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THE USE OF RESIDUAL MUNICIPAL SOLID WASTE AS AN ALTERNATIVE FUEL

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Abstract

The relevance of the work is determined by the war of the Russian Federation in Ukraine and the decision of the leading countries of the world, the EU and Ukraine to abandon energy dependence on energy from the Russian Federation. An analysis is provided of the main directions for reducing the European Union's dependence on Russian natural gas by a third by the end of 2022, in particular, the development of the Waste-to-Energy market in the EU and other leading countries of the world. The main ways are presented and computational investigations of the possibility of substitution of certain amounts of natural gas with artificial fuel from residual MSW are carried out.

Based on the performed calculations, the authors formulated proposals for the feasibility of constructing facilities for energy use of residual MSW in different regions of Ukraine, as well as connecting them to the systems of centralized heating in Ukraine. The paper proves the necessity of building Waste-to-Energy power plants in the largest, large and big cities of the country. The ecological expediency of recovery of residual waste is shown.

Keywords: **Natural Gas; Residual MSW; Waste-to-Energy; Solid Waste Incineration Plant with Heat Recovery; District Heating.**

1. INTRODUCTION

Russia's war with Ukraine has proved to the whole world the necessity of an urgent refusal to buy energy resources, including natural gas, from Russia. Already on March 3, 2022, the International Energy Agency presented a 10-point plan to reduce the dependence of the European Union on Russian natural gas by a third by the end of 2022 [1].

The plan proposes diversifying natural gas supplies, accelerating the introduction of renewable energy sources (RES), increasing electricity production using nuclear power, introducing heat pumps, encouraging consumers to temporarily reduce indoor temperatures by 1°C, improving energy efficiency, etc.

In order to quickly reduce the strategic energy dependence of the EU on energy from Russia, the European Commission on May 18, 2022 presented an action plan for the establishment of a sustainable energy system and the acceleration of the transition to "green" fuel – the REPowerEU plan [2].

REPowerEU plan provides:

– enhance long-term energy efficiency measures, including an increase from 9% to 13% of the binding Energy Efficiency Target under the "Fit for 55" [3] package from Energy efficiency directive [4] of European Green Deal legislation [5].
– Diversifying supplies of natural gas;
– accelerating the renewable energy sources (RES) implementation, etc.

Heating represents the largest energy sector today. Heat Roadmap Europe 4 (HRE4) is to develop low-carbon heating strategies to 2050 [6]. To decarbonise and reduce energy system costs, fossil fuel consumption can be replaced with energy efficiency and renewable energy. Use of local resources can create a heat supply which more resistant to fuel price fluctuations.

WtE plants in Europe generate enough electricity to supply almost 19 million people per year. Additionally, around 10% of Europe's energy provided to District Heating networks comes from WtE [7]

A more detailed study of the energy potential of the use of a local resource – MSW – in the heat power industry of Ukraine is an important practical task, necessary to justify the partial replacement of imported natural gas in the municipal heating of Ukraine. For Ukraine, this is an extremely urgent issue due to the fact that one of the greatest threats to national security of Ukraine is its energy dependence on imported natural gas and the threat to the stability of the heating season. In April 2022 the Bioenergy Association of Ukraine presented its proposals for ten steps necessary for Ukraine to avoid importing of natural gas [8], the main of which are the replacement of natural gas with solid biofuels derived from biomass plant waste, biomethane, further development of RES, diversification of natural gas supplies, extending the life of existing nuclear power plants, introduction of heat pumps, energy efficiency improvements, etc.

Supporting the above measures, we propose additional important and high priority for Ukraine directions of substitution of imported gas in centralized heating systems:

1) increasing our own production of natural gas;
2) leveling the daily schedule of electric loads during night consumption drops through the wide introduction of electric boilers and the use of modular heating substations with automatic electric heating of network return water before supplying to the boilers at boiler plants in the utilities sector;
3) urgent introduction of heat utilizers for large and medium sized heating boilers;
4) use of local fossil fuels, including peat;
5) use of alternative energy sources:

– residual municipal solid waste (MSW);
– waste gases from industrial enterprises.

The possibility of replacing natural gas in district heating systems with thermal energy from residual MSW is discussed in detail below.

The authors expect that the wide use of residual municipal waste in district heating will reduce the country's energy dependence, as well as allow for more efficient processing of the entire MSW stream, which will reduce the burden on the environment, in particular reducing greenhouse gas methane emissions from household waste landfills.

2. THE PURPOSE AND RESEARCH METHODS

The aim of the work is to assess the prospects of energy use of alternative fuel derived from residual MSW to replace the use of natural gas at the enterprises – producers of thermal energy, which are in state or municipal ownership in Ukraine. To determine the current situation in this area, the analytical method is used, in particular the method of statistical analysis of real data.

Table 1.
Waste Composition by Income Level [8]

Classified according to World Bank estimates of 2015 GNI per capita, PPP	Waste Composition by Income Level, %							
	Food and green	Paper and cardboard	Plastic	Glass	Rubber and leather	Wood	Metal	Other
High ($12.476 or more)	32	25	13	5	4	4	6	11
Upper middle ($4.036-$12.475)	54	12	11	4	1	1	2	15
Lower middle ($1.026-$4.035)	53	12,5	11	3	1	1	2	17
Low ($1.025 or less)	56	7	6.4	1	-	1	2	17

3. RESEARCH FIELD CHARACTERISTICS

The higher the purchasing ability of a population in a country, the more MSW it generates. This is evidenced by World Bank studies [9] and Eurostat data [10]. The World Bank estimates that 2.01 billion tonnes of MSW were generated in 2016 [9]. By 2030, the world is expected to generate 2.59 billion tonnes of waste annually and this number will rise to 3.40 billion tonnes by 2050 under a business-as-usual scenario. According to Eurostat, the average European will produce 505 kg of MSW per year in 2020, which is 38 kg more than in 1995. The Danes generate the most MSW – 845 kg per person and residents of Luxembourg – 790 kg per person, in Germany – 632 kg per person and in Poland – 346 kg per person.

The rapid growth of MSW generation in the world is leading to a drastic deterioration of the environmental situation on the planet. The solution to this problem in the transition to the Sustainable Development Concept, which "meets the needs of the present without compromising the ability of future generations to meet their own needs" [11].

European legislation in the field of waste management regulates the waste management hierarchy in order to utilise its material and energy potential and to cut the amount of waste sent to landfill. Directive 2008/98/EC "On waste..." introduces a five-step waste management hierarchy: prevention, reuse, recycling, recovery, including energy recovery, disposal [12]. The purpose of this Directive is to implement the principle "From recycling to a circular economy". Directive (EU) 2018/851 complements Directive 2008/98/EC in line with the current challenges of the need to increase efficiency in the use of fossil resources and to reduce the environmental impact of waste in order to move towards a circular economy [13]. The European Green Deal sets targets to achieve 65% recycling of MSW and a reduction to 10% of MSW landfill by 2035 [5]. The European Parliament has approved the inclusion of municipal incinerators within the scope of the EU Emissions Trading Scheme (ETS) as of 2026 [14].

According to a World Bank study, the morphology of MSW also depends on the buying capacity of the population (Table 1).

The data in Table 1 show that the MSW of High GNI per capita countries is dominated by resource components. In these countries, the goals of the Green Deal can be quickly achieved. In the remaining countries about 50% of the waste is food and green waste. In these countries it is advisable to implement, as required by Directive (EU) 2018/851[13], the separate collection of Biodegradable waste followed by Aerobic and anaerobic digestion to produce biogas or compost. Inert waste (Glass and Metal) is 3–10%.

The analysis of the morphological composition of municipal waste in Ukrainian cities, as well as a comparative analysis of the morphological composition of MSW in Finland, a country with High GNI per capita and Ukraine, a country with Lower middle GNI per capita [15] and eight cities from different regions of Ukraine [16] confirms the dependence of the amount and composition of waste on changes in population size and income levels.

But 25–30% of the waste that is not reusable or recyclable (as well as combined waste), i.e. residual waste, remains in the municipal waste composition. This waste contains energy potential, the recovery of which allows to reduce the consumption of fossil fuels. This is in line with the principles of a circular economy: «Waste-to-energy processes can play a role in the transition to a circular economy provided that the EU waste hierarchy is used as a guiding principle and that choices made do not prevent higher levels of prevention, reuse and recycling» [17].

Leading countries of the world consider MSW as an alternative local energy resource which is very logistically convenient. The environmental emission values of modern Waste-to-Energy (WtE) plants are below

Table 3.
CO_2 emission values [19]

Fuel	CO_2, $kgCO_2/Mg$
Coal	2 603
Biomassa (wood)	1 540
RDF	1 247
MSW	1 063

the environmental requirements of Directive 2010/75/EC [18] due to a perfect cleaning system.

As an example, Table 2 shows the compliance of pollutant emissions from 8 WtE plants operating in Poland [19] with the Directive 2010/75/EC.

MSW combustion contributes to the reduction of the greenhouse gas CO_2 emissions (Table 3).

The European Waste-to-Energy sector is already carbon neutral today and with adequate political support it can become carbon negative in the future, according to the new CEWEP Waste-to-Energy Climate Roadmap presented on 21st June 2022 in Brussels [20].

It should be noted that in addition to supplying energy to cities, incinerators solve an important social problem – cleaning up cities from MSW.

The global value of the WtE market reached $35.1 billion in 2019. By 2027, the WtE market is expected to be worth $50.1 billion [21]. There are now several thousand WtE installations in operation around the world. Most of them, namely 2,000 units, are located in Japan. China's WtE market size in 2021 was about 19 billion yuan (about $2.8 billion). The annual cumulative installed capacity of WtE installations in the UK has increased from 381 MW in 2009 to 1,421 MW in 2020.

In 2020, about 30% of all municipal waste in the EU was recycled, about 27% of waste was incinerated in WtE plants, co-incinerated with other fuels in cement or power plants. In 2019, there were 499 WtE plants operating in the EU, which processed 99 million tonnes of MSW [22]. Around 45–49% of residual MSW from France, Germany and Austria is incinerated, and together with incineration in cement plants, the energy recovery rate of residual waste reaches 67%. There are 96 WtE plants operating in Germany, which recover the energy of 26.3 million tonnes of MSW in 2018 [23] and 100 WtE plants operating in Germany (+4%), which recover the energy of 27.1 million tonnes of MSW in 2019 (+3%) [22]. In Poland, a country which is close to Ukraine in terms of population, geographically and mentally, but differs economically, the direction of thermal recovery of energy potential of residual MSW is actively developing.

Until 2013, municipal waste in Poland was incinerated in the only waste incineration plant in Warsaw. In 2020, there were already 8 incineration plants operating in the country. The installed capacity of WtE Poland is 2.569 mln t, including incineration plants 1.159 thousand t (about 8% of MSW), cement plants that co-incinerate MSW with the main fuel 1.150 mln t and energy plants that co-incinerate with the main

Table 2.
Compliance of the emissions of the 8 Waste-to-Energy plants operating in Poland [19] with the Directive 2010/75/EC [17]

Polluting substance	Emission limit values, mg/Nm^3	
	Directive 2010/75/EC [18]	8 WtE plants operating in Poland [19]
Total dust	10	2…4.6
Carbon monoxide (CO)	50	3.31…29.00
Nitrogen monoxide (NO) and nitrogen dioxide (NO_2), expressed as NO_2 for existing waste incineration plants with a nominal capacity exceeding 6 tonnes per hour or new waste incineration plants	200	74.85…176.13
Sulphur dioxide (SO_2)	50	5.4….19.9
Hydrogen chloride (HCl)	10	0.3…2.63
Hydrogen fluoride (HF)	1	0…0.44
Mercury and its compounds, expressed as mercury (Hg)	0.05	0.001…0.005
Cadmium and Thallium and its compounds, expressed as cadmium (Cd) and thallium (Tl)	0.05	0.001…0.023
Antimony, Arsenic, Lead, Chromium, Cobalt, Copper, Manganese, Nickel and Vanadium (Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V)	0.5	0.007…0.134
Dioxins and furans	0.1	0.00018...0.0824

fuel 0.250 mln t. In 2020, 5.5 million GJ of energy has been recovered [24]. The draft strategy for the development of district heating in Poland until 2030 with a perspective until 2040 foresees the combustion of residual waste in CHP or incineration boilers of the district heating system in order to substitute coal [25].

District heating for densely populated cities makes it possible to replace fossil fuels with RES or alternative energy sources. District heating and cooling currently provides around 10% of the EU's heat demand [26].

4. RESULTS AND DISCUSSION

4.1. Substitution of natural gas with heat from residual MSW in Ukrainian district heating systems

One of the main consumers of natural gas in Ukraine are heating public utility companies (PUC) that produce heat energy and provide centralised heating and hot water supply services to the population, governmental organisations and public utilities (276 million TJ). Boilers of such heating companies consume 23.5% of the total natural gas consumption in the country [27]. Ukraine has a well-developed district heating network. Overall there are over 1000 heat supplying companies in Ukraine, and centralised heat supply covers 40% of the population. Most multi-apartment buildings and some private buildings in cities and towns are connected to district heating networks with a total length of about 21 000 km [28].

The recovery of the energy potential of residual MSW, which cannot be recycled, is the most affordable urban alternative energy source in the conditions of Ukraine, located close to the heat consumers – PUC. The recovery of its energy potential can increase the energy safety of the centralised heat supply of Ukraine. Thermal energy from residual MSW can be a significant addition to other sources of natural gas substitution.

Electricity production in Ukraine exceeds consumption. According to the Ministry of Energy, total electricity consumption for 2021 was 125.5 billion kWh, and total electricity production was 156.6 billion kWh [29, 30].

The main share in total electricity generation in 2021 was generated by nuclear power plants (NPPs) – 55.1% [30]. The estimated cost of electricity from NPPs in Ukraine is many times lower than the cost of electricity generation from other sources. Therefore, it is not yet economically feasible to build Waste-to-Energy plants and use the energy of residual MSW to generate electricity in Ukraine.

It is advisable to incinerate Ukraine's residual MSW in a waste incineration plant (WIP) connected to the district heating system, i.e. operating as a boiler house with heat energy transfer for heating and possibly providing domestic hot water (DHW) services. That is why the National Waste Management Strategy in Ukraine until 2030 envisages the construction of 20 stationary MSW thermal recycling facilities [31].

To determine the feasibility of MSW incineration in WIP to substitute natural gas in district heating systems in Ukrainian cities it is necessary to estimate the number of urban population and the amount of MSW generated, its morphological composition, calorific value and moisture content of mixed residual MSW.

Ideally, up-to-date data should be obtained from the following official sources: statistical data from the Ministry of Statistics, the Ministry of Regional Development, data from experimental studies of the morphological composition of MSW of various categories, data from experimental caloric studies and moisture content of mixed MSW. In practice, under current martial law conditions, such data are fragmentary, which makes it impossible to base the analysis on them.

4.2. Basic scenario for determining the possibility of substitution of natural gas in district heating systems with residual MSW

The baseline scenario was estimated according to pre-quarantine and the most recent stable year 2019.

The population of Ukraine in 2019 was 41.9 million [32]. According to the Ministry of Regional Development of Ukraine, 10.4 million tonnes of MSW were collected in the country [33]. The annual MSW generation rate was about 300 kg per 1 inhabitant. Studies of the morphological composition of municipal waste are available in the sanitation schemes of Ukrainian cities.

Resource potential of waste use as a component of environmental and energy security of the state is analyzed in [34]. It has been shown that pre-war estimations of recycling were to provide more than 104 million tons of valuable materials and raw materials by 2025.

To determine the feasibility of replacing natural gas with the energy potential of residual MSW in district heating systems, the potential population and the amount of MSW formed was assessed. According to the Law of Ukraine "On Waste Management", by

2030 not less than 20% of the mass of MSW should be subject to recycling [35]. The amount of MSW formed in cities was estimated taking into account the need for 20% recycling.

Previous studies of the authors [36] proved that it is economically feasible to implement WtE in Ukraine in cities with a population of more than 700 thousand people. In the National Waste Management Plan of Poland until 2022 the country, which differs from Ukraine economically and, consequently, in terms of waste morphology, adopted the introduction of WtE installations in cities with a population of more than 300 thousand people [37].

According to the State Building Standards DBN B.2.2-12:2019 [38], cities with a population over 300,000 are divided into 3 groups: the largest (most significant) cities with a population over 800,000, large (significant) cities with a population of 500,000–800,000; and big cities with a population of 250,000–500,000.

In 2019, there were 22 such cities, excluding temporarily occupied territories, in Ukraine. The largest cities in Ukraine were six: Kyiv, Kharkiv, Odesa, Dnipro, Zaporizhzhia and Lviv. There were 3 large cities: Kryvyi Rih in Dnipropetrovsk oblast, Mykolaiv, and Mariupol in Donetsk oblast. There were 13 big cities: Vinnytsia, Zhytomyr, Ivano-Frankivsk, Kropyvnytskyi, Lutsk, Poltava, Rivne, Sumy, Ternopil, Khmelnytskyi, Cherkasy, Chernivtsi and Chernihiv.

In order to determine the feasibility of substitution of natural gas with the energy potential of residual MSW in district heating systems, the potential population and the amount of MSW generated in them have been estimated. According to the Law of Ukraine "On Waste Management", not less than 20% of the mass of MSW should be subject to recycling by 2030 [35]. The amount of MSW generated in cities has been estimated taking into account the need for 20% recycling.

The morphological composition of municipal waste in the largest cities of Ukraine is given in Table 4.

As it can be seen from Table 4, the prevailing component of MSW in the largest cities of Ukraine is food biowaste (30–40%). The share of energy components of residual mixed MSW is about 30%.

The degree of waste treatment depends on the approach to separate collection of MSW [45]

The results of the study of the energy potential of biogas formation during the fermentation of Ukrainian food waste is presented in paper [46].

The paper [47] assesses the features, volumes, morphological and elemental composition of municipal solid waste in Ukraine. The potential for RDF production on the basis of MSW in Ukraine for different cities and regions has been analyzed and determined. It was determined that the calorific value of unsorted MSW varies depending on the region of Ukraine in the range of 5.0–7.5 MJ/kg, depending on the city – in the range of 5.5–7.5 MJ/kg, on average in Ukraine – 6.8 MJ/kg. It is shown that the potential annual production of RDF in Ukraine is 2.8–3.2 million tons. The calorific value of RDF produced from MSW in Ukraine can be estimated at 13.1–15.9 MJ/kg, which corresponds to the 3^{rd} and 4^{th} quality classes according to DSTU EN 15359:2018.

The calorific value of municipal solid waste was calculated on the basis of the elemental composition of municipal solid waste.

The paper [48] presents the results of computer simulation of RDF influence on the process of co-combustion with natural gas at the existing boilers of small and medium steam capacity with a burner of

Table 4.
Morphological composition of MSW in the largest cities of Ukraine

	City					
	Kyiv [39]	Kharkiv [40]	Odesa [41]	Dnipro [42]	Zaporizhzhia [43]	Lviv [44]
Population, thsd.persons [32]	2 967.4	1 443.2	1017.7	990.7	731.9	724.3
MSW, %						
Food	32.85	41.38	29.33	37.85	29.3	26
Paper and cardboard	11.31	13.45	4.85	6.6	10.8	10
Plastic	17.64	7.67	13.02	7	14.4	13
Glass	10.51	7.74	23.74	11.7	11.0	4
Metal	1.75	2.87	3.84	0.45	0.8	1.5
Textiles	3.46	3.81	2.06	3.64	12.9	8
Wood	1.02	1.67	1.64	2.79	10.9	5.5
Unsorted residue	21.45	21.41	41.51	29.96	9.9	32

thermal capacity of 18.6 MW. Calculated dependences of temperatures, velocities, distributions of concentrations of gas components, carbon remaining in the solid phase, as well as concentrations of nitrogen oxides and carbon monoxide above the combustion chamber were obtained. According to preliminary estimates, it is possible to add about 20% RDF (of the total calorific value) during co-combustion with natural gas, which will not significantly change the technical and environmental parameters of the combustion chamber operation.

The paper [49] presents the results of experimental studies of the amount of generated heat during combustion of mixed municipal solid waste of the city of Kyiv.

The study of the amount of heat released during the combustion of mixed waste of the city of Kyiv was carried out on an experimental boiler. Up to 5 kg of mixed MSW, morphology and humidity of which corresponded to different seasons of the year, were loaded into the experimental boiler. The method developed by the authors, using the experimental-calculation method, revealed that the calorific value of municipal wastes of Kyiv was about 6–7 MJ/kg [49].

In Kyiv, 1,450 thousand tonnes of MSW were generated in 2019. Including 20% recycling, the total potential for heat production from MSW in the city was about 1.3 million Gcal/year, which corresponds to 6.3% of the existing heat consumption of the city.

The only incineration plant in the country, Energia, operates in Kyiv. The plant incinerates up to 25% of the city's MSW. The plant delivers about 250 thousand Gcal/year of heat energy to the district heating network for heating and hot water supply to the city residents. It is expedient to incinerate the remaining mixed residual MSW of the city in 3 WIP with transfer of heat energy to the district heating system of the city.

Prospective directions of use of energy potential of residual municipal solid waste on the example of Kyiv are analyzed in the paper [50].

It has been demonstrated that the most appropriate approach for burning of MSW in Kyiv is the construction of a Waste-to-Energy Plant. It is has been shown that the remaining mixed residual MSW of the city is advisable to burn in 3 SSW with the transfer of heat energy to the district heating system of the city.

In Kharkiv, Dnipro, Zaporizhzhia and Lviv it would be appropriate to burn mixed residual MSW in the Waste Incineration Plant with heat recovery to supply heat to the heat networks of the cities. In Odesa, as a resort city, the population increases almost twice between May and October, but the amount of food waste increases significantly in MSW morphology during this period. Therefore, in Odesa it is reasonable to install containers to collect biowaste for biogas production and incineration of the RDF (from remaining mixed MSW) in the WIP on RDF. This is the technical solution approved in the Heat Supply Scheme of the city of Odesa, developed with the authors' participation [51]. Results of calculation of the need for WIP and RDF boilers (without MSW incineration plant JV "Plant "Energy" KP "KYIVTEPLOENERGO") for the largest and large cities of Ukraine are presented in Tables 5 and 6, respectively.

The implementation of this concept would save about 375 million m^3 of natural gas (including about 26 million m^3 of biogas).

The population of big city Vinnytsia was 370,700 people. The population of twelve big cities had less than 300 thousand residents: Zhytomyr – 264.3 thousand, Ivano-Frankivsk – 237.7 thousand, Kropyvnytskyi – 225.4 thousand, Lutsk – 217.3 thousand, Poltava – 286.7 thousand, Rivne – 246 thousand, Sumy – 262

Table 5.
Feasibility of construction of Solid WIP and RDF boilers for the largest cities in Ukraine

#	Cities of Ukraine	Number of People in 2019, thsd. people	Quantity of mixed residual MSW, thsd. tonnes	Heat energy, thsd. Gcal		Number of WIP with heat recovery, Units		Capacity of WIP with heat recovery, thousand tonnes		Biogas, million m^3	Natural gas savings, million m^3
				MSW	RDF	MSW	RDF	MSW	RDF		
1	Kyiv	2 967	920	1000		3		300			130
2	Kharkiv	1 434	389	435		2		200			55
3	Odesa	1 016	436		220		1		200	26	27
4	Dnipro	991	281	315		1		300			40
5	Zaporizhzhia	732	215	240		1		200			30
6	Lviv	724	204	229		1		200			30
	Total:					8	1			26	312

Table 6.
Feasibility of construction of Solid WIP and RDF boilers for the large cities in Ukraine

#	Cities of Ukraine	Number of People in 2019, thsd. people	Quantity of mixed residual MSW, thsd. tonnes	Heat energy MSW, thsd. Gcal	Number of WIP with heat recovery, Units	Capacity of Solid WIP with heat recovery, thsd. tonnes	Natural gas savings, million m^3
1	Kryvyi Rih	619	214	240	1	200	30
2	Mykolaiv	480	171	192	1	150	18
	Total:				2		48

thousand, Ternopil – 223.5 thousand, Uzhhorod – 115.5 thousand, Khmelnytskyi – 273.7 thousand, Cherkasy – 274.8 thousand, Chernivtsi – 267.1 thousand and Chernihiv – 286.9 thousand, so it would not be feasible to build the WIP or WtE there.

4.3. Determination of the possibility of substitution of natural gas in district heating systems with residual MSW under martial law

Following Russia's annexation of some Ukrainian territories in 2022, the determination of the feasibility of substitution of natural gas with the energy potential of residual MSW in district heating systems was based on open-source information available at the time of writing.

According to the UN, as of 06 July 2022 about 5.7 million people had left the country, about 3.3 million had returned [46] and more than 6.2 million had been internally displaced [52]. The death toll will be known after the end of hostilities. The city of Kherson is temporarily occupied, Mariupol is completely destroyed and occupied, so these cities are excluded from this analysis.

The population of cities affected by hostilities in the north-eastern and southern parts of Ukraine (Zaporizhzhia, Kherson, Kharkiv, Kyiv, Donetsk, Luhansk, Sumy and Chernihiv regions and Kyiv city) moved to the central and western regions of the country (Zaporizhzhia, Dnipro, Kirovograd, Khmelnytskyi, Volyn, Rivne, Zhytomyr, Lviv, Ternopil, Ivano-Frankivsk, Transcarpathian, Vinnytsia and Poltava regions). A nationwide survey showed that the majority of those surveyed want to return to their homes [53]. A part of the displaced persons will remain in the cities of their new habitat due to the loss of their homes and jobs in their locality.

The calculations assumed that internal displacement led to an increase in the population of cities such as Lutsk, Uzhhorod, Ivano-Frankivsk, Kropyvnytskyi, Poltava, Rivne, Ternopil, Khmelnytskyi, Cherkasy, Chernivtsi to at least 300 thousand.

The population of the cities of Kyiv, Kharkiv, Odesa, Zaporizhzhia, Dnipro and Zhytomyr will decrease, but not significantly due to the resettlement of people from occupied and destroyed areas. The annual MSW generation rate under current conditions will decrease, the share of resource-valuable components in MSW will decrease and the share of food waste will increase, but will return to the pre-war amount after the economic situation is normalised. Therefore, we assume that the natural gas savings in the first and second group cities will remain similar to the baseline scenario.

In modern conditions in cities of the third group with the population of about 300 thousand people it is reasonable to introduce separate containers for collection of biowaste (food waste) with subsequent production of biogas or biomethane from it, according to the Directive (EC) 2018/851 [13].

The remaining mixed residual waste should be incinerated in the WIP with heat energy supply to the heating networks of the cities and to install containers to collect biowaste for biogas production. It is also feasible to build WIP on RDF and to incinerate RDF in the WIP on RDF with the supply of heat to the heating networks of the cities.

The implementation of this concept in 14 cities would save about 95 million m^3 of natural gas (including about 60 million m^3 of biogas).

The total savings would be about 470 million m^3 of natural gas, including about 86 million m^3 of biogas.

4.4. Barriers to implementation and how to overcome them

Throughout the years of independent Ukraine, the construction of a WIP-on-MSW with a modern gas emission treatment system has been unprofitable for city administrations due to the need for substantial capital investment with a long payback period (up to 10 years).

The plans for a WIP-on-MSW have been resisted by the population and by public environmental organisations.

After the end of hostilities, hopefully the post-war reconstruction programme for Ukraine will come into force. In the framework of the programme it is advisable to install ten WIP-on-MSWs in Ukraine with modern gas emission treatment system for large cities of the first and second groups. The rise in the cost of energy on world markets will significantly reduce the payback period of investments. Once the economic situation has stabilised, it is advisable to build another 14 WIP-on-RDFs in big cities.

Reducing the use of natural gas (and completely avoiding imports) will contribute to making cities more energy independent.

Incineration of MSW in WIP-on-MSW and WIP-on-RDF will significantly reduce the amount of landfill disposal, which will improve the ecology of the surrounding area as well as lead to lower fuel consumption and a smaller fleet of rubbish trucks, reducing congestion on suburban roads. These factors increase the economic and environmental feasibility of the construction of the WIP-on-MSW.

5. CONCLUSION

1. On the basis of the conducted calculation studies, the expediency of the construction of ten WIP on MSW is shown, which allows to replace 470 million m^3 of natural gas, including 86 million m^3 of biogas. This will allow, after the construction, to replace up to 10% of natural gas used for heating and hot water supply of the population of the largest, large and big cities of Ukraine.
2. Now about 18.5–19 billion m^3 of natural gas is produced in Ukraine annually. Demand of heat and utility companies and household consumers is cumulatively about 20.5-21 billion m^3. Savings of 1.5-2 billion m^3 of natural gas will allow the heat supply sector to completely abandon imported natural gas. As calculations have shown, residual MSW is a resource capable of replacing part of this volume of gas.
3. The studies presented in the article are the basis for the Concept of the State Targeted Economic Program for Substitution of Natural Gas Consumption through Energy Recovery of Solid Waste in State or Municipal Ownership at Heat Producers for the Period to 2030, with plans to install WIP-on-RDF in Odesa, Ternopil and Lviv as pilot projects.

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