36. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*. L 328/82 of 21.12.2018. 128 p.

37. Basok B.I., Dubovskoy S.V. (2017). [Methodological features of assessing the available capacity of heat pumps in Ukraine]. *Nasosi i oborudovanie*. No. 3. pp. 42–44. (Rus.)

38. [The minimum allowable value of the average calculated seasonal efficiency factor]. *Official website of State Statistic Service of Ukraine*. — URL: http://ukrstat.gov.ua (Last accessed: 12.12.2022). (Ukr.)

39. Kudrya S.O., Budko V.I. (2013). [Introduction to the specialty. Non-traditional and renewable energy sources]. Lecture course. Kyiv : NTUU "KPI". 387 p. (Ukr.)

40. Morozov Yu., Chalaev D., Nikolaievska N., Dobrovolskyi M. (2020). [Evaluation of the efficiency of using the thermal potential of the environment and the top layers of the land of Ukraine]. *Vidnovluvana energetika*. Iss. 4. pp. 80–88. doi: 10.36296/1819-8058.2020.4(63).80-88. (Ukr.)

41. Morozov Yu., Barylo A., Chalaev D., Dobrovolskyi M. (2019). [Energy efficiency of the shallow aquifers utilization for the district heating and cooling]. *Vidnovluvana energetika*. Iss. 2. pp. 70–78. doi: 10.36296/1819-8058.2019.2(57).70-78. (Ukr.)

42. [Development of renewable energy sources in Ukraine]. — URL: https://www.minregion.gov.ua/wp-content/uploads/2017/03/Rozvitok-VDE-v-Ukraini.pdf (Last accessed: 12.12.2022). (Ukr.)

43. Kudrya S.O. (2015). [Potential for the development of non-traditional and renewable energy sources. Improving energy efficiency and stimulating the use of renewable energy in agro-, food and other small and medium-sized enterprises in Ukraine]. Kyiv : United Nations Industrial Development Agency, 48 p. (Ukr.)

44. [Energy of the environment]. *Official website of State Agency on Energy Efficiency and Energy Saving of Ukraine*. — URL : https://saee.gov.ua/ae/termoenergy. (Last accessed: 12.12.2022). (Ukr.)

45. [Atlas of the energy potential of renewable and non-traditional energy sources of Ukraine]. Kyiv : Institute of Electrodynamics of National Academy of Sciences of Ukraine, 2001. 41 p. (Ukr.)

46. [Production of industrial products by types by regions of Ukraine in 2019]. *Official website of State Statistic Service of Ukraine*. — URL: http://www.ukrstat.gov.ua/operativ/operativ2021/pr/ovp/vppr_ue_2019.xlsx (Last accessed: 12.12.2022). (Ukr.)

47. [Energy supply and use in 2020], *Official website of State Statistic Service of Ukraine*. — URL: https://ukrstat.gov.ua (Last accessed: 12.12.2022). (Ukr.)

48. Derii V.O., Sokolovska I.S., Teslenko O.I. (2021). [Prospects for using heat pumps in district heating systems around the world and Ukraine]. *Problemi zagalnoi energetiki*. Iss. 3. pp. 43–52. doi: 10.15407/pge2021.03.043. (Ukr.)

Received April 13, 2023

Дерій В.О., *канд. техн. наук, ORCID: 0000-0002-5689-4897,*
Тесленко О.І., *канд. техн. наук, ORCID 0000-0002-3772-5991,*
Соколовська І.С., *канд. техн. наук, ORCID 0000-0003-1959-9837*
Інститут загальної енергетики Національної академії наук України, Київ
вул. Антоновича, 172, 03150 Київ, Україна, e-mail: info@ienergy.kiev.ua

Методичний підхід щодо оцінювання потенціалу виробництва теплової енергії теплонасосними установками у разі їх впровадження в регіональних системах централізованого теплопостачання

Наведено результати оцінки річного потенціалу виробництва теплової енергії з використанням теплових насосів (ТН) у системах централізованого теплопостачання (СЦТ) для регіонів України та для країни в цілому. Актуальність цього дослідження обумовлено високім рівнем розвитку СЦТ в Україні, який досягає 52 %. На сьогодні застаріле обладнання СЦТ України потребує суттєвої технологічної модернізації. Також вже у найближчий перспективі необхідно відновлення СЦТ, зруйнованих внаслідок тотального знищення цивільної інфраструктури російським агресором. Повоєнне відновлення міст України має унікальний шанс радикально осучаснити СЦТ із використанням відновлюваних джерел енергії та інноваційних технологій, у тому числі й ТН. Запропоновано новий методичний підхід щодо регіонального визначення прогнозних масштабів впровадження ТН у СЦТ. З використанням цього підходу визначено економічно доступний енергетичний потенціал виробництва теплової енергії ТН у СЦТ від різних джерел низькопотенційної теплоти (ДНТ) як за регіонами України, так і для країни в цілому. Станом на 2020 р. цей енергетичний потенціал для СЦТ України дорівнює 62,601 млн Гкал/рік (262,1 ПДж/рік): 22,2 % забезпечується природними ДНТ (теплота повітря (2,2 %), води річок (16,9 %) та ґрунту і ґрунтових вод (3,1 %)) та 77,8 % забезпечується антропогенними ДНТ (теплота вентиляційних викидів будівель (43,0 %), які приєднані до СЦТ, стічних каналізаційних вод (9,7 %), димових газів котелень та ТЕЦ (14,3 %), води охолодження технологічних процесів (10,8 %)). Наведено розраховані енергетичні потенціали виробництва теплової енергії ТН від різних ДНТ для СЦТ 24 областей України. Як вихідні дані для розрахунків використовувалася інформація з наукових видань, нормативних документів, щорічних звітів статистичної служби України та інших державних органів. Для обчислювання та візуалізації результатів застосовувалися апробовані методики теплотехнічних розрахунків, методи статистичного та розрахунково-порівняльного аналізу з використанням комп'ютерного забезпечення Microsoft Excel. Наведено методичні рекомендації щодо визначення пріоритетності та локацій впровадження ТН у регіональних СЦТ України, які розроблені авторами статті. *Бібл. 48, рис. 2, табл. 4.*

Ключові слова: централізоване теплопостачання, теплові насоси, джерела низькопотенційної теплоти.

Список літератури

1. Децентралізоване опалення в Україні: потенціал та шляхи впровадження. — URL: https://www.minregion.gov.ua/wp-content/uploads/2017/03/Detsentralizovane-opalennya.-Potentsial-ta-shlyahi-vprovadzhennya.pdf (Дата звернення 12.12.2022).

2. Дерій В.О. Тенденції розвитку систем централізованого теплопостачання України. *Проблеми загальної енергетики*. 2021. Вип. 1. С. 52–59. doi: 10.15407/pge2021.01.052.

3. Lund H., Möller B., Mathiesen B.V., Dyrelund A. (2010). The role of district heating in future renewable energy systems. *Energy*. Vol. 35, Iss. 3, pp. 1381–1390. doi: 10.1016/j.energy.2009.11.023.

4. Pelda J., Holler S. (2019). Spatial distribution of

the theoretical potential of waste heat from sewage: A statistical approach. *Energy*. Vol. 180, pp. 751–762. doi: 10.1016/j.energy.2019.05.133.

5. Dénarié A., Muscherà M., Calderoni M., Motta M. (2019). Industrial excess heat recovery in district heating: Data assessment methodology and application to a real case study in Milano, Italy. *Energy*. Vol. 166, pp. 170–182. doi: 10.1016/j.energy.2018.09.153.

6. Sayegh M.A., Jadwiszczak P., Axcel B.P., Niemierka E., Bry′s K., Jouhara H. (2018) Heat pump placement, connection and operational modes in European district heating. *Energy & Buildings*. Vol. 166, pp. 122–144. doi: 10.1016/j.enbuild.2018.02.006.

7. Barla M., Donna A.D., Perino A. (2016). Application of energy tunnels to an urban environment. *Geothermics*, Vol. 61, pp. 104–113. doi: 10.1016/j.geothermics.2016.01.014.

8. Ninikas K., Hytiris N., Emmanuel R., Aaen B., Younger P.L. (2016). Heat recovery from air in underground transport tunnels. Renew. *Energy*. Vol. 96, pp. 843–849. doi: 10.1016/j.renene.2016.05.015.

9. Lagoeiro H., Revesz A., Davies G., Maidment G., Curry D., Faulks G., Murawa M. (2019). Opportunities for Integrating Underground Railways into Low Carbon Urban Energy Networks: A Review. *Applied Sciences*. Vol. 9, 3332. doi: 10.3390/app9163332.

10. Harvey L.D.D. (2015). A Handbook on Low-Energy Buildings and District-Energy Systems. Fundamentals, Techniques and Examples. Earthscan by Routledge. 720 p.

11. The international network for district energy, promoting sustainable heating and cooling in Europe and beyond. *Euroheat & Power*. — https://www.euroheat.org/knowledge-hub/district-energy-explained.html (Last accessed: 12.12.2022).

12. King M. (2018). Community Energy: Planning, Development & Delivery. Guidebook. International District Energy Association (IDEA). 57 p. — URL: https://www.heatnetworksupport.scot/wp-content/uploads/2015/12/CommunityEnergyPlanning-DevelepmentAndDelivery.pdf (Last accessed: 12.12.2022).

13. District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy, UN Environment. UNEP DTIE. Energy Branch. 71 p. — URL: https://www.unep.org/resources/report/district-energy-cities-unlocking-potential-energy-efficiency-and-renewable-energy (Last accessed: 12.12.2022).

14. Möller B., Wiechers E., Persson U., Grundahl L., Connolly D. (2018). Heat Roadmap Europe: Identifying local heat demand and supply areas with a European thermal atlas. *Energy*. Vol. 158, pp. 281–292. doi: 10.1016/j.energy.2018.06.025.

15. Карп І.М., Нікітін Є.Є., П'яних К.Є. Стан та шляхи розвитку систем централізованого теплопостачання в Україні. Київ: Наукова думка, 2021. 264 с.

16. Нікітін Є.Є., Комков І.С. Цілісний підхід до розробки планів трансформації систем електро- та теплопостачання населених пунктів. *Енерготехнології та ресурсозбереження*. 2022. № 2. С. 4–16. doi.org/10.33070/etars.2.2022.01.

17. Нікітін Є.Є., Дутка О.М. Техніко-економічна ефективність комбінованих систем централізованого теплопостачання з локальним тепловим джерелом для гарячого водопостачання. *Энерготехнологии и ресурсосбережение*. 2020. № 1. С. 34–40. doi.org/10.33070/etars.1.2020.4.

18. Snezhkin Y.F., Bileka B.D. (2020). Use of Combined Cogeneration–Thermal Pumping Plants for Municipal Heat Power Engineering and Heat Technologies. *Journal of Engineering Physics and Thermophysics.* Vol. 93, pp. 376–383. doi: 10.1007/s10891-020-02131-6.

19. Басок Б., Дубовський С., Куделя П. Сучасні проблеми функціонування ТЕЦ України. *Технічна електродинаміка*. 2022. № 6. С. 52–57. doi: 10.15407/techned2022.06.052.

20. Снєжкін Ю.Ф. Енергоефективні теплонасосні технології: стан та перспективи їх впровадження в Україні. *Промышленная теплотехника*. 2017. Т. 39, № 2. С. 18–24.

21. Енергоефективність та відновлювальні джерела енергії / Під заг. ред. А.К.Шидловського. Київ : Українські енциклопедичні знання, 2007. 560 с.

22. Celsius Initiative. Heat pumps in district heating systems. — URL: https://celsiuscity.eu/heat-pumps-in-district-heating-systems/ (Last accessed: 16.12.2022).

23. Lund H., Werner S., Wiltshire R., Svendsen S., Thorsen J.E., Hvelplund F., Mathiesen B.V. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy*. 2014. Vol. 68, pp. 1–11. doi: 10.1016/j.energy.2014.02.089.

24. Revesz A., Jones P., Dunham C., Davies G., Marques C., Matabuena R., Scott J., Maidment G. Developing novel 5th generation district energy networks. *Energy*. 2020. Vol. 201, 117389. doi: 10.1016/j.energy.2020.117389.

25. Buffa S., Cozzini M., D'Antoni M., Baratieri M., Fedrizzi R. 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*. 2019. Vol. 104. pp. 504–522. doi: 10.1016/j.rser.2018.12.059.

26. Wirtz M., Heleno M., Moreira A., Schreiber T., Mыller D. 5th generation district heating and cooling network planning: A Dantzig–Wolfe decomposition approach. *Energy Conversion and Management*. 2023. Vol. 276, 116593. doi: 10.1016/j.enconman.2022.116593.

27. Large scale heat pumps in Europe. — URL: https://planenergi.eu/activities/district-heating/heat-pumps/ (Last accessed: 12.12.2022).

28. Large scale heat pumps in Europe. — URL: http://dry-f.eu/News-Events/News/ArtMID/422/ArticleID/57/Large-scale-heat-pumps-in-Europe-2nd-edition (Last accessed: 12.12.2022).

29. Bunhill Heat and Power Islington. — URL:

https://heatpumpingtechnologies.org/annex47/wp-content/uploads/sites/54/2019/07/bunhill-heat-and-power.pdf (Last accessed: 16.12.2022).

30. David A., Mathiesen B.V., Averfalk H., Werner S., Lund H. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. *Energies*. 2017. Vol. 10. P. 578. doi: 10.3390/en10040578.

31. Gaur A.S., Fitiwia D.Z., Curtisa J. Heat Pumps and Their Role in Decarbonising Heating Sector: A Comprehensive Review. *Working Paper*. 2019. № 627. — URL: http://aei.pitt.edu/102238/1/WP627_0.pdf (Last accessed: 16.12.2022).

32. Powering a climate-neutral economy: An EU Strategy for Energy System Integration. Brussels, 08.07.2020. COM(2020) 299 final. 22 p.

33. Дерій В.О., Соколовська І.С., Тесленко О.І. Огляд джерел низькопотенційної теплоти для теплонасосних установок систем централізованого теплопостачання. *Проблеми загальної енергетики*. 2022. Вип. 1–2. С. 30–41. doi: 10.15407/pge2022.01-02.030.

34. Дерій В., Соколовська І., Тесленко О. Оцінка потенціалу джерел низькопотенційної теплоти для теплонасосних установок систем централізованого теплопостачання. *Системні дослідження в енергетиці*. 2022. Вип. 1. С 4–18. doi: 10.15407/srenergy2022.01.004.

35. Закон України «Про альтернативні джерела енергії». *Офіційний сайт Верховної Ради України*. — URL: https://zakon.rada.gov.ua/laws/show/555-15#Text (Дата звернення: 12.12.2022).

36. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*. L 328/82 of 21.12.2018. 128 p.

37. Басок Б.И., Дубовской С.В. Методологические особенности оценки располагаемой мощности тепловых насосов в Украине. *Насосы и оборудование*. 2017. № 3. С. 42–44.

38. Мінімальне допустиме значення середнього розрахункового сезонного коефіцієнту корисної дії. *Офіційний сайт Державної служби статистики України*. — URL: http://ukrstat.gov.ua (Дата звернення 12.12.2022).

39. Кудря С.О., Будько В.І. Вступ до спеціальності. Нетрадиційні та відновлювані джерела енергії : Курс лекцій. Київ : НТУУ «КПІ», 2013. 387 с.

40. Морозов Ю.П., Чалаєв Д.М., Ніколаєвська Н.В., Добровольський М.П. Оцінка ефективності використання теплового потенціалу довкілля та верхніх шарів землі України. *Відновлювана енергетика*. 2020. Вип. 4. С. 80–88. doi: 10.36296/1819-8058.2020.4(63).80-88.

41. Морозов Ю.П., Барило А.А, Чалаєв Д.М., Добровольський М.П. Енергетична ефективність використання перших від поверхні водоносних горизонтів для тепло- і хладопостачання. *Відновлювана енергетика*. 2019. Вип. 2. С. 70–78. doi: 10.36296/1819-8058.2019.2(57).70-78.

42. Розвиток відновлюваних джерел енергії в Україні. — URL: https://www.minregion.gov.ua/wp-content/uploads/2017/03/Rozvitok-VDE-v-Ukraini.pdf (Дата звернення 12.12.2022).

43. Кудря С.О. Потенціал розвитку нетрадиційних і відновлюваних джерел енергії. Підвищення енергоефективності та стимулювання використання відновлюваної енергії в агро-, харчових та інших малих та середніх підприємствах (МСП) України. Київ : Агентство ООН з питань промислового розвитку, 2015. 48 с.

44. Енергія довкілля. *Сайт Державного агентства з енергоефективності та енергозбереження України*. — URL: https://saee.gov.ua/ae/termo-energy (Дата звернення 12.12.2022).

45. Атлас енергетичного потенціалу відновлюваних та нетрадиційних джерел енергії України. Київ : Інститут електродинаміки НАН України, 2001. 41 с.

46. Виробництво промислової продукції за видами по регіонах України за 2019 р. *Офіційний сайт Державної служби статистики України*. — URL: http://www.ukrstat.gov.ua/operativ/operativ2021/pr/ovp/vppr_ue_2019.xlsx (Дата звернення 12.12.2022).

47. Постачання та використання енергії у 2020 році. *Офіційний сайт Державної служби статистики України*. — URL: https://ukrstat.gov.ua (Дата звернення 12.12.2022).

48. Дерій В.О., Соколовська І.С., Тесленко О.І. Перспективи використання теплових насосів у системах централізованого теплопостачання країн світу та України. *Проблеми загальної енергетики*. 2021. Вип. 3. С. 43–52. doi: 10.15407/pge2021.03.043.

Надійшла до редакції 13.04.2023