https://doi.org/10.15407/scine19.04.057

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ASSESSMENT OF THE EFFECT OF STRUCTURAL CHANGES IN UKRAINE'S DISTRICT HEATING ON THE GREENHOUSE GAS EMISSIONS

Introduction. *The energy sector makes the largest contribution of about 65% of the total amount to greenhouse gas (GHG) emissions in Ukraine. District heating systems (DHS) as an energy subsector are a significant source of GHG emissions as a result of the combustion of fossil carbon fuels (natural gas, coal, petroleum products, peat, etc.).*

Problem Statement. *Due to its obvious advantages, DHS will continue to develop with the use of advanced technologies that allow a significant increase in the efficiency and a reduction in heat losses, and accordingly ensure the lowest cost of heat energy for consumers. However, at the moment, no forecast has been made for the dynamics of Ukraine's DHS fuel balance, the heat generation structure, and, accordingly, GHG emissions until 2050.*

Purpose. *The purpose of this research is to estimate the impact of structural changes in the DHS on the greenhouse gas emissions.*

Material and Methods. *Publications in scholarly research journals, official documents, statistical data, methods of statistical and comparative analysis have been used. Calculations have been made with the use of the Methodology of the United Nations Intergovernmental Panel on Climate Change (UN IPCC).*

Results. *Changes in the fuel balance and the generation structure of DHS of Ukraine have been forecasted. According to the forecast results, the natural gas consumption will decrease 1.4—2 times, while that of coal will fall 1.4—5.9 times. Petroleum products will not be used in DHS after 2040, but the electricity consumption will increase 7.7—19 times. At the same time, the biomass consumption will increase 2 times, and that of solar energy will grow 77 times, as compared with 2020. In 2050, the GHG emissions from DHS will amount to 3.9—6.9 million tons of CO2-eq., depending on the DHS structural dynamics scenario.*

Conclusions. *The forecast of the structure of Ukraine's DHS heat energy generation has predicted a 4.4 times reduction in the greenhouse gas emissions by 2050 for the optimistic and 2.5 times reduction for the pessimistic scenario of the DHS development, as compared with 2020.*

Keywords: district heating systems, fuel balance, heat energy generation structure, greenhouse gas emissions, and fuel.

Citation: Derii, V. O., Nechaieva, T. P., and Leshchenko, I. C. (2023). Assessment of the Effect of Structural Changes in Ukraine's District Heating on the Greenhouse Gas Emissions. *Sci. innov.*, 19(4), 57—65. https://doi.org/10.15407/scine19.04.057

Activities to prevent climate change have become the main priority of the domestic and foreign policy of many countries in recent years, since the actions of humanity to reduce greenhouse gas (GHG) emissions during the next 10—15 years will determine the fate and living conditions of future generations. Ukraine is no exception, there is an aggravation of abnormal meteorological phenomena: long-term heat waves, desiccation of rivers, an increase in the number and scale of fires, an atypical amount of precipitation, etc. All this indicates the urgent need to solve the problem of climate change and, above all, to reduce GHG emissions [1].

According to Ukraine's Greenhouse Gas Inventory for 1990—2020, the largest source of GHG emissions in Ukraine is the energy sector that accounted for 66% of emissions in 2019 and about 65% in 2020 [2]. District heating systems (DHS), as a result of the combustion of fossil carbon fuels (natural gas, coal, oil products), also contribute to these emissions.

In order to develop forecasts of GHG emissions from DHS, the trends in the development of DHS in different countries have been analyzed. The analysis has shown that the development of these systems in the advanced economies is based on the two main principles: expansion and enhancement of energy efficiency [3]. The expansion of DHS is due to technical, technological, ecological, economic, and social advantages in comparison with other types of heat supply in populated areas. That is why DHS have been widely used in European countries, making a significant contribution to heat supply, in particular, in Latvia (65%), Denmark (63%), Poland (53%), and Finland (50%). In general, in the EU countries, DHS account for 13% of heat supply sources, but it is planned to increase their share to 50% by 2050 [3, 4].

The analysis of the development trends in the DHS of European countries [3] has shown that renewable energy sources, waste heat, and cogeneration technologies will be widely used there. The use of advanced energy-efficient technologies ensures that the cost of heat energy for consumers is lower than for other heat supply options.

Ukraine is one of the countries with a high level of DHS, but recently there have been reported negative trends in their contribution to the total heat energy supply for heating and hot water needs, from 65.2% in 2014 [3] to 52% in 2017 [5] (the needs of industry are not taken into account).

One of the main factors that influence the DHS development trends is the demand for heat energy, dynamics of the fuel-energy balance structure that depends on the volumes of extraction of primary and production of secondary energy resources and their prices, government policy, etc.

Most boiler plants in Ukraine use natural gas for the production of heat energy (about 10 bln m^3). However, as of July 6, 2022, 11 bln m^3 gas was kept in Ukrainian underground storages, and the Government instructed *Naftogaz* to accumulate at least 19 bln m^3 gas in gas storages for the beginning of the heating season [6, 7]. Before the war, Ukraine consumed about 30 bln m^3 gas annually, while after February 24, 2022, the consumption decreased and is expected to be at the level of 20—21 bln m^3. The domestic production of gas in previous years was about 20 bln m^3, now it has decreased, therefore, it is necessary to import at least 3—4 bln m^3. At the same time, since there are no long-term gas supply contracts in Ukraine, natural gas has to be purchased on the spot markets of Europe, where its prices as of July 14, 2022, ranged from EUR 181.5 to 185.5/MWh (over EUR 1,900 per 1000 m^3) [8]. Such prices for natural gas are extremely high for Ukrainian consumers.

Therefore, when making a decision on the restoration of the DHS infrastructure, it is necessary to choose either to reconstruct with a focus on the conventional heat load and fuel, or to change the technologies of heat energy generation.

The development of DHS of Ukraine has been forecasted by the following methodology. In order to develop a forecast of the demand for heat energy of DHS, the influencing factors have been determined and the trends in their dynamics have been assessed. The factors influencing the demand for heat energy in the Central and Eastern Europe include as follows: the size of population, the urbanization processes, the construction of new buildings and improvement of their comfortability, the enhancement of the heat energy consumption efficiency (improvement of thermal insulation of buildings, consumer demand management systems), availability of heat supply services, processes of decentralization, availability of 24-hour hot water services in settlements with district heat supply, climate change, and the introduction of cooling systems in summertime. Further, each factor affecting the demand and the trends in their dynamics have been evaluated [3].

In [3], the forecast of heat energy demand in the DHS of Ukraine is determined depending on the dynamics of in the influencing factors listed above, and is estimated as follows: 48.5 mln Gcal/year in 2020 (actual), 51 mln Gcal/year in 2025, 46 mln Gcal/year in 2030, 41 mln Gcal/year in 2035, 38 mln Gcal/year in 2040, 36 mln Gcal/year in 2045, and 35 mln Gcal/year in 2050. Therefore, the demand for heat energy of the DHS will decrease by almost 30% by 2050 as compared with 2020.

The forecast of the demand for heat energy generation by the DHS has been determined based on the forecasted demand for heat energy, given the own needs of heat energy sources and losses in networks according to the method proposed in [3]. The parameters used in the calculations are shown in Fig. 1.

The forecast of demand for heat energy generation, together with the fuel balance, are the initial data for the development of the structure of heat energy generation by DHS. The forecast of demand gives an answer to the question of how much heat energy needs to be generated, and the forecast of fuel balance shows what types of energy carriers will be used.

The fuel balance of Ukraine's DHS has been forecasted given the impact of obligations regarding the decarbonization of Ukraine's economy

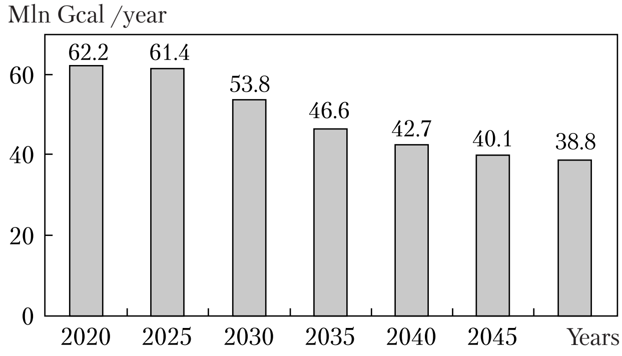

Fig. 1. Forecast of the demand for heat energy generation by DHS to 2050

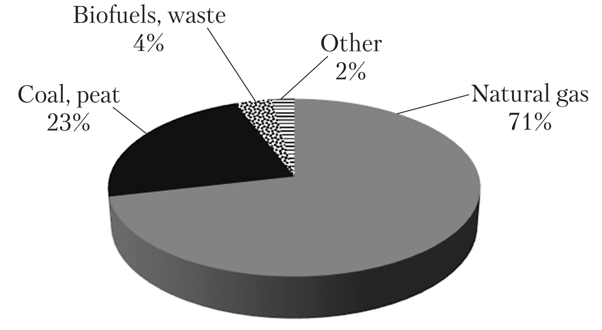

Fig. 2. The DHS Fuel Balance Structure in 2014 [10]

under the Paris Agreement. It is based on the trends in the dynamics of the components of the DHS fuel balance structure forecast until 2050, as prepared by the International Energy Agency in [9] for the world countries that use DHS. This study has shown the dynamics of the types of fuel and energy resources for the period 2000—2015 and made their forecast until 2050. In particular, it has been noted that the use of biofuels, waste and other renewable energy sources will significantly increase, while the consumption of coal and oil products will decrease. As a result, starting with 2025, a rapid reduction in CO_2 emissions, which meets the main requirements of the Paris Climate Agreement, is expected. Therefore, the trends in the dynamics of the DHS fuel balance structure, as given in [9], can be considered recommendations to the Paris Agreement signatory countries, including Ukraine, to fulfill their obligations.

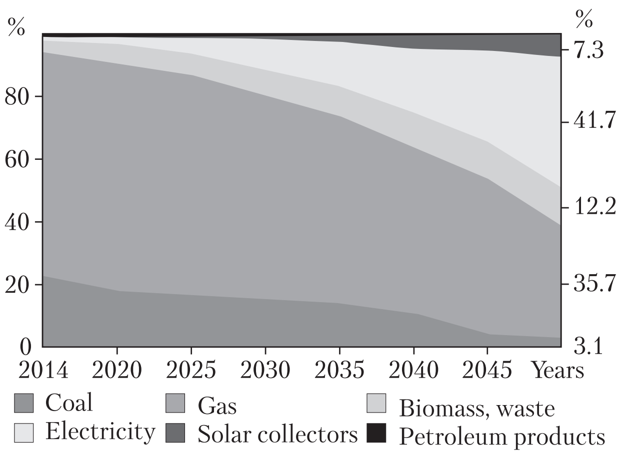

Fig. 3. The optimistic scenario of the forecast of Ukraine's DHS fuel balance structure till 2050 [3]

Note. Figures 3 and 4 show the percentage of heat energy to be generated from a certain energy carrier.

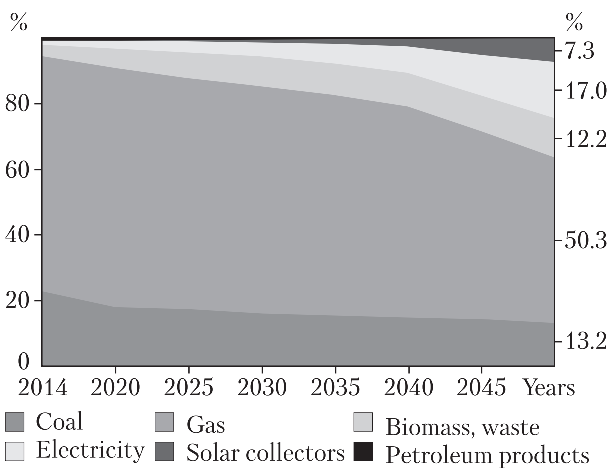

Fig. 4. The pessimistic scenario of the forecast of Ukraine's DHS fuel balance structure till 2050

The fuel balance of the DHS of Ukraine in 2014 is used as a base. Its structure is shown in Fig. 2.

In the fuel balance structure (Fig. 2), there are distinguished natural gas, coal and peat, biofuel and waste, with other types of fuel and energy resources not singled out. Therefore, it is assumed that in 2014 the share of petroleum products was 0.9%, that of electricity accounted for 1.2%, and that of solar energy made up 0.1%.

In the research, two scenarios of Ukraine's DHS fuel balance dynamics, the optimistic and the pessimistic ones, have been developed. In addition to the trends given in [9], the optimistic scenario takes into consideration the government policy that foresees reducing the natural gas consumption and using renewable energy sources and local fuels [11]. In the pessimistic scenario of the fuel balance forecast, it is assumed that in the process of Ukraine's DHS modernization, the pace of reducing the use of fossil fuels and increasing the use of electricity for heat energy generation is slower. The resulting forecast of Ukraine's DHS fuel balance structure, given the scenario assumptions for the pessimistic scenario, is shown in Fig. 2. The forecast of Ukraine's DHS fuel balance structure for the optimistic scenario is taken from [3].

Using the data shown in Figs. 1, 3, and 4, it is possible to make a forecast of the structure of the heat energy generation by DHS, based on the share of each type of energy carrier in the total demand for the heat energy generation by DHS. The forecast of the structure of heat energy generation for both scenarios have been determined based by the following formula [3]

$$Q_{it}^{d} = Q_{t}^{d} \beta_{it} / 100, \qquad (1)$$

where Q_{it}^{d} is the demand for heat energy generation from the *i*-th energy carrier per year *t*; Q_{t}^{d} is the total demand for heat energy generation by DHS per year *t*; and β_{it} is the percentage of the demand for heat energy generation from the *i*-th energy carrier per year *t*.

The resulting forecasts of the structure of heat energy generation by DHS for the mentioned scenarios are shown in Table 1.

Greenhouse gas emissions from the consumption of fossil fuels by thermal power plants and boilers are determined in accordance with the 2006 UN IPCC Guidelines for National Greenhouse Gas Inventories [12] using the formula:

$$E_{gt} = \sum_{r} \sum_{k} b_{kig} B_{kit}, \qquad (2)$$

where E_{gt} is the amount of greenhouse gas emissions *g* in year *t*, t; b_{kig} is the specific *g* greenhouse gas emissions for the *i*-th fuel consumption by the heat energy source *k*, t/TJ; B_{kit} is the *i*-th fuel consumption for heat energy generation by DHS for heat energy source k in year t, TJ.

The total GHG emissions from fossil fuel consumption are defined as the sum of emissions of each GHG in the CO_2 equivalent:

$$E_t^{CO_2} = \sum_g E_{gt} \kappa_g^{CO_2}, \quad (3)$$

where $E_t^{CO_2}$ is the total amount of GHG emissions in the CO_2 equivalent in year t, t; $\kappa_g^{CO_2}$ is the g greenhouse gas global warming coefficient (for the national inventory of greenhouse gas emissions, there are used the following values of the GHG global warming potential as specified in the Fourth Assessment Report of the IPCC [13]: 25 for methane CH_4 and 298 for nitrous oxide N_2O).

The calculations of greenhouse gas emissions are based on the specific emissions of greenhouse gases (CO_2, CH_4, and N_2O) from combustion of fossil fuels (solid, liquid, gaseous) in boiler houses and thermal power plants, which are given in the National Cadaster of GHG emissions for 2019 (Table 1. A (a) s 1 of CRF Tables for 2019) [14].

Table 3 shows the total amount of heat energy generated together by coal-fired boilers and CHPs, and natural gas-fired boilers and CHPs. To calculate the GHG emissions from fossil fuel consumption, it is necessary to make a breakdown of the generated heat energy by types of heat generators.

Statistical information of the State Statistics Service of Ukraine [15] has been used for structuring the heat energy generation by gas-fired CHP plants and gas-fired boiler plants. According to it, in 2018, the boiler plants and CHP plants produced 276,862 TJ heat energy from natural gas, which is equivalent to 66,170 thousand Gcal heat energy. In the same year, according to the information given in [16], the gas-fired CHP plants produced 19,213.9 thousand Gcal heat energy. Thus, in 2018, the share of gas-fired CHP plants in the heat energy generation accounted for 29%. These data are taken as input ones for building a forecast of the gas-fired CHP plant share in the DHS generation for the above scenarios of the fuel balance structure, which are given in Table 2.

Knowing the relative share of CHP plants and the total demand for heat energy generation by DHS using natural gas, it is possible to determine the heat energy generation demand of gas boilers and CHP plants (in absolute values), respectively, by the expressions:

$$Q_{it}^{B} = Q_{it}^{d}\,(1-\beta/100), \quad (4)$$

$$Q_{it}^{CHP} = Q_{it}\,\beta_{it}/100, \quad (5)$$

Table 1. **The Forecast of the Structure of Heat Energy Generation by DHS for the Optimistic (O) and the Pessimistic (P) Scenarios, mln Gcal per year**

Heat source	Year													
	2020		2025		2030		2035		2040		2045		2050	
	O	P	O	P	O	P	O	P	O	P	O	P	O	P
Boiler rooms, coal-fired CHP plants	11.28	11.25	9.91	10.69	8.23	8.72	6.62	7.22	4.51	6.45	1.68	5.80	1.20	5.13
Boiler rooms, gas-fired CHP plants	45.14	45.14	43.32	43.13	35.02	37.12	27.63	31.17	22.54	27.24	19.80	22.80	13.87	19.54
Biofuel boilers	3.79	3.79	4.42	4.92	4.36	4.90	4.57	4.57	5.00	4.48	4.76	4.48	4.74	4.74
Oil boilers	0.53	0.53	0.42	0.42	0.27	0.28	0.14	0.16	0.04	0.04	0.00	0.00	0.00	0.00
Solar collectors	0.06	0.06	0.37	0.12	0.54	0.54	1.03	0.70	1.92	1.07	2.12	2.12	2.84	2.84
Heat pumps, electric boilers	1.37	1.37	3.01	2.15	5.38	2.26	6.62	2.80	8.68	3.42	11.64	4.80	16.20	6.60
Total	**62.2**		**61.4**		**53.8**		**46.6**		**42.7**		**40.0**		**38.8**	

where i is natural gas; Q_{it}^{B}, Q_{it}^{CHP} are the demand for heat energy generation by gas-fired boilers and CHP plants in year t, respectively, mln Gcal; β_{it} is the percentage of the demand for heat energy generation by gas-fired CHP plants in year t, %.

The results of the forecast of heat energy generation by gas-fired boilers and CHP plants for the above scenarios are shown in Table 3.

The fossil fuel consumption by boilers and CHP plants is calculated given the determined demand for generation and the energy conversion losses:

$$B_{kit} = \frac{Q_{kit}}{\eta_{kt}\ k_i}, \quad (6)$$

where Q_{kit} is the demand for heat energy generation by heat energy source k using fuel i in year t, η_{kt} is the efficiency of the k-th heat generator in year t, %; k_i is the coefficient of conversion from natural units into t/TJ for the i-th fuel.

The forecast of changes in the efficiency of gas-fired boilers and boiler houses used in the DHS is given in Table 4.

The forecast of consumption of natural gas by CHP plants and boiler plants, consumption of coal by CHP plants, and consumption of petroleum products by boiler plants for the two scenarios of Ukraine's DHS development are given in Table 5.

Table 2. **The Share of CHP Plants in the Heat Energy Generation from Natural Gas, %**

Year	2020	2025	2030	2035	2040	2045	2050
Optimistic scenario	29	33	35	38	42	46	50
Pessimistic scenario	29	31	32	33	34	36	38

Table 3. **Demand for Heat Energy Generation by Gas-Fired Boilers and CHP Plants, mln Gcal/year**

Heat energy source		Year						
		2020	2025	2030	2035	2040	2045	2050
Total for gas-fired boilers and CHP plants, including	Scenario	**45.1**	**43.3**	**35.0**	**27.6**	**22.5**	**19.8**	**13.9**
Gas-fired CHP plants	O	13.1	14.3	12.3	10.5	9.5	9.1	6.9
	P	13.1	13.4	11.9	10.3	9.3	8.2	7.4
Gas-fired boilers	O	32.0	29.0	22.8	17.1	13.1	10.7	6.9
	P	32.0	29.8	25.2	20.9	18.0	14.6	12.1

Table 4. **Forecast of Changes in the Efficiency of Gas-Fired Boilers and Boiler Houses, for the Two Scenarios**

Indicator		Year						
		2020	2025	2030	2035	2040	2045	2050
Relative heat energy demand of heat energy sources, %		4	3	2.5	2	1.5	1	0.8
Boiler efficiency, %	O	90	92	94	95	96	97	98
	P	90	92	93	94	95	96	97
Boiler house efficiency, %	O	86	89	92	93	95	96	97
	P	86	89	91	92	94	95	96

Table 5. **Forecast of Consumption of Natural Gas by CHP Plants and Boiler Plants, Consumption of Coal by CHP Plants, and Consumption of Petroleum Products by Boiler Plants for the Two Scenarios**

Consumption		2020	2025	2030	2035	2040	2045	2050
Consumption of natural gas by boilers, billion m³/year	O	4.6	4.0	3.1	2.3	1.7	1.4	0.9
	P	4.6	4.1	3.4	2.8	2.4	1.9	1.6
Consumption of natural gas by CHPP, billion m³/year	O	1.9	2.0	1.7	1.4	1.2	1.2	0.9
	P	1.9	1.9	1.6	1.4	1.2	1.1	1.0
Coal consumption at the CHPP, thousand c.f. t	O	1740.5	1528.5	1270.2	1020.9	695.9	258.6	185.8
	P	1736.7	1649.8	1345.0	1114.4	994.9	895.0	791.3
Consumption of oil products by boilers, thousand c.f.t	O	101.9	80.6	51.6	26.8	8.5	0.6	0.0
	P	101.9	80.6	52.9	30.8	8.5	0.6	0.0

Table 6. **Total GHG Emissions from the Consumption of Fossil Fuels by DHS, CO_2-equivalent mln t**

Scenario	Year						
	2020	2025	2030	2035	2040	2045	2050
Optimistic	17.3	15.8	12.6	9.8	7.5	5.7	3.9
Pessimistic	17.3	16.0	13.4	11.1	9.6	8.0	6.9

The calorific value of natural gas is 8.1 Gcal/ 1000 m³, the conversion factor is 35.17 mln m³/ TJ. These data have been used in the calculations of GHG emissions from the consumption of natural gas by CHP and boiler plants.

The consumption of coal by CHP plants and oil products by boiler plants has been calculated similarly, by expression (6), with the use of the specific fuel consumption indicators from statistical data for 2015 [17] for heat energy produced and released by power plants (164.6 kg of standart coal/Gcal) and by boiler plants (163.0 kg of standart coal/Gcal), and a conversion factor of 29.3 kg of standart coal/MJ for the estimate of GHG emissions. These specific fuel consumption data for 2015 are the latest officially published statistics.

The calculations of GHG emissions for each type of fuel by formula (2) and their conversion to CO_2 equivalent by formula (3) have made it possible to determine the total GHG emissions from the consumption of fossil fuels for the above scenarios of Ukraine's DHS, as shown in Table 6.

As can be seen from Table 6, the proposed structures of heat energy generation by DHS ensures a 4.4 times reduction in the GHG emissions in 2050 for the optimistic scenario and 2.5 times reduction for the pessimistic scenario, as compared with the reference year 2020. The factors that cause this reduction are the changes in the DHS fuel balance (an increase in the use of renewable energy sources and a decrease in the use of fossil fuels) as well as the dropping demand for DHS heat energy.

It should be noted that the GHG emissions from biomass consumption are not included in these calculations, because this type of energy carrier is considered carbon-neutral. In addition, the increase in the electricity consumption share in the structure of the DHS fuel and energy balance (see Table 2) implies an increase in the GHG emissions from its production. However, such emissions are estimated in the electricity sector, which has led to their omission in this study, in order to avoid double counting.

CONCLUSIONS

1. The dynamics of Ukraine's DHS fuel balance have been forecasted. According to the forecast, the use of natural gas will decrease 1.4—2 times, that of coal will fall 1.4—5.9 times, while petroleum products will cease to be consumed after 2040. At the same time, the consumption of electricity will increase 7.7—19 times, that of biofuel will grow 2 times, and that of solar energy will hike 77 times.

2. The proposed structure of Ukraine's DHS heat energy generation ensures a significant reduction in the GHG emissions to 2050, both under the optimistic (4.4 times) and under the pessimistic (2.5 times) scenarios as compared with the reference year of 2020. By 2050, depending on the scenario, the GHG emissions will be 3.9 and 6.9 mln tons CO_2 eq., respectively.

3. For the first time, for the conditions of Ukraine, an achievable reduction in the GHG emissions from the DHS to 2050 relative to the level of 2020 has been estimated. This reduction may be achieved due to the expected decrease in heat energy generation as a result of dropping demand for heat energy and changing shares of the fuel balance components and generation structure (a reduction in the share of coal-fired and gas-fired CHP and boiler plants, as well as an increase in the share of biofuel boilers, solar collectors, heat pumps, and electric boilers).

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Received 12.09.2022
Revised 31.12.2022
Accepted 16.01.2023

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ОЦІНКА ВПЛИВУ СТРУКТУРНИХ ЗМІН В ЦЕНТРАЛІЗОВАНОМУ ТЕПЛОПОСТАЧАННІ УКРАЇНИ НА ОБСЯГИ ВИКИДІВ ПАРНИКОВИХ ГАЗІВ

Вступ. Найбільшу частку у викидах парникових газів (ПГ) в Україні має енергетика — близько 65 % від загального обсягу. Системи централізованого теплопостачання (СЦТ), які є одним із підсекторів енергетики, є вагомим джерелом викидів ПГ внаслідок спалювання викопного вуглецевого палива (природного газу, вугілля, нафтопродуктів, торфу тощо).

Проблематика. Завдяки своїм очевидним перевагам СЦТ будуть розвиватися з використанням нових технологій, що дозволить значно підвищити їхню ефективність, зменшити втрати тепла, забезпечити найнижчу вартість теплової енергії для споживачів. Проте на сьогодні не зроблено прогнозу щодо зміни паливного балансу СЦТ України, структури їхньої генерації та, відповідно, викидів ПГ до 2050 року.

Мета. Оцінення впливу структурних змін в СЦТ на обсяги викидів парникових газів.

Матеріали та методи. Використано наукові публікації, офіційні документи, статистичні дані; застосовано методи статистичного та порівняльного аналізу. Розрахунки виконано з використанням методології Міжурядової групи експертів ООН зі зміни клімату (МГЕЗК ООН).

Результати. Розроблено прогнози змін паливних балансів та структури генерації СЦТ України, які передбачають зменшення споживання природного газу в 1,4—2 рази, вугілля — в 1,4—5,9 рази. Згідно з прогнозами після 2040 року нафтопродукти не використовуватимуть як джерело енергії в СЦТ, натомість споживання електроенергії зросте в 7,7—19 разів, біомаси — у 2 рази, а сонячної енергії — у 77 разів порівняно з 2020 роком. Викиди ПГ від СЦТ у 2050 році становитимуть 3,9—6,9 млн т CO_2 екв. залежно від сценарію структурних змін СЦТ.

Висновки. Запропонована прогнозна структура виробництва теплової енергії в СЦТ України здатна забезпечити скорочення викидів парникових газів до 2050 року в 4,4 рази за оптимістичним та в 2,5 рази за песимістичним сценарієм їхнього розвитку порівняно з 2020 роком.

Ключові слова: системи централізованого теплопостачання, паливний баланс, структура виробництва теплової енергії, викиди парникових газів, паливо.