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Violeta MISEVIČIŪTĖ
Rapolas TUČKUS
Artur ROGOŽA
Vilnius Gediminas Technical University, Faculty of Environmental Engineering, Department of Building Energetics
Corresponding author: violeta.miseviciute@vilniustech.lt

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MULTI-CRITERIA EVALUATION OF TECHNOLOGICAL SOLUTIONS TO IMPROVE GAS DISTRIBUTION STATION EFFICIENCY

Abstract: *Due to the global energy crisis, rising energy demand, and climate change, there must be a way to recover energy that is not used for beneficial purposes, reduce primary and final energy consumption, and reduce emissions. The natural gas sector and its transmission networks, including gas distribution stations (GDSs), are an important component of Lithuania's energy sector. Because the gas pressure is reduced by the use of gas pressure regulators (GPR), the energy potential in high pressure gas is not used effectively, the need to heat natural gas is conducted with the use of natural gas boilers, and additional environmental pollution is caused by the use of GDS. The purpose of the study is to analyse GDSs, identify areas where the energy potential is not being exploited and the environment is polluted, and propose reasonable solutions. After reviewing the literature, alternative technological solutions were selected, including turbine expanders, gas preheating systems that were modified from gas boilers to geothermal heat pumps, solar collectors, and photovoltaic solar cells. To evaluate the potential of technological solutions to improve GDS efficiency and reduce emissions, the proposed solutions are analysed according to the multi-criteria analysis that consider solutions proposed from an energy, economic, and environmental perspective. Based on multi-criteria evaluation, the best alternative technological solution for GDS is recommended.*

Keywords: *gas distribution station (GDS), gas pressure regulator (GPR), groud source heat pump (GSHP), multi-criteria evaluation, natural gas, photovoltaic solar cells (PV), solar collectors system (SCS), turbine-expander (TE).*

Introduction

In recent years, due to rising energy prices, concerns about energy security, and the urgent need to address climate change, improving energy efficiency in Europe has become increasingly important. In response to these trends, several institutional reforms have been carried out to promote energy efficiency, including the European Directive on Energy Efficiency [1] establishing energy reduction targets and a series of national and private initiatives [2]. The natural gas sector and its transmission network, including gas distribution stations (GDS), are essential components of Lithuania's energy sector. The GDS has an insufficient energy recovery potential as a result of the reduction in gas pressure by gas pressure regulators (GPRs), and the potential energy potential of high-pressure gases is not fully exploited, and the necessary preheating of natural gas is carried out using natural gas boilers, which cause additional pollution.

Several studies have been conducted on the potential for energy recovery in the GDS depressurisation process using turboexpanders (TE) [3]. These applications are also used in GDSs in other countries, and their effects on isoenthalpic GPR are being studied. In these studies, the authors observed that DSS pressure relief units equipped with TE are sensitive and are not suitable for stations with seasonal characteristics (such as flow and pressure). Furthermore, most authors noted that the temperature decreased higher with a TE system (0.45-0.6°C/bar in conventional GPR, 1.5-2°C/bar in TE systems) [4].

With conventional pressure reduction techniques (GPR) and alternative technologies (TE), additional gas preheating is required to prevent the formation of hydrate crystals and ensure the proper operation of the device. Most GDSs have similar design and operation, using gas boilers that heat gas before entering pressure relief devices, and reduce gas temperature to the 3°C due to Joule-Thompson effect.

Some of the published studies examine various alternatives to conventional gas sources. Ghezelbash et al. [5] reviewed a ground-source heat pump (GSHP) (if electricity is supplied from the grid/turbine expander) as an alternative for retrofitting GDS. In one study, parallel solar collectors with storage tanks and TE were proposed as energy recovery systems to replace heat sources (natural gas boiler) and reduce the amount of gas used for preheating [6, 7]. In another study, an evaluation of a photovoltaic (PV) solar power plant (PV) and a compressed air energy storage system was carried out from an energy-economic point of view [8], as well as an energy-environmental study of the use of a concentrated solar plant for preheating of GDS gas.

According to [5-14] the above-mentioned studies results it was observed that GDS has unused energy recovery potential and that gas preheating can be carried out by other alternative sources. Above mentioned studies have examined only one or a few technologies, did not compare them, only considered solutions of one or two of the three criteria (energy, economic, ecology – 3E) and did not consider Lithuania's GDS. This research presents multi-criteria analysis of GDS gas preheating and pressure reduction techniques, comparing measures with each other under all 3E criteria.

The objective of the research is to analyse the structure and functioning of GDS, identify processes where potential energy is not used and where the environment is polluted, and propose solutions to improve efficiency based on energy, economic and ecological criteria.

Research object

The Lithuania's gas transmission system consists of 64 GDSs. The main purpose of the GDS is to measure the gas pressure and reduce it to required by the system user [15]. Many of the GDSs in the Lithuania's gas transmission network are new or have been rebuilt and have similar or identical structures. Therefore, the study collected data on new construction GDS, which were used for further calculations (Table 1).

Table 1. *Data on new construction GDS*

Parameter (unit of measurement)	Average gas flow (n.m^3/h)	Gas temperature at the inlet to the GDS (°C)	Gas pressure at the inlet to the GDS (bar)	Gas temperature at the outlet of the GDS (°C)	Gas pressure at the outlet of the GDS (bar)	Area of a roof (m^2)
Designed	10 ÷ 5000	+2 ÷ +10°C	20 ÷ 55	+3 ÷ +7°C	3 ÷ 16	50
Actual	107 ÷ 918	+5 ÷ +11°C	39 ÷ 41	+3°C	3	50

The study showed that gas filtration points have a small loss of gas pressure throughout the site (nearly analysed GDS and other GDS, normal filter pressure drops do not exceed 0.5 bar). In other parts of the system, measuring units, turbine or rotating gas meters are commonly used in stations of this size, but the significance of these measuring devices for energy variations is relatively small (according to one of the most popular manufacturers, the gas pressure loss of the turbine meters is less than 17.3 mbar [16] and the rotary meters are less than 4.97 mbar [17]. Similarly, when a particular odor-enhancing odorant is added to the flowing gas at the end of the GDS system, the change in gas mass and energy is insignificant (the odorization rate is 16 g per 1000 m^3 of gas) [18]. For these reasons, the impact of gas filtration, measurement, and odorization systems on the mass and energy balance of GDS is believed to be negligible, and therefore the boundaries of the subject are changed and only the gas preheating and pressure control system is considered for research purposes. The study used a simplified GDS scheme, along with the key indicators and proposed alternatives, is depicted in Figure 1.

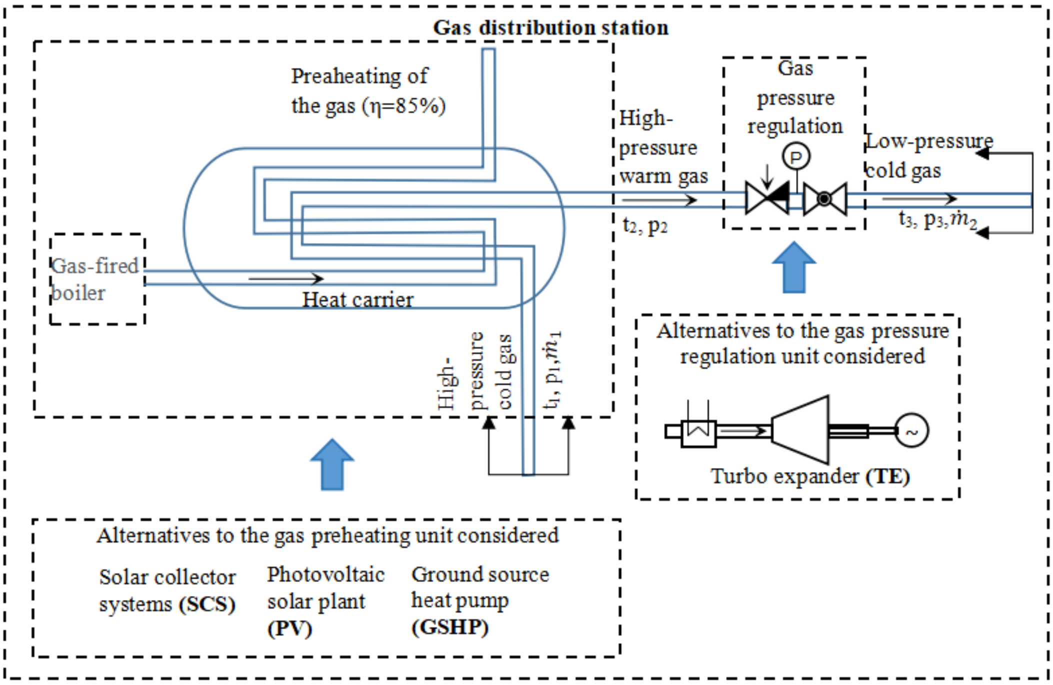

Figure 1. *A simplified scheme of the GDS, its main performance indicators, and alternatives based on master thesis [19]*

Three alternative sources of gas pre-heating are considered: solar collector systems (SCS), photovoltaic solar plant with electrical heater (PV), ground-source heat pump (GSHP), and alternative gas pressure control device (TE). The following alternative combinations were calculated: TE+GSHP; TE+PV; GSHP+PV; TE+GSHP+PV; TE+SCS; TE+GSHP+SCS.

Calculation of the heat demand for gas preheating

Based on the collected data (gas flow rate, upstream and downstream gas pressures), the amount of heat (1) needed to preheat the gas is estimated:

$$G = \frac{B \cdot \left(\left(p_1 - p_2 \right) \cdot \mu + \left(t_{out} - t_{\min} \right) \right) \cdot c_p \cdot \rho \cdot k}{3.6}, \quad \text{W} \tag{1}$$

where:

B – gas flow rate, n.m³/h;

p_1 – upstream gas pressure, bar;

p_2 – downstream gas pressure, bar;

μ – Joule Thomson coefficient, μ = 0.6°C/bar;

t_{out} – gas temperature at the outlet of the GDS, °C;

$t_{\min}$ – minimum gas temperature at the inlet of the GDS, °C;

c_p – specific heat of the gas, c_p = 2.25 kJ/kg·K;

ρ – density of the gas, ρ = 0.73 kg/m³;

k – coefficient of assessment of the heater's fouling, k = 1.05.

The gas flows and the calculated heat demand for gas preheating are shown in Figure 2.

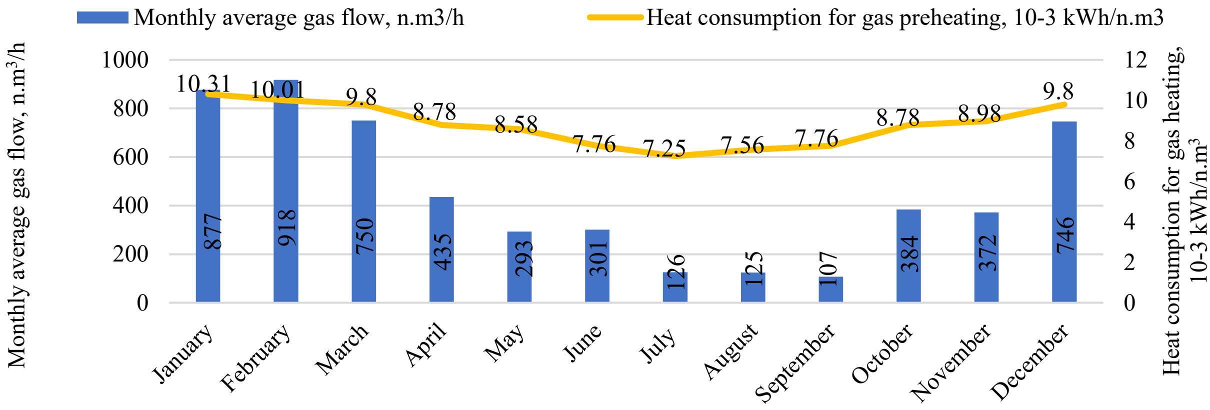

Figure 2. *Monthly GDS gas flows and estimated heat input for gas preheating*

Figure 2 represents the monthly heat demand required to heat GDS gas without installed alternatives. If TE is installed instead of a GPR, the heat quantities must be recalculated.

Multi-criteria evaluation of alternatives

To evaluate GDS alternatives, a multi-criteria analysis taking into account energy, environmental and economic indicators is applied. The energy criterion evaluates the energy consumption and/or production of the object under consideration, the environmental criterion covers the impact of the life cycle assesment on the environment, and the economic criterion covers cost indicators (capital investment, operating costs, potential revenues in terms of net present value (NPV). All these criteria are represented in the multi-criteria analysis by 1 n.m^3 of gas flowing through the GDS (Fig. 3).

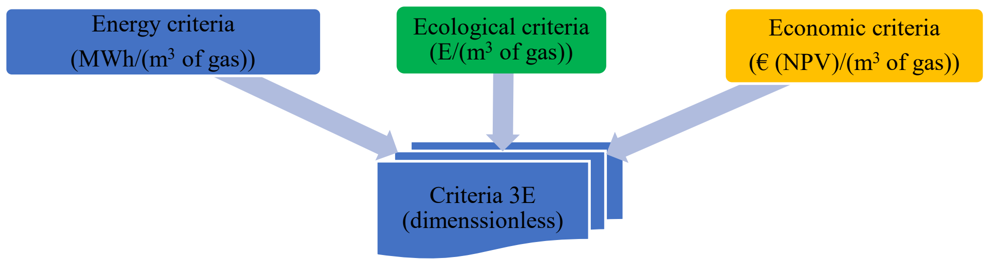

Figure 3. *The principle of multi-criteria evaluation*

Once all of the above criteria are identified and evaluated for individual solutions, the feasibility and sustainability of the different GDS alternatives can be assessed, and the options best suited to the objectives can be selected. It is assumed that all three criteria are equal, that is, that they have received the same weight as 0.3. Consideration was also taken into account that two of the criteria (energy and environment) are best at the lowest level and the third (GDV) at the highest level, so that the weighting of several criteria is calculated by formula:

$$3E = 0.3 \cdot (€(\mathrm{NPV})/(\mathrm{m}^3\ \mathrm{of\ gas})) - 0.3 \cdot \mathrm{MWh}/(\mathrm{m}^3\ \mathrm{of\ gas})) - 0.3 \cdot (E/(\mathrm{m}^3\ \mathrm{of\ gas})) \tag{2}$$

where:

€(GDV)/(m^3 of gas) – relative magnitude of the economic evaluation criterion;
MWh/(m^3 of gas) – relative magnitude of the energy evaluation criterion;
E/(m^3 of gas) – relative magnitude of the ecological evaluation criterion.

According to this calculation methodology, the solution with the highest 3E value is the best solution for all three evaluation criteria.

Methodology for calculating the energy criterion

The energy criterion assesses the energy consumption (electricity, gas) of the pilot site when the proposed alternatives are installed at the GDS. The energy consumption (kWh/n.m³) for the gas preheating of the GDS should be chosen to express this criterion. In some solutions, the system within the study limits is no longer an energy-consuming facility, but an energy-generating facility, so the functional value is negative.

The energy calculation of the first alternative, the gas expansion device (turbine expander (TE)), is calculated according to the formula (3) given in [9]

$$E_{el,\exp} = \dot{m}_{step} \cdot \Delta h_{is,step} \cdot \eta_{is,step} \cdot \Delta t_{step} \cdot \eta_{el}, \text{ kWh} \tag{3}$$

where:

$E_{el,\exp}$ – amount of electricity produced by the TE, kWh;

$\dot{m}_{step}$ – mass flow rate of the gas, kg/s;

$\Delta h_{is,step}$ – isentropic enthalpy difference between the upstream and downstream expander, kJ/kg;

$\eta_{is,step}$ – turbine's isentropic efficiency, in units;

η_{el} – generator efficiency, η_{el} =0.9;

Δt_{step} – expander operating time, in hours.

TE reduces natural gas temperature much more than GPR (throttle valves), as the TE depressor process reduces gas temperature by converting thermal energy into motion energy, while conventional GPR cause isoenthalpic process, which does not cause such a significant temperature change. For this reason, gas is cooler during expansion than GPR operation and requires additional heating to keep the output temperature below 3°C. Therefore, when the TE is used to calculate, the heat needed to heat up the gas is recalculated according to the formula (1), but instead of the usual GPR = 0.6°C/bar, a Joule Thomson coefficient of = 1.5°C/bar is used [12].

Calculations are assumed to be conducted with a single-stage TE radial type with a design efficiency of 0.85. It is worth noting that the efficiency of TE depends on the expansion ratio (r_{dp}) and gas flow. In this study, the expansion rate is statistically almost constant ($r_{dp} \approx 13.0 \div 13.7$), so the efficiency caused by the variation in the expansion pressure rate is not evaluated. The efficiency of the TE due to flow variations is assessed based on the dependence presented in the study by [9] and assumes that the maximum efficiency (0.85) is at 500 n.m³/h, ranging from 0.51 to 0.85 (Fig. 4).

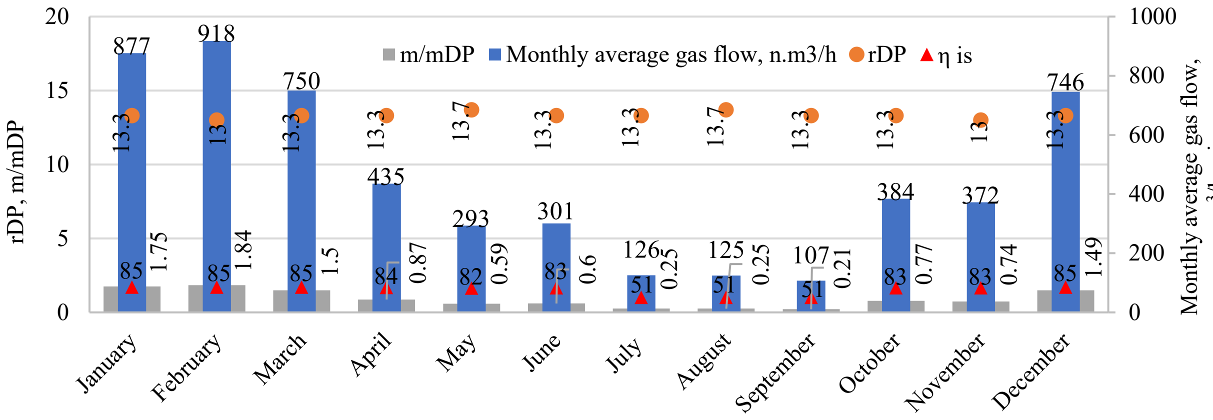

Figure 4. *TE efficiency versus flow and pressure ratio r_{dp}*

The modelling of the gas preheating alternatives (GSHP, PV and SCS) is carried out using the energyPro software [20], where the basic environmental data (annual solar radiation intensity, outdoor air temperature, ground temperature) are entered, the system scheme is drawn according to the available technical data and the heat produced and the electricity consumption calculated. The analysis showed that the heat demand for heating natural gas fed through the GDS using TE technology is 106.34 MWh/year.

However, the heat demand for the alternate heating of the non-TE is only 37.01 MWh/year for the same amount of gas. Thus, TE technology significantly increases the heat demand required to heat the natural gas flowing through the GDS, and these calculated demands are used as inputs for the assessment of the energy criterion. The input data and performance characteristics of all alternatives are given in Table 2.

Table 2. *Description and input data for the evaluation of the energy criterion in the proposed alternatives*

Indication of the proposed alternative	Description	Input data to energyPro software	
		Heat demand for preheating GDS gas, MWh/year	Description
TE	The electricity generated by TE is primarily used to heat the gas using electric heaters*	106.34	The energy produced by TE is calculated according to formula (3)
GSHP	Covers the entire heat demand for natural gas heating (output 70 kW). Electricity is supplied from the grid	37.01	Power of the GSHP**: 70 kW, COP = 4.09. The annual variation of the soil temperature, the decrease of the soil temperature due to the operation of the HP (-4°C) is introduced. A storage tank of 1 m^3 shall be installed with the GSHP, with a bottom temperature of 40°C and a top temperature of 45°C. The temperature of the heat transfer fluid to/from the gas preheater (heat exchanger) shall be 45°C/40°C
TE+GSHP	The electricity produced by the TE is used by the GSHP	106.34	The other inputs are the same as for the GSHP
PV	The electricity generated by PV is primarily used to heat gas using electric heaters*	37.01	Installed on the roof of the GDS building (area 50 m^2). It is assumed that in this case, a rooftop power plant of 5.7 kW (16 units of 355 W modules with a size of 1x2 m and a tilt angle of 35°) can be installed
TE+PV	The electricity generated by TE and PV is primarily used to heat gas using electric heaters*	106.34	The other inputs are the same as for the TE and PV
GSHP+PV	The electricity generated by the PV is used by the GSHP	37.01	The other inputs are the same as for the GSHP
TE+GSHP+PV	The electricity produced by TE and PV is used in the GSHP	106.34	The other inputs are the same as for TE, GSHP and PV
SCS	The heat produced by SCS is used to heat natural gas. In case of heat shortages, an electric heater* is used to heat the gas and electricity is supplied from the electricity grid	37.01	Installed on the roof of the GDS building (area 50 m^2). It is assumed that in this case a 32 m^2 flat-plate solar collector system (Vitosol, 2022) can be installed on the roof. A larger storage tank of 3 m^3 is also calculated, with a temperature of 40°C at the bottom of the tank and 55°C at the top of the tank
TE+SCS	The heat produced by SCS and the electricity produced by TE are used to heat natural gas	106.34	The other inputs are the same as for TE and SCS
TE+GSHP+SCS	The SK and GSHP are used to heat natural gas. The electricity produced by the TE is used in the GSHP	106.34	The other inputs are the same as for TE, GSHP and SCS

* The efficiency of the electric heater – 98.5%.
** Heat source for the GSHP: 15 vertical boreholes, 120 m deep (if the COP of the GSHP is 4, it can be assumed that ¾ of the heat will come from the boreholes in the open air, and that the heat emission from the ground is 60 W/m).

The calculations assume that all energy or heat produced and consumed locally is given priority. If there is a surplus of electricity, it is assumed that the energy is fed into the grid for storage; otherwise, electricity is taken from the grid. The multi-criteria analysis uses the results of the calculation of the energy criterion (kWh/m^3) for each alternative.

Methodology for calculating the ecological criterion

This analysis evaluated the combination of the GDS and each of the proposed energy and emission reduction solutions (TE installation, conversion of the gas preheating system from gas boilers to GSHP (vertical boreholes), SCS installation, installation of PV solar plant with electric heater, and the combinations of these alternatives: TE+GSHP; TE+PV; GSHP+PV; TE+GSHP+PV; TE+SCS; TE+GSHP+SCS) from the point of view of the non-renewable primary energy consumed during the production, use, and disposal phases and the emissions of CO_2 (global warming), SO_2 (aquatic acidification), PO_4 P-lim (aquatic eutrophication), CFC-11 (ozone layer depletion). Alternatives are first subject to a material inventory that breaks the proposed systems into elements, then materials and quantities, which are then evaluated according to impact categories. For this analysis, the Ecoinvent v3.7 database was used with SimaPro software to evaluate materials for the European market. Only the emissions of the materials from which the elements and systems are manufactured were evaluated in the manufacturing phase. In the use phase, the replacement of elements is not assessed because all proposed alternatives are assumed to have a life expectancy of 25 years. At this stage, only the environmental impact of the proposed system's energy consumption (gas and/or electricity consumption according to energy assessment) during its use is assessed. The disposal phase evaluates emissions resulting from recycling, combustion, or disposal at the end of the material's life. The transportation of all elements from the production site in Europe to the research centre in Lithuania and the environmental impact of the transport to the disposal site are also evaluated. Once the post-impact environmental performance of all proposed systems has been calculated for all life cycle impacts, it is summarized by emission type and converted to dimensionless values, giving each indicator a weight (Table 3). The total resulting is divided by the annual flow of the GDS gas to obtain the dimensionless functional unit E/n.m^3 that evaluates the environmental impact of the proposed system.

Table 3. *Methodology for calculating the ecological criterion*

Life cycle assessment of ecological criterion (impact category)	kg CFC-11 eq (ozone layer depletion)	kg SO_2 eq (aquatic acidification)	kg PO_4 P-lim (aquatic eutrophication)	kg CO_2 eq (global warming)	MJ (non-renewable energy)
Weight of the indicator	0.2	0.2	0.2	0.2	0.2
Production phase of the element	$X_{1.1}$	$X_{2.1}$	$X_{3.1}$	$X_{4.1}$	$X_{5.1}$
Use phase of an element	$X_{1.2}$	$X_{2.2}$	$X_{3.2}$	$X_{4.2}$	$X_{5.2}$
Destruction phase of an element	$X_{1.3}$	$X_{2.3}$	$X_{3.3}$	$X_{4.3}$	$X_{5.3}$
Transport phase of the element	$X_{1.4}$	$X_{2.4}$	$X_{3.4}$	$X_{4.4}$	$X_{5.4}$
Intermediate environmental indicator	$E = 0.2 \times (X_{1.1} + X_{1.2} + X_{1.3} + X_{1.4}) + 0.2 \times (X_{2.1} + X_{2.2} + X_{2.3} + X_{2.4}) + 0.2 \times (X_{3.1} + X_{3.2} + X_{3.3} + X_{3.4}) + 0.2 \times (X_{4.1} + X_{4.2} + X_{4.3} + X_{4.4}) + 0.2 \times (X_{5.1} + X_{5.2} + X_{5.3} + X_{5.4})$				
Key ecological criteria	$ECO = E/n.m^3$				

The results of the calculation of the ecological criterion (E/n.m^3) for each proposed alternative are used in a multi-criteria analysis.

Methodology for calculating the economic criterion

Under this criterion, a single indicator, Net Present Value (NPV), was calculated for all the proposed alternatives. This is calculated by discounting all the expected cash flows from the investment project. This assessment is useful because it shows whether the measures will generate sufficient savings and whether the project will be profitable over its lifetime after taking into account the depreciation of the money.

The NPV is calculated according to formula (4):

$$NPV_t = -I_0 + \sum_{i=1}^{n} \frac{CF_t}{(1+k)^t} \tag{4}$$

where:

NPV_t – net present value after a given time t, €;

I_0 – initial investment, €;

CF – cash flow per year, €;

k – discount rate;

t – elapsed time, in years.

In this case, annual savings are the average cash flows over the year, i.e. the annual balances of income, expenditure, and investment, which should result in a positive result (5):

$$\overline{CF_t} = P - C - I \tag{5}$$

where:

P – annual income or economic benefit, €;

C – annual cost, €;

I – investment, €.

The discount rate is taken into account in the calculation of the NPV. The discount rate at the moment under consideration is calculated according to formula (6):

$$d = \frac{1+i_{pal}}{1+i_{\inf}} - 1 = \frac{1+0.048}{1+0.046} - 1 = 0.0019 \tag{6}$$

where

d – the discount rate;

i_{pal} = 4.61% – prevailing market rate in December 2022 for loans offered by known banks;

$i_{\inf}$ = 4.6% – projected inflation rate for 2023.

Before calculating the NPV, for each proposed alternative, the initial investment and annual costs are calculated, which include the annual maintenance costs of the proposed systems, the cost of gas (1.91 €/m^3 [21], electricity (0.28 €/kWh [22] consumption and electricity storage in the grid (0.045 €/kWh [23]. The NPV of each measure under evaluation is then divided by the total GDS gas flow during the assessment period (25 years) to obtain a relative indicator of €(NPV)/n.m^3, which assesses the profitability of the proposed investment over its lifetime.

Results

First, the proposed alternatives are compared by category (energy, environment, and economy). The results of the evaluation of each creteria are shown in Figure 5.

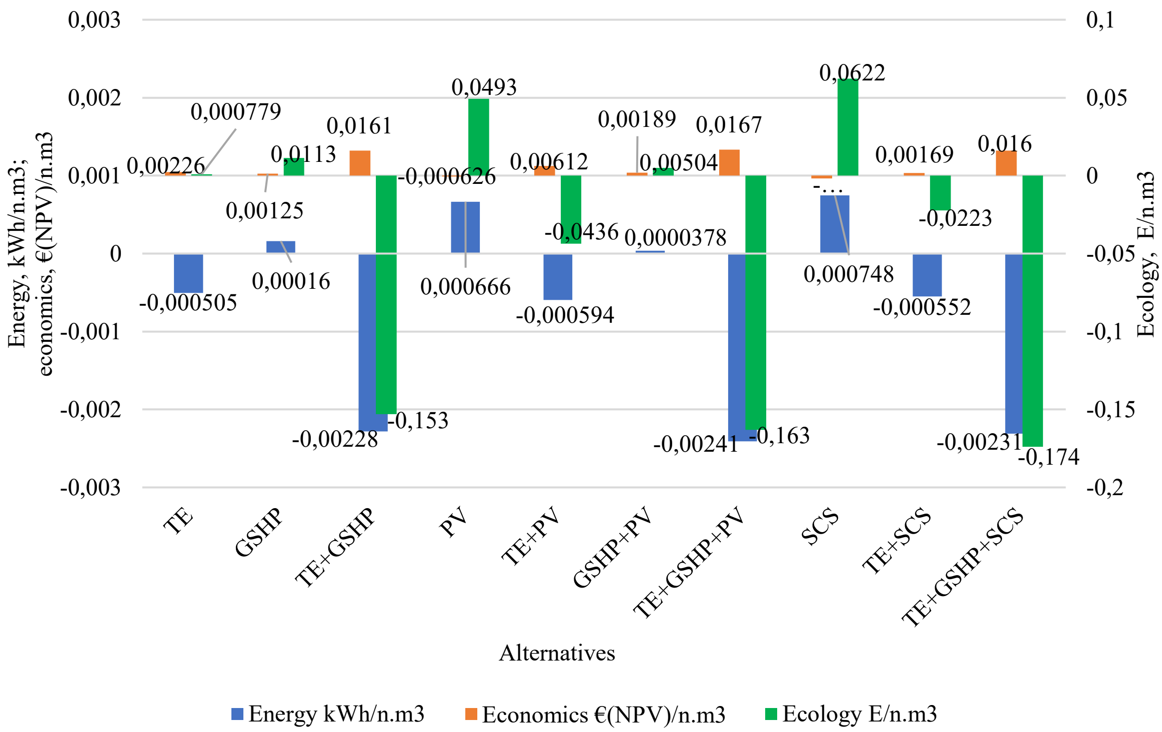

Figure 5. *Results of the evaluation of the energy, economic and ecological criterion*

For all proposed alternatives, gas is not used for preheating. If the system does not produce enough electricity or does not have electricity generation facilities (PV and TE), the demand for electricity is met by the electricity grid. The positive bars in blue indicate that this is the heat demand to heat the gas and the amount of electricity left over after the gas has been heated by an electric heater is returned to the grid. Based on the results of the energy calculation, all the proposed measures have reduced the energy consumption of the GDS to heat a unit of gas. PV or SCS installed on the roof of the GDS would reduce the energy consumption by 27% and 18%, respectively. The use of a GSHP would reduce energy consumption by 83% and the addition of a PV system to the GSHP would reduce consumption by 96%. It is estimated that for all solutions using TE, the facility is already a system that not only consumes energy but also supplies it. If only a TE is installed and the gas is heated by an electric heater, 0.5 Wh of electricity/n.m^3 of gas remains after the gas is fully treated (heated), 0.552 Wh of electricity/n.m^3 of gas remains if a TE+SCS is installed, 0.594 Wh of electricity/n.m^3 of gas remains if a TE+PV is installed, while the highest energy savings and production are achieved with TE+GSHP – 2.3 Wh of electricity/n.m^3 of gas, 2.4 Wh of electricity/n.m^3 of gas with TE+GSHP+PV, 2.31 Wh of electricity/n.m^3 of gas with TE+GSHP+SCS (Fig. 5).

Another evaluation criterion is the economic criterion, expressed in €(NPV)/n.m^3. The higher this indicator, the more economically attractive the proposed measure (Fig. 5).

The results (Fig. 5) show that the PV and SCS alternatives alone will not pay for themselves over the entire lifetime (negative €(NPV)/n.m^3). The other proposed measures have an € (NPV)/n.m^3 of 0.0023 €(NPV)/n.m^3 for TE only, 0.0012 €(NPV)/n.m^3 for GSHP only, 0.0061 €(NPV)/n.m^3 for TE+PV, 0.0019 €(NPV)/n.m^3 for GSHP + PV, and 0.0017 €(NPV)/n.m^3 for TE+SCS. The most economically attractive are the alternatives with TE and GSHP: TE+GSHP and TE+GSHP+SCS have a criteria of 0.016 €(NPV)/n.m^3, and TE+GSHP+PV has a criteria of 0.017 €(NPV)/n.m^3.

The alternatives were also evaluated according to the ecological criterion (Fig. 5), with a single, dimensionless value (E/n.m^3), which takes into account the primary energy consumption of the alternatives and the amount of CO_2, SO_2, PO_4 P-lim, CFC-11 emissions that are released to the environment during the production, use, and disposal phases of the material. The lower the value obtained, the more environmentally acceptable the proposed solution.

Several of the alternatives received, GSHP, PV, GSHP+PV and SCS, would have a greater negative impact on the environment over their lifetime than no alternatives. Using only TE would reduce the environmental impact by about 78%. The environmental impacts of the other proposed measures can be accepted as positive (negative values of the bad environmental impacts score), as the green energy produced by their use, which can be exported off-site, is higher than the gas preheating needs to be covered. Alternatives with TE and GSHP have the highest positive environmental impacts. TE+GSHP+PV (–0.163 E/n.m^3) and TE+GSHP+SCS (–0.174 E/n.m^3).

Since the alternatives are evaluated together, they are subject to multi-criteria analysis, and each evaluation criteria (economy, environment, and energy) is multiplied by weight factor (0.3). The results of the multi-criteria analysis of alternatives are shown in Figure 6.

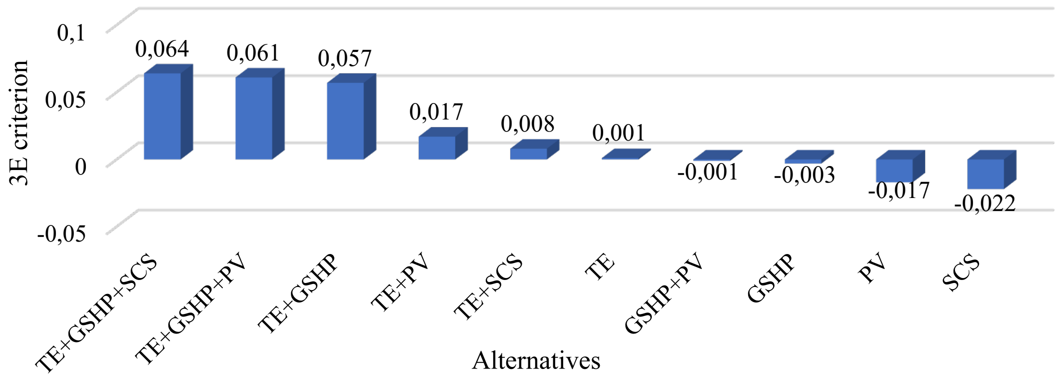

Figure 6. *Results of multi-criteria analysis*

In general, the alternatives of GSHP, PV, GHS + PV and SCS are not appropriate for the intended use and purposes of the study, as they have negative effects on the analysis of multi-criteria. This is due to the excessive demand for electricity from the grid, insufficient energy generation during the operational phase, and high costs during alternative operation. However, installation of an additional generation unit (TE) changes the alternative evaluation: a value of 0.001 is generated only by TE, a value of 0.017 is generated by TE+PV, a value of 0.008 is generated by TE+SCS. The results show that the best alternatives are TE+GSFP+SCS (0.064), TE+GSHP+PV (0.061) and TE+GSHP (0.057).

Conclusions

1. The calculations show that the GDS has an unexploited energy generation potential in the pressure relief unit. This energy can be used for electricity generation using TE, but it would increase the demand for heat for gas preheating by a factor of three.
2. In Lithuania's GDS, solar photovoltaic and SCS will save only a minor amount of GDS energy, and these measures are not advantageous in a cumulative multi-criteria way if deployed separately.
3. The PV and SCS alternatives have negative economics, whereas the other have positive economics. TE+GSHP+PV and TE+GSHP+SCS produce the majority of electricity, releasing 1 n.m^3 of gas and emitting less CO_2, SO_2, PO_4 P-lim and CFC-11.4.
4. The alternatives TE+GSHP, TE+GSHP+SCS and TE+GSHP+PV are the most economical, with 0.016 to 0.017 €(NPV)/n.m^3.
5. Taking all the criteria individually and in a multi-criteria approach, the best alternatives included both GSHP and TE: TE+GSHP; TE+GSHP+PV and TE+GSHP+SCS. The reason for this is that GSHP is an efficient and environmentally friendly heating method if the electricity source is also environmentally friendly. In particular, with the installation of CHP, the green electricity generated would be fully sufficient to run the GSHP and the surplus could be fed into the common electricity grid.

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Zhanna PETROVA, Yurii SNIEZHKIN
Anton PETROV, Yuliia NOVIKOVA
Andrii BADEKHA
Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine,
bldg. 2, Marii Kapnist Str., 2a, Kyiv, 03057, Ukraine
Corresponding author: bergelzhanna@ukr.net

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IMPROVING THE TECHNOLOGY OF OBTAINING HUMIC SUBSTANCES FROM PEAT

Abstract: *The study of the extraction of humic substances from peat is considered in the work. During the studies of various mode parameters of extraction, the optimal one was determined, which obtained a higher yield of humic substances.*
For decades, the arguments of plant growers about which forms of fertilizers are more useful for soil fertility and more effective for plants – organic or mineral – have not subsided. Each of these types has its own disadvantages and advantages, and as it turned out later, it is possible to keep the soil healthy and get the maximum benefit only with a competent combination of them.

Keywords: *humic substances, extraction, technology.*

Introduction

Humic substances are specific complexes of organic compounds with a complex structure. They are divided into two main groups: the group of dark-colored humic acids, which includes humic acids (gray), ulmic acids (brown), and alcohol-soluble hematomethane acids, and the group of yellow-colored fulvic acids. Humic and fulvic acids, taken together, are called "humic substances".

Humic acids have high biological activity, which determines the possibility of their use as plant growth stimulants and components of microfertilizers. As already mentioned, humic acids with alkali metals form easily soluble salts that increase the activity of enzymes, increase the permeability of cell membranes, stimulating the processes of respiration, synthesis of proteins and carbohydrates in plants. That is why their use allows to increase the yield of agricultural crops in stressful conditions.

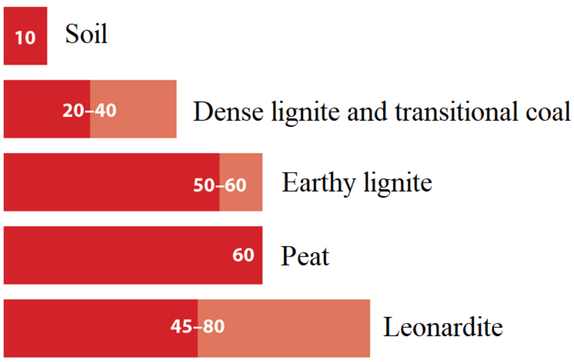

Figure 1. *The content of humic substances in different sources, %*

Humic acids are one of the most common carbon-containing materials on Earth's surface, as well as one of the most complex substances on the planet. It is very difficult to artificially synthesize humic acids, but there is no urgent need for this today, since these substances are widely distributed in nature. They are found in soils, coal, sea and fresh water, peat and sapropels, some number of humic acids is even in the air. Figure 1 shows the content of humic substances in various sources. In soils, humic substances are 1-10%, while the most of them are in chernozems. The leaders in terms of the content of these compounds are organogenic rocks, which include coal, peat, sapropel, and oil shale.

An important source of humic substances is peat. Basically, peat is used for fuel and local fertilizers. If humic substances are removed from it, and the rest is burned, then this unique natural resource can be used more rationally. The main method of obtaining humic substances is an alkaline reaction with ammonia solutions or potassium or sodium hydroxides. Such processing turns them into water-soluble salts – potassium or sodium humates with high biological activity. The composition of functional groups and the structure of molecular fragments of humic acids depends on the method of their production [1].

Despite the fact that quite a few sources of humic acid extraction have been found in Ukraine, fertilizers with their content continue to be imported in significant quantities. These are fertilizers based on humic and fulvic acids, made from leonhardite, potassium and sodium humate, as well as microbiological means for fertilizing and improving the soil.

Today, preparations made from the ash of various agricultural crops (granulated sunflower ash), the production of which has been established in Ukraine, are gaining more and more relevance. Microbiological preparations based on soil bacteria, which do not undergo chemical treatment, are also announced on the country's organic fertilizer market.

Figure 2 shows the countries from which fertilizers with humic acids are imported into Ukraine: China, Germany, Spain, Turkey, Slovakia, the Russian Federation, the USA.

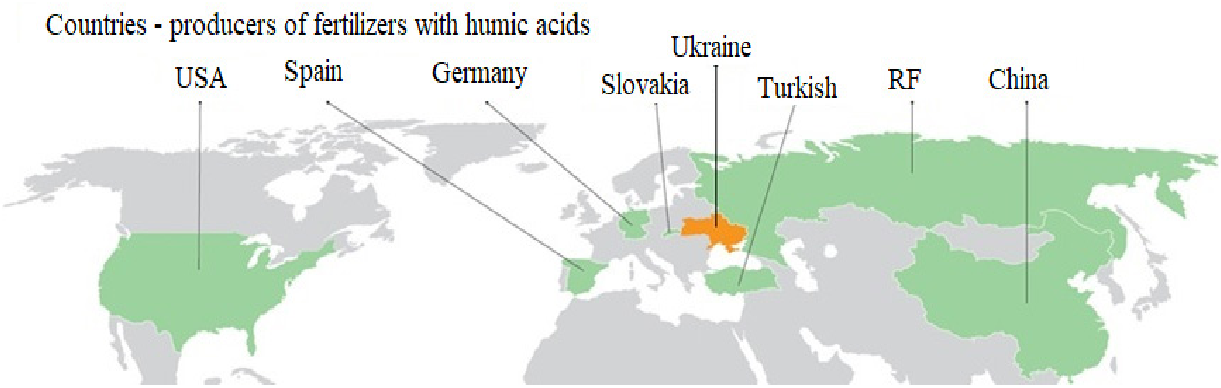

Figure 2. *Countries from which fertilizers with humic acids are imported into Ukraine*

The production of organic fertilizers in Ukraine is represented by preparations made from vermicompost, based on chicken droppings and cattle manure, biohumus, as well as organo-mineral fertilizers of plant origin. Domestic fertilizers are mainly exported to Lithuania.

The effectiveness of applying preparations based on HA depends on the biological activity of the constituent substances. More biologically active humic acids have the greatest effect on increasing yield. It can be natural raw materials: manure, sapropel, peat, brown coal, as well as artificial ones produced from the by-products of the wood processing and paper industries. Of course, naturally occurring humates are more active and have a much stronger effect on the plant.

Materials and methods

Peat from various deposits in the city of Chernihiv and the floodplain of the city of Irpin was used for the research.

The classic technology for extracting humic substances is based on high temperatures of 130-140°C, which destroy the organic component of fertilizers. Experiments were carried out on the EI-10 laboratory stand, which reproduces the operation of a pulsating disperser with an active diaphragm in the dispersion and extraction modes during the processing of aqueous mixtures of lowland peat for the purpose of extracting biologically active humic substances. The mode of extracting the humus component with an ambient temperature of 60°C and a hydromodule of 1:15 with an alkali concentration of 1% was proposed [2].

Research was also carried out to improve this technology with a change in the hydromodule of 1:6 and a temperature of 60°C with intensive mechanical stirring for 20-30 minutes and an alkali concentration of 2%. A weight of milled peat is loaded into the receiving container, poured with 2% alkali in a ratio of 1:6, and the components of the mixture are mixed with a mechanical device for 20 minutes at 20°C. The mixture is heated to a temperature of 60-70°C and kept for 40-60 minutes. After that, the mixture is settled for 10-12 hours. Then the mixture is centrifuged. Also, samples of extracts of humic substances obtained by the traditional method were taken for comparison.

Results

Studies were conducted on the extraction of humic substances from various peat deposits. Peat from the deposit of Chernihiv and the floodplain of Irpenyu was used for research. As can be seen from Table 1, different deposits do not have the same concentration of humates, which differs by several times.

Table 1. *The number of humic substances in native peat depending on the deposits*

Peat	The number of humic substances, %
Floodplain of Irpin	43
Chernihiv deposit	9

Studies on the completeness of humic component extraction using improved technology from various deposits are presented in Figure 3. As can be seen from Figure 3, the content of humic substances in native peat is 43% and 9%, depending on the deposit. After extraction, the maximum yield of humic substances is 39%, which is more than 80% of the amount in native peat from the Chernigov deposit. Humic substances in the solid residue of peat are 4%, which indicates effective extraction and an optimally selected mode.

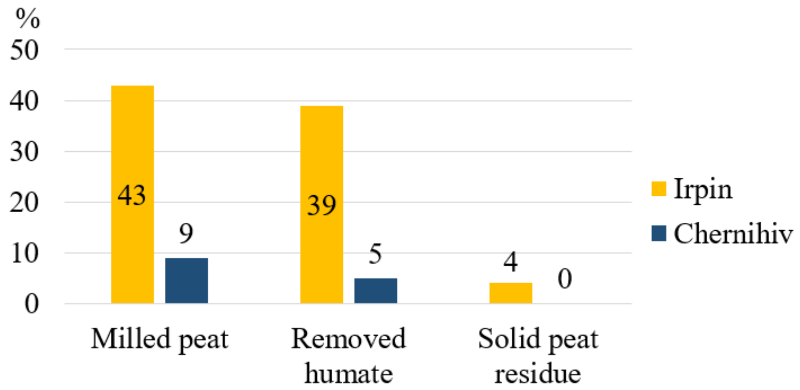

Figure 3. *The number of humic substances on 100% dry basis according to the improved technology*

The amount of 100% dry humic substances extracted from milled peat samples of the Irpin floodplain using discrete-pulse energy management technology and improved technology are presented in Figure 4.

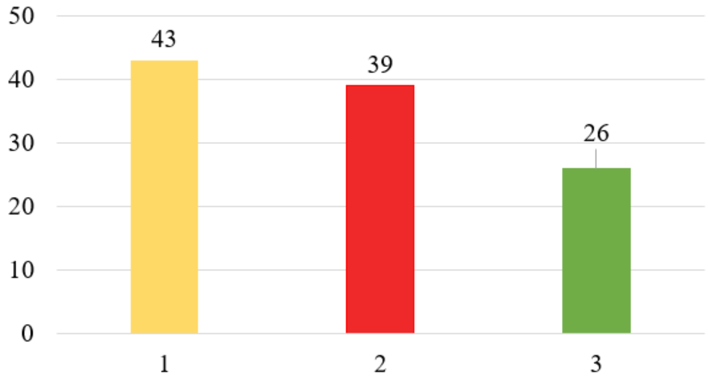

Figure 4. *Amount of 100% dry humic substances from the Irpin floodplain: 1 – milled peat in its native state; 2 – milled peat of the Irpin floodplain using improved technology with regime parameters of hydromodule 1:6 and lye concentration of 2%; 3 – the technology of using devices for discrete-pulse energy input and mode parameters hydromodule 1:15 and alkali concentration 1%*

As can be seen from Figure 4, the yield of humates with the improved technology is 1.5 times higher than with the use of discrete-pulse energy management devices, this can be explained by the fact that the extraction of 12 hours is the best among the studied values, regardless of the source of peat. This time interval is necessary for breaking bonds between inorganic components and organic matter of peat and depolymerization of complexes with high molecular weight [3].

Conclusions

Conducted research on the extraction of humic substances using various technologies made it possible to obtain their maximum output according to the developed requirements by 9.7 times.

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Borys BASOK[1], Oleksandr NEDBAILO[1]
Ihor BOZHKO[1], Volodymyr MARTENIUK[2]
[1] *Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine, bldg. 2, Bulakhovskogo str., Kyiv, 03164, Ukraine*
[2] *National University of Food Technologies, 68, Volodymyrska str., Kyiv, 01601, Ukraine*
Corresponding author: nan_sashulya@ukr.net

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ANALYSIS OF THE ENERGY PARAMETERS OF THE HEAT PUMP HEAT SUPPLY SYSTEM OF ENERGY EFFICIENT BUILDING

Abstract: *In order to further increase the energy efficiency of the experimental building, field experiments were conducted to maintain the proper thermal regime of its premises when using a heat pump heating system. The paper presents the results of experimental studies of the operating parameters of the heat pump heat supply system of an energy-efficient building of the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine. The given analysis of the energy efficiency of the operation of the "soil-water" type heat pump in the nominal mode with the maximum load showed a high value of the energy conversion coefficient.*

Keywords*: heat pump, heat supply, coefficient of performance (COP).*

Introduction

Increasing the energy efficiency of heat supply systems using renewable energy sources [1] is a priority direction in the development of modern construction sector. The overall energy efficiency of the buildings is inextricably linked to its infrastructural support systems for supporting of the comfort human life. At the same time, the air conditioning of the premises in accordance with the proper sanitary and hygienic requirements is the main requirement for the possibility of a person's long-term stay inside premises of the building.

Literature review

The object of experimental research is the heat pump system of heat supply of an energy-efficient house [2-6], which simply consists of ground and heating circuits, as well as an intermediate circuit connecting the heat pump and the heat storage tank.

Problem formulation

The main aim of the article is to demonstrate the possibility of integration of the energy-efficient heat pump heat supply system into new construction sites and during thermal modernization of existing buildings of various types and purposes.

Object, subject, and methods of research

The energy-efficient building is a three-story building with a basement located on the territory of the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine in Kyiv with a heating area of 306 m^2 and an estimated specific energy consumption for heating and hot water supply of approximately 14.8 kWh/(m^2·year) [7-10]. At the same time, the heat pump has a capacity of 6.1 kW.

The soil circuit consists of a horizontal soil heat exchanger – a group of multi-pass and coil heat exchangers connected in parallel, made of polyethylene pipes 40x3.2 mm and 32x2 mm, located next to the house at a depth of 2.2 m. The site of their location has a surface area of about 180 m^2. The heat carrier in the soil circuit is a 30% aqueous solution of propylene glycol.

The intermediate circuit is made of a polypropylene pipe 40x6.7 mm filled with treated water. The tank-accumulator is designed for hydraulic decoupling of circuits of heat sources and consumers. It is a heat-insulated cylindrical container with a volume of 300 liters with coil heat exchangers inside.

The heating circuit consists of a set of heating devices connected in parallel, which includes water-heated floors of various configurations (including the so-called capillary floor heating device), coils in the walls of the house, as well as water-air heating devices (fan coils). The heat carrier used is prepared water.

The circulation of heat carrier in each of the above-described circuits is made by pumps with the possibility of adjusting their pressure-flow characteristics. Hourly measurements during the day in each of the circuits of the amount of heat, the volume of the heat carrier, as well as its temperature values in the supply and return pipelines were carried out by Sharky 773 heat meters (optionally every 10 minutes). For further analysis, recalculation of thermal power and volume flow was carried out, taking into account the dependence of the thermophysical properties of the heat carrier on changes in its temperature.

Study results and their discussion

The values of the heat carrier parameters in each of the circuits in one of the operating modes (nominal heat load) are shown below.

In Figure 1 shows the operating parameters of the soil heat exchanger circuit.

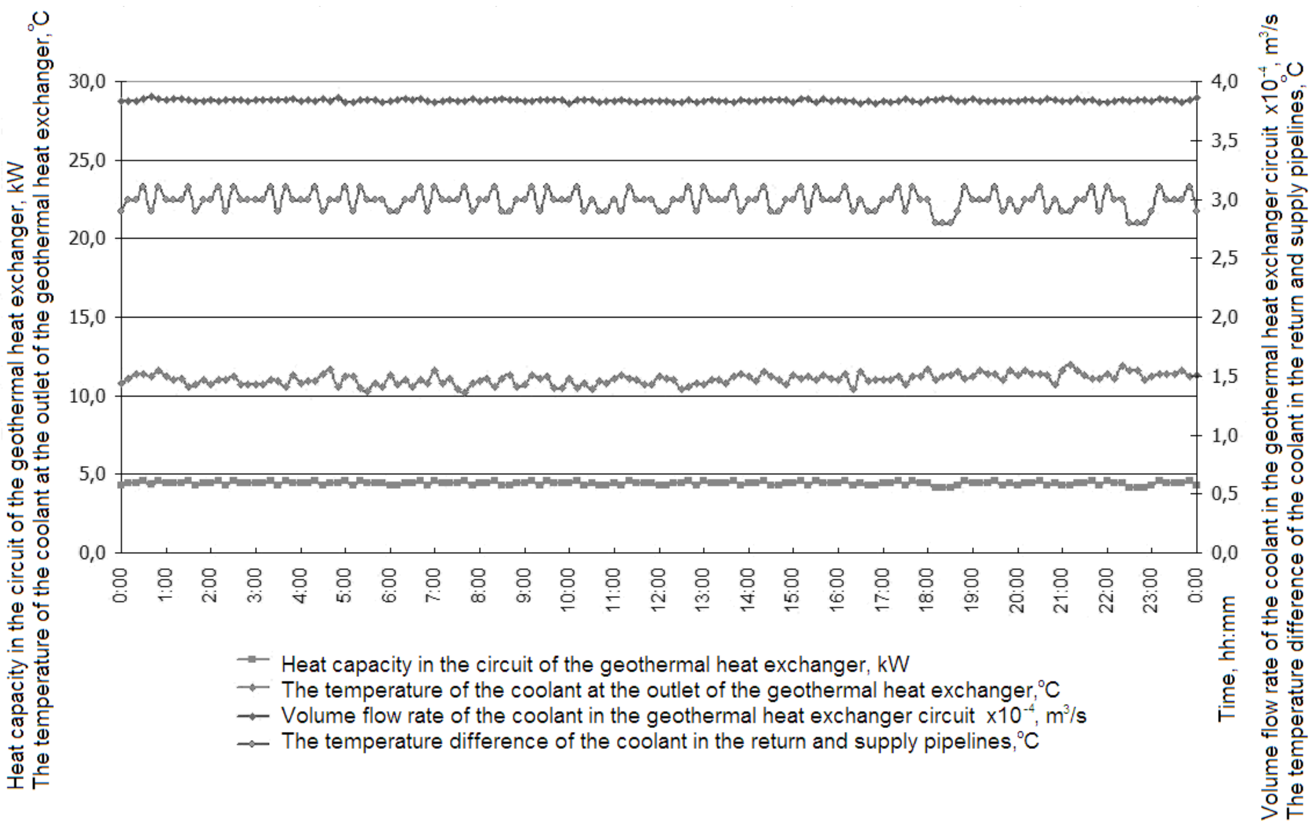

Figure 1. *Operating parameters of the soil heat exchanger circuit*

In Figure 2 illustrated operating parameters of the circuit heat pump – heat storage tank.

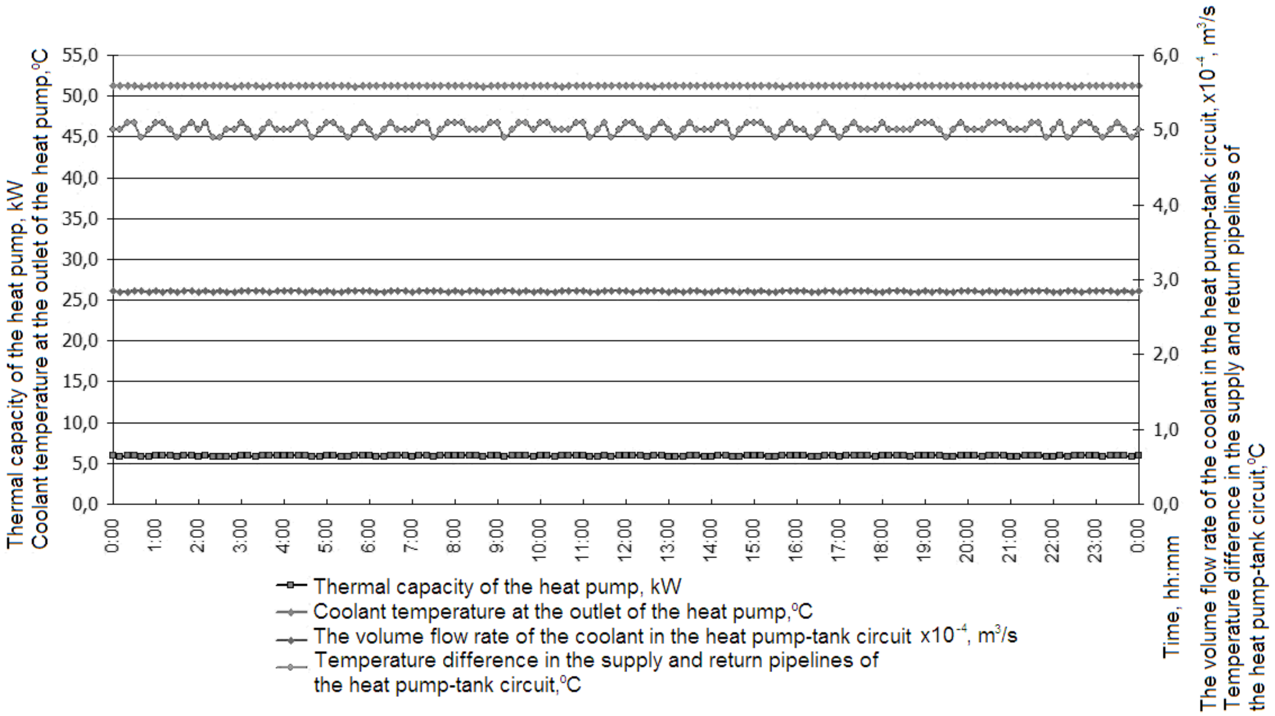

Figure 2. *Operating parameters of the circuit heat pump – heat storage tank*

In Figure 3 shows the operating parameters of the heating circuit.

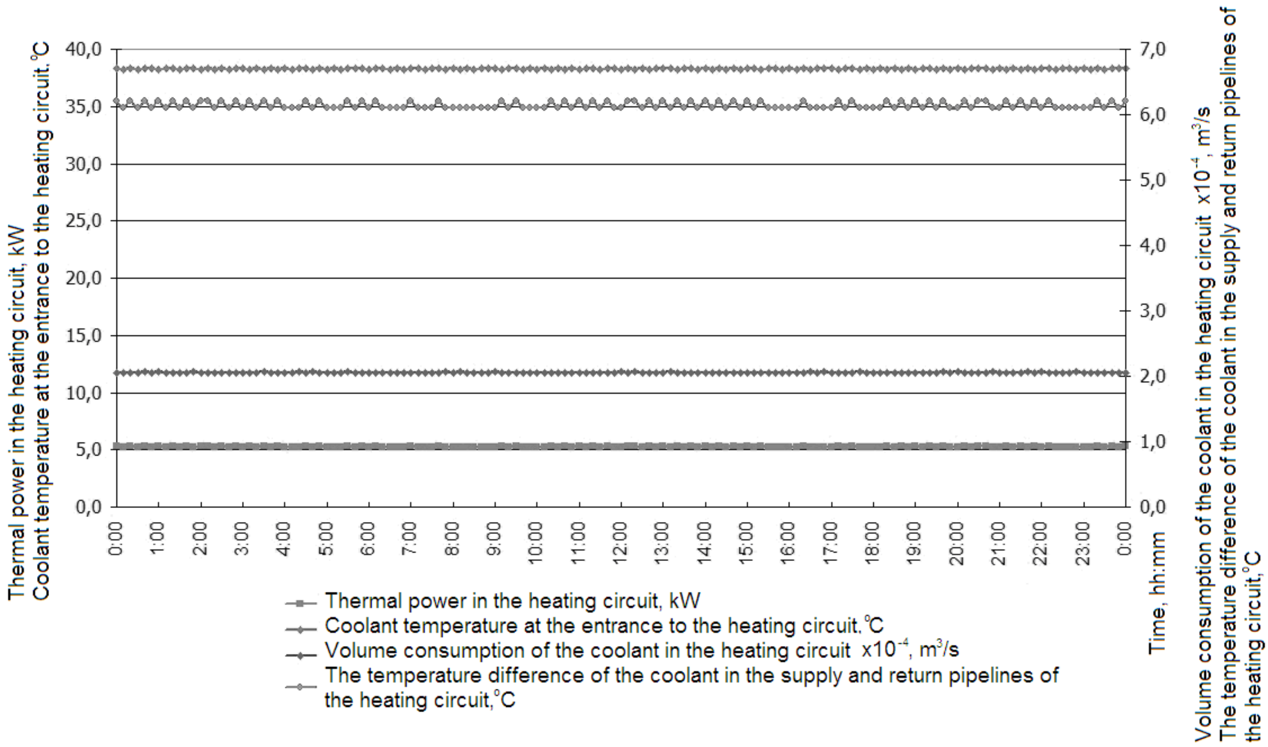

Figure 3. *Operating parameters of the heating circuit*

The calculation of the coefficient of heat transformation of the heat pump (COP – Coefficient of Performance) in the mode of its constant full load based on the balance of the amount of transferred heat

$$\mathrm{COP} = Q_1/(Q_1 - Q_2) = 5.90/(5.90 - 4.42) = 3.98$$

where:
Q_1 – the average daily value of the thermal power of the heat pump-tank circuit, kW;
Q_2 – the average daily value of thermal power of the geothermal circuit, kW.

At the same time, by definition, based on the law of energy preservation

$$COP = Q_1/N_{el} = 5.90/1.66 = 3.55$$

where:
N – the total average daily electric power consumtion by the heat pump, kW.

The amount of electricity consumed by the heat pump and circulation pumps was measured using an electric power inverter with its own meter.

Conclusion

A short analysis of the operation of the heat pump in the nominal mode showed its high energy efficiency due to its use as a source of low-potential heat of the soil massif, and as consumers – low-temperature heating systems.

The thermal regime with appropriate characteristics, which was created in the laboratory premises of an energy-efficient building with the help of heat pump technology, made it possible to conduct a number of experimental studies of the thermal parameters of various types of double-glazed windows and window profiles within the framework of the implementation of project No. 208/0172 of the National Research Foundation of Ukraine of the competition "Science for the Recovery of Ukraine in the War and Post-War Periods".

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Hanna KOSHLAK
Department of Sanitary Engineering, Kielce University of Technology,
al. Tysiąclecia Państwa Polskiego 7, 25-314, Kielce, Poland
Corresponding author: hkoshlak@tukielce.pl

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DEVELOPMENT OF RENEWABLE ENERGY SOURCE IN POLAND

Abstract: *The article analyzes statistical data on the production of electricity from fossil and renewable energy sources over the last twenty years, presenting forecasts, prospects and factors that will stimulate the growth of renewable energy sources in the Polish energy balance.*

Keywords: *electricity production, energy mix, renewable energy sources.*

Introduction

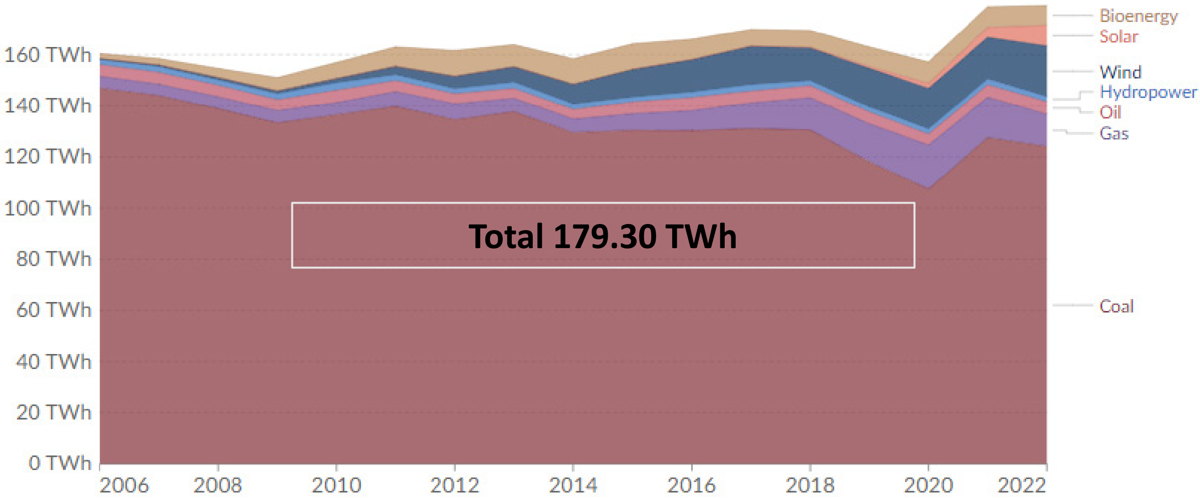
In the 21st century, the energy mix of most countries around the world is still dominated by fossil fuels. There is an increase in energy demand and this trend will not abate in the coming years, which may lead to even greater changes in the energy sector. If this trend continues, the burning of fossil fuels will have serious consequences for the global climate, as well as for human health.

To reduce CO_2 emissions and local air pollution, the world needs to quickly transition to low-carbon energy sources – nuclear and renewable technologies. Low-carbon development, including renewable and clean energy technologies, is a particularly promising area for developing future cooperation, transforming existing relationships, and promoting increased action around the world through greater use of diplomatic resources. The globally adopted 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change commit to a transition to low-carbon technologies in record time. To have a better than 66 percent chance of limiting warming to 1.5°C or less, the world would need to achieve net-zero greenhouse gas emissions by 2050, 30 years from now, according to the UN Intergovernmental Panel on Climate Change. Many fossil fuel exporting countries, including Poland, have enormous potential for increased cooperation on sustainable energy development. Today, one of the promising energy resources is renewable energy sources, which enjoy growing cost advantages and are becoming an internationally recognized main energy resource [1].

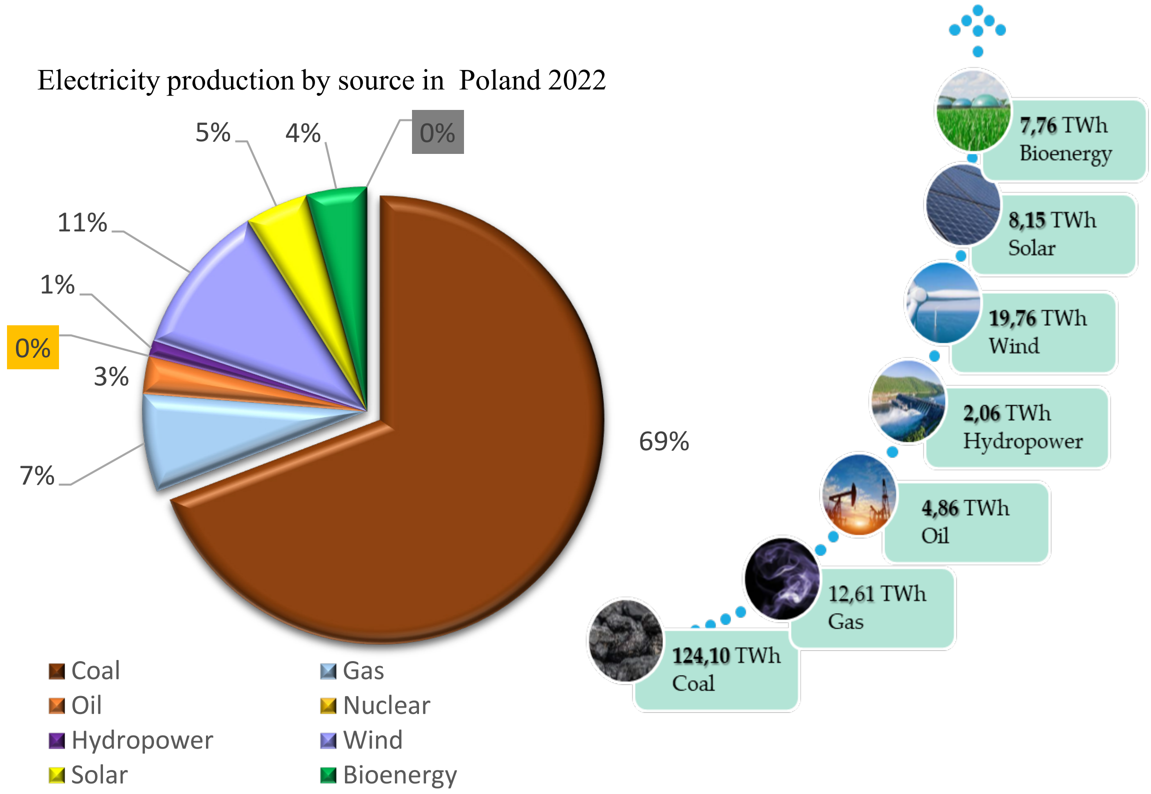
Poland is a significant source of carbon dioxide emissions, the main sources of which are coal power and industry. It is estimated that these industries emit about 150 million tons of carbon dioxide per year. The share of coal in the country's electricity production exceeds 70 percent. Although Poland had the highest share of coal in electricity production among IEA member countries in 2020, as well as the second highest share in heat production, in 2023, thanks to government programs to financially support the development of renewable energy sources, Poland has made significant progress in advancing the energy transition. Government support for solar photovoltaics (PV) has made Poland one of the fastest growing PV markets in the EU. The purpose of this study was to identify prospects for the development of renewable energy sources in Poland. Data on electricity production from fossil and renewable energy sources over the last twenty years are analyzed, forecasts, prospects and factors that will stimulate the growth of renewable energy sources in the Polish energy mix are presented.

Electricity production by source

In Poland, electricity is mainly produced in power plants. The most important fuel for electricity production in Poland in 2022 was coal with a share of 69%. Renewable energy sources produced 36.70 TWh. This value amounted to about 20% of the total amount of electricity produced – 179.30 TWh. Figure 1 shows electricity production data by source in Poland in 2022.



a)



b)

Figure 1. *Electricity production data by source [2]*

Electricity production remains dominated by fossil fuel (Fig. 1b), with the largest share coming from coal (69%), followed by wind (11%) and natural gas (7.03%). Coal plays a central role in Poland's energy system and economy. Among IEA member countries in 2020, Poland had the highest shares of coal in energy production, TES, TFC and electricity generation, and the second-highest share in heat production. The high shares of coal place Poland second among IEA member countries for CO_2 intensity of energy supply and fourth for CO_2 intensity of GDP.

Rapid growth in solar

Despite the continued dominance of coal, Poland has had notable success in pushing for energy transition. Government support for solar photovoltaics (PV) has made Poland one of the fastest growing PV markets in the EU. From 2016 to 2021, Poland's PV capacity increased from just 0.2 GW to 7.7 GW, driven mostly by residential deployment of small-scale distributed PV systems 5.9 G (Fig. 2).

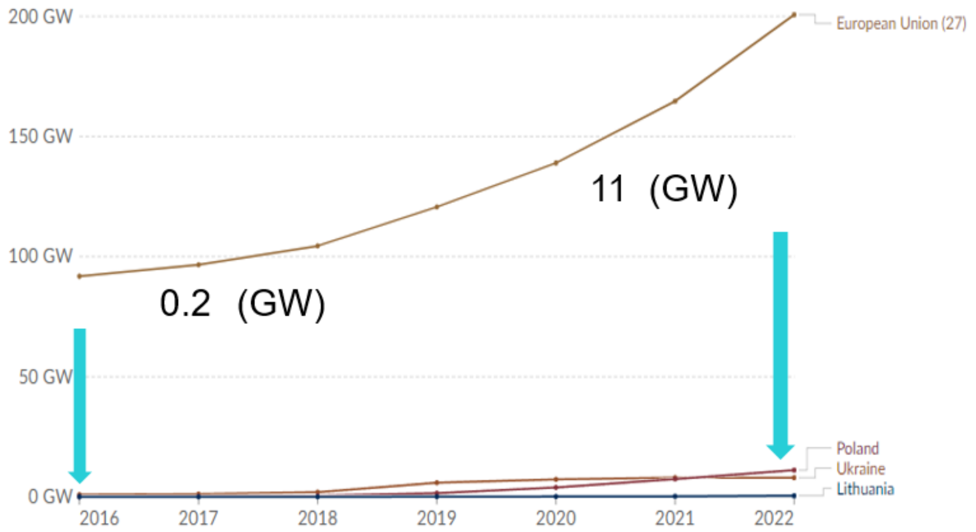


Figure 2. *Installed solar energy capacity [3]*

Large PV investors are supported by the government via RES auctions, which have been organized each year since 2016 by the Polish Energy System Regulator. This has resulted in more than 1000 projects with a total capacity of over 1.6 GW that will be eligible for government premium payments over 15 years.

Wind power

The amount of energy produced from wind sources and introduced into the Polish power system is systematically increasing. There are more than 1339 installations in Poland using wind as a renewable energy source with a capacity of more than 6 GW (Fig. 3). These installations account for about 65% of Poland's renewable energy capacity.

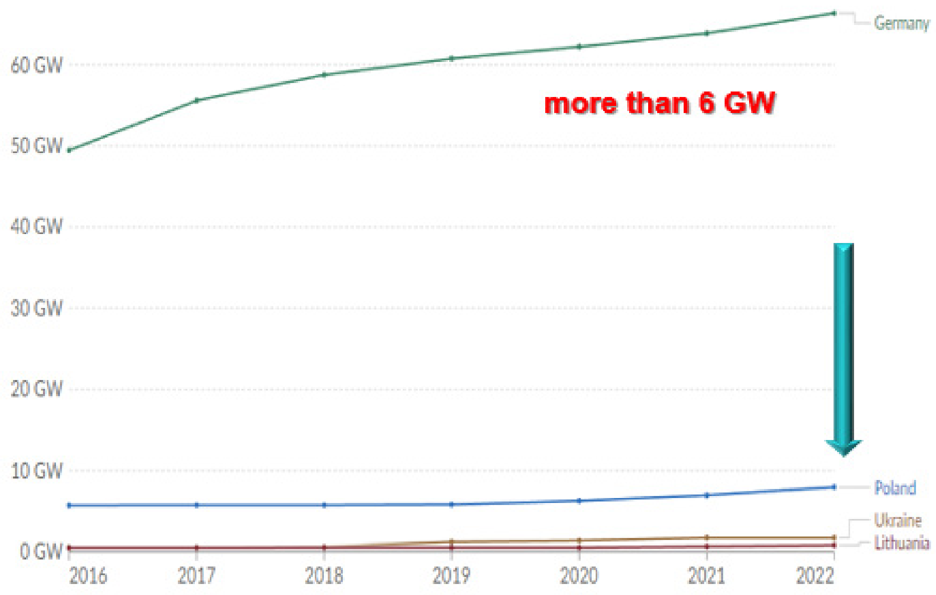


Figure 3. *Installed wind energy capacity [3]*

Poland also has a comprehensive and well designed offshore wind strategy that has resulted in deals for 5.9 GW of capacity to come online by 2027 and plans for at least 11 GW by 2040.

To meet Poland's 2020 and 2030 RES obligations, the Polish government plans extensive development of its offshore wind farms. The Polish Energy Policy (PEP) Road Map 2040 provides for a visible participation of offshore wind in Poland's 2027 energy mix, and the first mature projects should appear by 2024. In the 2040 prospectus, the strategic document sets the potential of 10.3 GW [4].

Biofuels

Traditional biomass – the burning of charcoal, organic wastes, and crop residues – was an important energy source for a long period of human history.

With a population of 38 million, almost half of all land used for agriculture and being a net energy importer, Poland has the feedstock, workforce, growing economy, and commitment to environmentally sustainable growth needed to foster a thriving biogas sector. Agricultural biogas plants are supported by a new energy auction and are expected to drive biogas growth in Poland. Figure 4 shows modern biofuel production in Poland.

In 2013 and 2015–2017, there was a significant decrease, and the rest of the period saw stabilization or a slight increase in biofuel production.

The highest electricity production from biofuels of 12.44 TWh was recorded in 2023, while the lowest electricity production of 0.07 TWh was recorded in 2004.

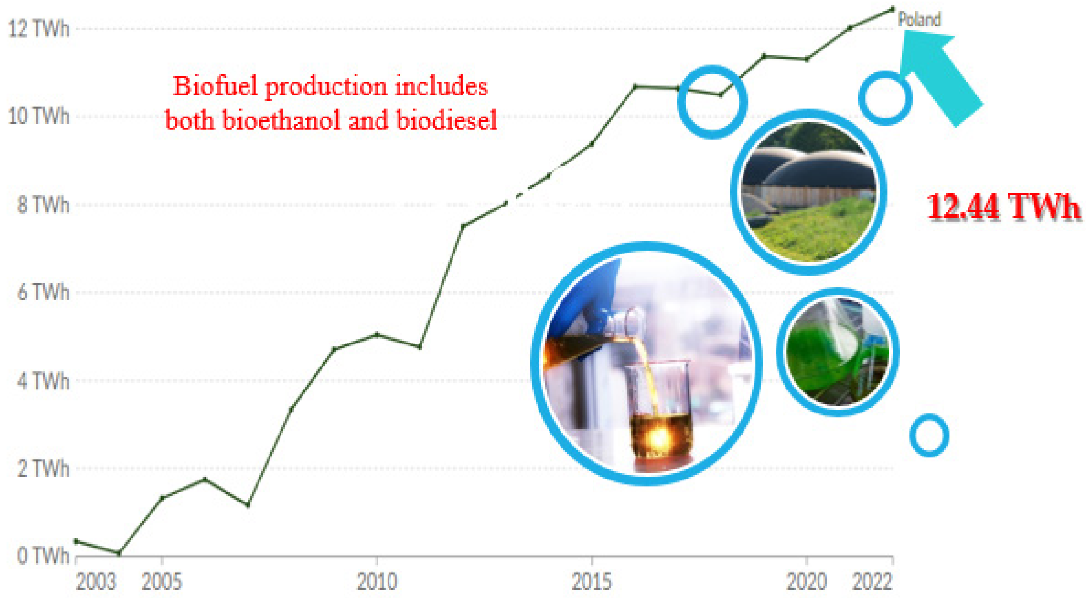


Figure 4. *Biofuel energy production [3]*

Conclusion

In 2023, the main sources for the generation of electrical energy in Poland were coal (69.21%), wind (11.02%) and natural gas (7.79%).

In December 2022, the total electricity production from all generation sources in Poland amounted to 179.30 TWh. Electricity production from renewable energy sources amounted to 36.7 TWh, which already accounts for 20.4% of the total energy balance. Currently, wind power dominates electricity production from renewable sources at 11%. In second place is photovoltaics with 4.55%, in third place are biomass power plants (4.33%), followed by hydroelectric power plants with 1.15%.

Electricity production in Poland in 2022 reached a record level of 179.30 TWh. This was largely due to a large increase of almost 9 TWh in wind and solar power generation.

Currently, wind energy and photovoltaics are two segments of renewable energy sources that record the fastest development dynamics. In the longer term, biogas plants and biofuels, whose potential remains untapped, may gain a considerable portion in the mix.

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[2] Ritchie, H., Rosado, P. (2020). *Electricity Mix*. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/electricity-mix [Online Resource].

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