

Article

Environmental and Economic Forecast of the Widespread Use of Anaerobic Digestion Techniques

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Abstract: The concept of the circular economy represents the most relevant mainstream approach to reducing the negative environmental impact of waste. Anaerobic digestion has proved to be one of the leading and widely adopted techniques for sewage sludge treatment under the principles of the circular economy. The purpose of this study is to forecast environmental and economic indicators through modeling the extensive utilization of biogas technologies with a case study of an administrative territorial unit. The proposed methodological framework involves the use of averaged specific indicators and is based on the relationship between inhabitants, waste generation rates, biogas yield, greenhouse gas emission mitigation and biogas energy potential. The widespread use of anaerobic digestion techniques according to the proposed methodology in the instant scenario will ensure the biogas yield of 10 million Nm³ within the considered administrative territory unit with a population of 4.2 million P.E., which ultimately can be expressed in electricity and thermal generation potential of 20.8 and 24.8 million kWh*y, respectively, annual greenhouse gas elimination of 119.6 thousand tons of CO₂ equivalent and capital investment attraction of EUR 65.18 million. Furthermore, all sewage sludge will be subjected to disinfection and stabilization procedures to ensure its safe utilization. The findings of this study offer an opportunity for a wide range of stakeholders to assess the environmental and economic benefits of the widespread adoption of biogas technologies. The developed methodology can be utilized to inform management decisions through the use of the instant and scenario forecasts.

Keywords: anaerobic digestion; circular economy; forecast; sewage sludge; widespread introduction



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1. Introduction

The exponential growth of the global population, coupled with the concomitant rise in living standards and the development of sanitation infrastructure, inevitably results in a significant annual increase in the volume of waste generated. Sewage sludge (SS) is a by-product originating from the wastewater treatment (WWT) process. It contains large quantities of organic matter and various contaminants. The biodegradation of organic matter in SS results in the release of significant volumes of greenhouse gases (GHGs), mainly consisting of methane (CH₄) and carbon dioxide (CO₂), into the atmosphere. Therefore, adequate waste management and efficient SS utilization techniques are very important to prevent or, at least, to reduce the pressure on nature. Otherwise, the entire set of pollutants and emissions can lead to soil and air pollution [1–6].

Nowadays, the concept of the transition towards a circular economy (CE) is considered as the most relevant mainstream approach for reducing the negative impact of waste on the environment [7,8]. In this context, SS can be used as a raw material for energy production and the extraction of useful substances and subsequently utilized as organic fertilizer [9–13].

Anaerobic digestion (AD) represents one of the most prominent and widely utilized techniques for SS treatment in accordance with CE principles. This sustainable approach

aligns with the principles of CE by transforming waste into valuable resources, thereby promoting environmental sustainability and resource efficiency [14,15]. AD is a microbiological process of decomposition of the organic fraction of the substrate under oxygen-free conditions, which results in biogas yield and digestate production. Biogas can be utilized directly for thermal or electrical energy, or combined energy production (e.g., in combined heat and power units) or upgraded to biomethane for injection into the natural gas grid or municipal transport applications. Meanwhile, digestate is commonly used as biofertilizer for agricultural purposes [16,17].

According to the forecast for the development of AD to 2030 by Meticulous Market Research Inc. (San Francisco, CA, USA) [18], the growth of the global AD technology application market will be driven by the emerging demand for renewable energy sources, government restrictions for nature protection, the growing need for waste disposal safety and increasing awareness regarding the advantages of the AD infrastructure. Developed countries are currently leading the implementation of AD technologies due to a number of factors, including the following:

- Availability of developed waste management infrastructure;
- Relevant legislation framework aimed at achieving sustainable development goals and zero emissions;
- Strict standards regarding GHG emissions and effluent discharge, which are enforced by substantial penalties in the case of non-compliance;
- High energy prices;
- Tax and subsidies for the implementation of biogas projects.

The majority of projects based on AD are implemented in Germany, Denmark and the UK, collectively representing 68% of the total number of AD installations in Europe. Additionally, the developed countries leaderboard also includes the USA, China, France, Italy, Poland, Spain, Austria and the Netherlands [19,20].

However, despite the considerable expertise and knowledge base in the AD area, as well as the available equipment and highly skilled specialists within the considered industry, the widespread implementation of biogas projects remains a significant challenge even in developed countries. In developing countries, especially with significant fossil fuel reserves, the number of biogas projects is negligible, since the implementation of these initiatives is hampered by high equipment costs, low profitability, an extended payback periods of return on the investment and a lack of governmental support. The absence of comprehension and clear vision of the benefits of biogas technology applications among various stakeholders is impeding legislative activities and the processes of developing strategic plans and private initiatives for the implementation of biogas projects.

The results of literature review highlight the following research focused on the development of forecast models for evaluating the benefits of AD infrastructure.

A number of manuscripts are devoted to the formulation of predictive mathematical models and software products based on them for the calculation of operational parameters for specific utilities, e.g., WWTPs or distributed AD infrastructure. Kiselev et al. [21] introduced the Biogas & Biomethane Computation Model, which compiles the mass and energy balance of a single AD plant with alternative options for biogas utilization: energy production within the combined heat and power (CHP) unit and upgrading biogas to biomethane. The mass balance includes values for biogas yield and captured GHG, while the energy module is associated with potential energy data through the use of biogas utilization options. Salamattalab et al. [22] considered an innovative approach for predicting biogas production from large-scale anaerobic digesters using artificial neural networks with the objective of achieving the lowest possible errors.

Other studies presented methods for calculating specific case studies under diverse conditions and applied techniques. For instance, Ahmed et al. [5] considered the values of biogas yield from anaerobic thickened sewage sludge, both separately and in conjunction with rice straw in Cairo, Egypt, while Donacho et al. [23] examined the biogas and biofertilizer potential of human feces in Jimma City, Ethiopia.

The methods outlined in the aforementioned publications are of significant interest to a wide range of scientists and specialists. However, due to the specific conditions and the necessity for a large set of accurate initial data, they are not conducive to making an extensive forecast.

A series of studies are related to the global assessment of the prospects for the implementation of AD techniques. In a report for the project “Provision services in the area of sewage sludge and the circular economy” [10], the European Environment Agency presented the assessment methodology to predict energy and nutrient recovery potential of AD applications for the European Union member states (EU-27) and European Economic Area member countries (EEA-32). The methodology employed in this study considers the static Eurostat data with absolute (not specific) values under various scenarios to assess the potential for additional unused energy recovery on a global territory, with certain assumptions. A study conducted by the World Biogas Association [24] focused on the global energy, GHG emissions and nutrient recovery potential for various substrates, including sewage sludge. It was based on a simplified model with a set of assumptions regarding specific biogas production/energy generation per capita and relied on data from the early 2000s.

The literature review revealed current gaps in scientific knowledge within the forecast methodology for evaluation of the AD infrastructure benefits of arbitrary territory under various dynamic scenarios based on relevant and research-supported data. The purpose of this study is to forecast environmental and economic indicators through modeling the extensive utilization of biogas technologies with a case study of an administrative territorial unit. The present study investigates the forecast methodology based on the following points, which represent a scientific novelty in this matter:

- the possibility of evaluating the environmental and economic impact on an arbitrary administrative territory;
- the use of specific indicators based on the number of inhabitants in the territory under consideration;
- a consistent calculation model based on the “residents-waste-biogas-benefits” logic;
- reliance on scientifically proven data;
- the availability of instant and development scenario forecast options.

2. Results

2.1. Instant Forecast

The first step of applying the proposed methodological approach is an instant evaluation of the benefits of the widespread implementation of biogas projects. The instant forecast considers the following conditions of the case study of the Sverdlovsk region:

- The current urban population is taken into account for the selected 32 cities;
- Full coverage of the entire population with centralized sewerage services is expected;
- The sewage sludge treatment infrastructure with AD applications has been fully commissioned and is functioning at WWTPs within the selected 32 cities;
- A total of 100% of originated sewage sludge is subjected to AD;
- The resulting biogas is completely utilized for the combined electrical and thermal energy production.

The prospective benefits obtained according to the instant forecast of the widespread implementation of biogas projects are presented in Table 1.

To calculate the energy potential values for Table 1, specific energy values were considered, namely, 1 Nm³ of biogas with an appropriate proportion of methane content contains approximately 6 kW of energy, which is transformed via utilization in a CHP-unit into 2.1 kW and 2.5 kW of electrical and thermal energy, respectively [25–27].

The total volume of the required capital investments was predicted based on the cost of implementing the project for the construction of AD infrastructure at the Northern WWTP in Ekaterinburg [28], considering the adjustment coefficients for the cost for cities with a smaller population served:

- Cost $\times$ 1.5, for 100,000 to 500,000 population equivalent (P.E.);
- Cost $\times$ 1.75, for 50,000 to 100,000 P.E.;
- Cost $\times$ 1.9, for 30,000 to 50,000 P.E.;
- Cost $\times$ 2.0, for 20,000 to 30,000 P.E.

Table 1. Benefits for the instant forecast of the widespread implementation of biogas projects.

Indicator	Unit	Value
Population of 32 cities, including Ekaterinburg	Inhabit.	3,294,518
Population of Ekaterinburg	Inhabit.	1,539,371
Annual SS production in DM	Tons	40,642.04
Annual SS production in VS/DM	Tons	32,139.72
Annual biogas yield	Nm ³	9,913,818.43
Annual GHG emission mitigation	Tons of CO ₂	119,648.84
Electricity generation potential	kWh	20,819,018.69
Thermal generation potential	kWh	24,784,546.06
Required capital investment	mln. EUR	65.18

Based on the data resulting from the instant forecast, the following benefits can be identified for the Sverdlovsk region with the widespread introduction of biogas technologies:

- The development of distributed renewable energy in the region. According to preliminary calculations, the resulting volume of biogas will provide the production of 20.82 GW of electrical energy and 24.78 GW of thermal energy per year. The indicated energy capacity enables it to be used primarily for self-consumption by treatment facilities, thereby ensuring the reliability of the power supply to the facilities;
- The stabilization of sewage waste and reduction in its hazard class by creating a recycling chain;
- Capturing large volumes of GHG (by 0.45% compared to the total emissions in the Russian Federation) for the group “Treatment of liquid waste and effluents”;
- Attracting investments in the region in the amount of 65.18 million Euros, which is more than 1% of total investments in the region.

The instant forecast of the widespread use of biogas technologies represents an ideal model that allows for the investigation of potential benefits across a range of categories. However, the instant transition towards a promising state is not feasible for a number of reasons. The next sub-section proposes a certain development scenario for the widespread introduction of AD technologies.

2.2. Development Scenario Forecast

The forecast of a realistic model for the widespread introduction of AD technologies assumes the progressive implementation of biogas projects over the long-term period. The projected timeline for the current research is defined from 2024 to 2045, with an intermediate milestone of 2030. The benefits are calculated for each milestone, with consideration given to the factors that influence the outputs. Accordingly, to use the proposed methodological framework, it is essential to predict the value of the following variables: the population of the cities under consideration, the sewage sludge production per capita in DM and the level of implementation of AD techniques.

The share of VS in DM, the ratio of biogas production, as well as the specific potential for electrical and thermal energy generation, will remain constant over the entire timescale, like the values from the instant forecast. The initial data for development scenario modeling are presented in Table 2.

The initial data for Ekaterinburg were determined separately from the other cities under consideration due to differences in the assessment of territorial development. In the case of Ekaterinburg, the urban population is expected to increase by up to 1,906,200 inhabitants [29], while the total population of the region is anticipated to decrease [30]. However, the total increase in the population of these cities can be attributed to the exclusion

of the rural population and cities with a population of less than 20,000 people from the case study.

Table 2. Initial data for development scenario modeling.

Indicator	Unit	Year/Value		
		2024	2030	2045
Population of 32 cities, including Ekaterinburg	Inhabit.	3,294,518	3,409,127	3,663,107
Population of Ekaterinburg	Inhabit.	1,539,371	1,700,000	1,906,200
SS production intensity rate of Ekaterinburg	%	100	105	120
SS production in DM per capita of Ekaterinburg	kg/capita	15	15.75	18
SS production intensity rate excluding Ekaterinburg	%	100	110	140
SS production in DM per capita excluding Ekaterinburg	kg/capita	10	11	14
AD implementation progress	%	11 (only Northern WWTP of Ekaterinburg)	59 (only WWTPs of Ekaterinburg)	80

The development scenario includes an increase in the SS production intensity rate which is calculated per capita. This increase is explained by the improvement in the technologies used for WWT and SS processing. It should be noted that, for Ekaterinburg, it is less intensive, considering the actual situation [31].

The maximum level of AD implementation progress by 2045, which is calculated as the ratio of SS subject to AD to the total amount of SS originated at WWTPs, was determined to be 80%. In consideration of the year 2024, the actual progress was taken into account with the Northern WWTP of Ekaterinburg serving as the sole subject of analysis, while the implementation of biogas projects that would completely cover the WWTPs of Ekaterinburg is projected to be a realistic goal by 2030.

The benefits for the development scenario forecast of the widespread implementation of biogas projects are presented in Table 3.

Table 3. Benefits for the development scenario forecast of the widespread implementation of biogas projects.

Indicator	Unit	Year/Value		
		2024	2030	2045
Annual SS production in DM for Ekaterinburg	Tons	4456.65	26,775.00	26,775.00
Annual SS production in DM for case study, excluding Ekaterinburg	Tons	0.00	0.00	19,301.08
Annual SS production in DM for case study	Tons	4456.65	26,775.00	46,076.08
Annual SS production in VS/DM for case study	Tons	3524.32	21,173.67	36,436.96
Annual biogas yield	Nm ³	1,087,111.38	6,531,230.25	11,239,345.79
Annual GHG emission mitigation	Tons of CO ₂	13,120.23	78,824.74	135,646.50
Electricity generation potential	kWh	2,282,933.90	13,715,583.52	23,602,626.17
Thermal generation potential	kWh	2,717,778.46	16,328,075.62	28,098,364.49

3. Materials and Methods

3.1. The Methodological Framework of This Research

Modeling the process of widespread use of biogas technologies on a certain territory involves the use of assumptions and averaging of parameters throughout the entire life cycle. The methodological framework based on the life cycle of the AD process is presented at Figure 1.

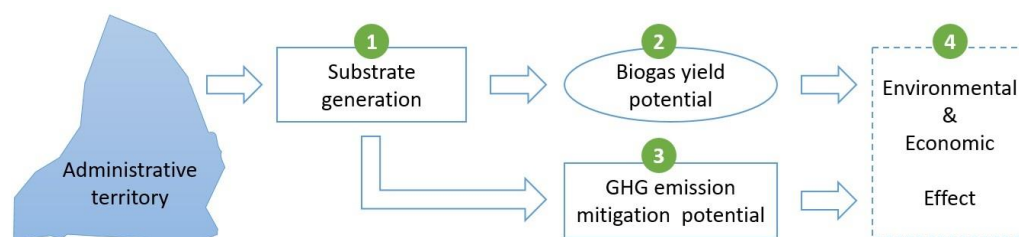


Figure 1. The methodological framework of this research.

At the preliminary stage, it is necessary to identify the basic parameters of the scenario under consideration according to the following checklist: (a) determination of the territory for the case study and evaluation of its characteristics; (b) indication of potential sites for the introduction of biogas techniques; (c) assessment of the current progress in the implementation of biogas projects within the considered territory.

After that, the environmental and economic effect of the biogas project implementation is evaluated (Figure 1).

The final stage of the assessment is the interpretation of the obtained results and the comparison of the achieved effects.

3.2. Case Study Territory

The Sverdlovsk region is located in the Ural Federal District of the Russian Federation, 2000 kilometers east of Moscow, on the border of Europe and Asia. It occupies an area of 194.3 thousand square kilometers. The population as of 1 January 2023 is 4,239,161 inhabitants, 85% of whom are urban residents. In the territory of the Sverdlovsk region, there are 47 cities, 26 workers' settlements and urban-type settlements, and 1841 rural settlements. The administrative center of the region is the city of Ekaterinburg with a population of 1,539,371 inhabitants [32–34].

The WWTPs within the considered area primarily employ the conventional two-stage treatment technique, including mechanical and biological phases. The installation of SS treatment facilities (for example, sludge dewatering) has only been implemented in cities with a population over 100,000 inhabitants; others allocate SS on specially prepared sites for drying and subsequent disposal [21].

Currently, only one biogas project has been implemented in the region. In 2018, AD facilities with digesters of a total volume of 10,000 m³ were put into operation at the Northern WWTP (Ekaterinburg). Prior to the implementation of the biogas project, sewage sludge was utilized at sludge fields or transported to specialized landfills. In this form, the sludge was subject to biological degradation with methane emission into the atmosphere [28].

This study focuses on the forecast for the implementation of the biogas projects in the specific field of WWTPs. The potential for AD technologies to be used for municipal solid waste was not considered due to the lack of viable prospects in the majority of regions of the Russian Federation. The solid waste reform came into force on 1 January 2019. The government of the Sverdlovsk region has identified the following priority tasks: resolving the issues of landfill overfilling, reducing the number of unauthorized landfills and increasing the implementation of waste sorting and reuse rates [35]. However, the feasibility of implementing the projects for landfill gas generation under conditions of low electricity prices and the necessity of addressing other urgent regional development issues remain uncertain.

To simulate the process of widespread use of biogas technologies, 32 cities with a population of over 20,000 inhabitants were selected, representing 77.72% of the actual population of the region. This choice is justified by the fact that WWTPs facilities in the cities and towns with fewer inhabitants usually do not apply the biological phase of WWT to subsequent sludge treatment or that there is no centralized sewerage system at all. In

turn, rural settlements are not taken into account due to the lack of centralized sewerage within the considered area.

3.3. Substrate Generation

A substrate is defined as any organic substance that undergoes transformation into biogas and digestate under conditions of bacterial activity and oxygen deficiency. Biogas is used for energy generation purposes, while digestate is usually utilized in agriculture as a fertilizer. The most popular types of substrate include sewage sludge, the organic fraction of municipal solid waste (OFMSW), food waste, agricultural and livestock waste, etc. [36–38].

To predict the volume of substrate generation, it is necessary to use a specific indicator, which is then multiplied by a quantitative metric, e.g., the population size or the number of livestock and poultry units within the territory under consideration. In accordance with the basic parameters of the investigated scenario, the specific indicator used is “Urban sewage sludge production rate, kg of dry matter (DM) per capita per year”. Following the detailed literature review, a series of representative values for the aforementioned indicator were established, representing the experience of different territories (Table 4).

Table 4. The sewage sludge production rate experience of different territories.

Object	Type	DM, Kg/Capita Per Year	Source	Refs.
Belgium	Country	14.38	Eurostat metadata, Sewage sludge production and disposal (2020)	[39]
Czech	Country	20.48	Eurostat metadata, Sewage sludge production and disposal (2020)	[39]
Ekaterinburg	City (Russia)	15.17	Laboratory tests	[21]
Estonia	Country	14.28	Eurostat metadata, Sewage sludge production and disposal (2020)	[39]
Greece	Country	9.63	Eurostat metadata, Sewage sludge production and disposal (2019)	[39]
Norway	Country	29.21	Eurostat metadata, Sewage sludge production and disposal (2020)	[39]
Object	City	13.48	The name of the object and city is not provided due to confidentiality issues (2020)	[40]
Poland	Country	15.01	Eurostat metadata, Sewage sludge production and disposal (2020)	[39]
Portugal	Country	11.54	Eurostat metadata, Sewage sludge production and disposal (2016)	[39]
Romania	Country	13.2	Eurostat metadata, Sewage sludge production and disposal (2020)	[39]
WWTP	84 utilities in Italy	11.29	Investigation conducted by authors (data are relevant to 2015)	[41,42]

The information presented in Table 4 gives the idea that the sewage sludge generation rate is not constant and has a significant spread in values. This is influenced by the configuration and technologies employed at certain WWTP, the coverage of the sewage pipe network and the differences in the domestic habits among residents within the considered territories [43].

For Ekaterinburg, the specific indicator “Urban sewage sludge production rate” is assigned a value of 15 kg of DM per capita per year, while other cities within the considered scenario are assigned a value of 10 kg of DM per capita per year. The former is set equal to the Northern WWTP value, while the latter is considerably lower, reflecting the current technological state of the infrastructure, low population density and lack of distribution pipework.

3.4. Biogas Yield Potential

The biogas yield is defined as the potential biogas produced per substrate mass (or volatile solids) [44]. It is affected by the feedstock characteristics and the applied techniques. The use of different temperature conditions in AD, the loading of raw materials with a high organic content, the use of different hydraulic settings (e.g., hydraulic loading rates and hydraulic retention time (HRT)) and even the presence of impurities and toxins significantly impact both the volume of biogas produced and its composition [45].

The estimated volume of biogas production (V_{BG}^p) was calculated using the following equation [44]:

$$V_{BG}^p = m_{ss}^{DM} \times VS^{DM} \times Y_{BG} \quad (1)$$

where m_{ss}^{DM} is the weight of substrate (dry matter (DM)), tons; VS^{DM} is the share of volatile solids (VS) in DM, %; Y_{BG} is the specific biogas yield potential, Nm^3 /tons of VS.

The biogas volume was normalized at a standard temperature of 0 °C and a pressure of 1 atm.

Within the framework of this study, to predict the volume of biogas produced, it was necessary to select two values of the indicators VS^{DM} and Y_{BG} . For this purpose, a literature review was carried out, and the results are presented in Table 5.

Table 5. Key parameters of biogas productivity.

Object/Location	AD Mode *	VS^{DM}	HRT	Y_{BG}	CH ₄ Content	References
Northern WWTP/Ekaterinburg, Russian Federation	M	79.08%	27	308.46	60.20%	[21]
WWTP with a capacity of 68,000 people equivalent/Slovenia	M	80.87%	40	430.00	72.00%	[46]
WWTP/Shimodate, Ibaraki, Japan	M	87.04%	24	336.44	76.20%	[47]
WWTP/Japan	T	82.59%	30	438.00	61.55%	[48]
66 conventional full-scale WWTPs/the United Kingdom of Great Britain and Northern Ireland	M	76.10%	21.2	398.70	N/A	[49]

* AD mode: M—mesophilic, T—thermophilic.

To calculate the volumes of biogas production within all 32 cities of the Sverdlovsk region, the values of the Northern WWTP of Ekaterinburg presented in Table 5 were adopted as part of the current use.

3.5. GHG Emission Mitigation Potential

Biogas obtained from sewage sludge mainly consists of methane (CH₄) and carbon dioxide (CO₂), with traces of other gases, including carbon monoxide (CO), hydrogen (H₂), hydrogen sulfide (H₂S), oxygen (O₂), nitrogen (N₂) and ammonia (NH₃) [50,51]. According to the laboratory tests data of biogas produced at Northern WWTP in Ekaterinburg, Russian Federation, the total share of methane and carbon dioxide in the biogas volume is 96.6% [21].

This study will consider only the emissions of methane and carbon dioxide in carbon dioxide equivalent, as it is not feasible to accurately determine the contribution of other gases. Additionally, only emissions from the process of biological decomposition of organic waste will be considered. The potential impact of reducing greenhouse gas emissions through the utilization of biogas as an alternative energy source is not taken into account.

The weight of potential greenhouse gas emissions in the CO₂ equivalent without the application of AD techniques (G_{eqCO_2}) was calculated using equation (2). Moreover, the CO₂ released into the atmosphere through the biodegradation of organic matter is considered to be “carbon neutral”; thus, its environmental impact can be neglected [28].

$$G_{eqCO_2} = k_{GWP}^{CH_4} \cdot G_{CH_4} + k_{GWP}^{CO_2} \cdot G_{CO_2} = k_{GWP}^{CH_4} \cdot G_{CH_4}, \quad (2)$$

where $k_{GWP}^{CH_4}$ and $k_{GWP}^{CO_2}$ are the global warming potentials; and G_{CH_4} and G_{CO_2} are the weights of CH_4 and CO_2 in tons, subsequently.

Methane is the second most significant GHG in terms of its influence on climate change, surpassed only by carbon dioxide. The global warming potential of methane ($k_{GWP}^{CH_4}$) over a 100-year timescale is 28 times stronger compared to that of carbon dioxide [52].

Expressing the mass of methane through its volume calculated by Equation (1), G_{eqCO_2} can be estimated using Equation (3):

$$G_{eqCO_2} = 28 \cdot V_{BG}^p \cdot \varphi_{CH_4} \cdot \rho_{CH_4} \quad (3)$$

where φ_{CH_4} is the volume fraction of methane in biogas and ρ_{CH_4} is the density of methane, 0.716 kg/m^3 [53].

4. Discussion

The benefits of energy generation potential of the instant and development scenario forecasts are presented at Figure 2. The instant forecast was employed to assess the potential benefits of biogas project implementation and provide comparison to the amount of energy being replaced (or added), while the development scenario forecast considered benefits on a timescale over the course of implementing strategic energy industry planning goals.

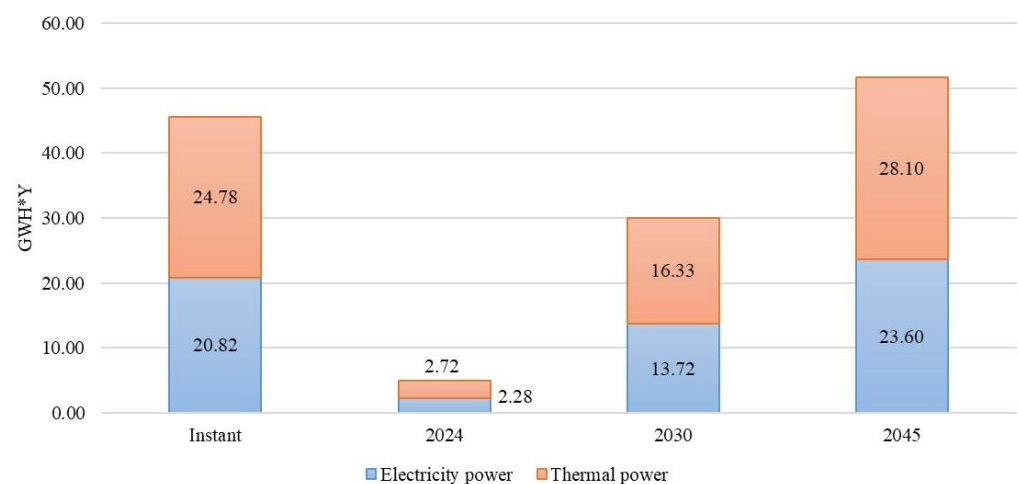


Figure 2. The benefits of energy generation potential of the instant and development scenario forecasts.

The total installed capacity of the power system in the Sverdlovsk region as of 01.01.2022 amounted to 10,591.5 MW, and the total consumption of electrical energy in 2021 was 43,208 million kWh (Russian power system operator, 2024). The volume of potential electrical energy obtained via utilization of biogas originated through the AD process represented an insignificant share of 0.05% in the total balance of electricity consumption within the region.

Although biogas projects have a limited impact on the energy system as a whole, the purpose of their application is the development of distributed generation to meet the energy needs of the WWTPs by themselves and their surrounding areas, in the context of reducing transmission and transportation costs together with limited environment pressure and higher reliability of electrical grids. According to Kiselev et al. [54], the electricity generation at a biogas-fired CHP-unit located in the Russian Federation has the potential to provide over 50% of a WWTP's self-consumption on site.

The results presented in Figure 2 could be further improved by introducing pre-treatment methods into the AD technology, which would ultimately increase the biogas yield [55]. However, there are a significant number of different approaches that depend on many factors and do not allow defining indicators for a real forecast.

Figure 3 illustrates the benefits of forecasting GHG emission mitigation in the instant and development scenario.

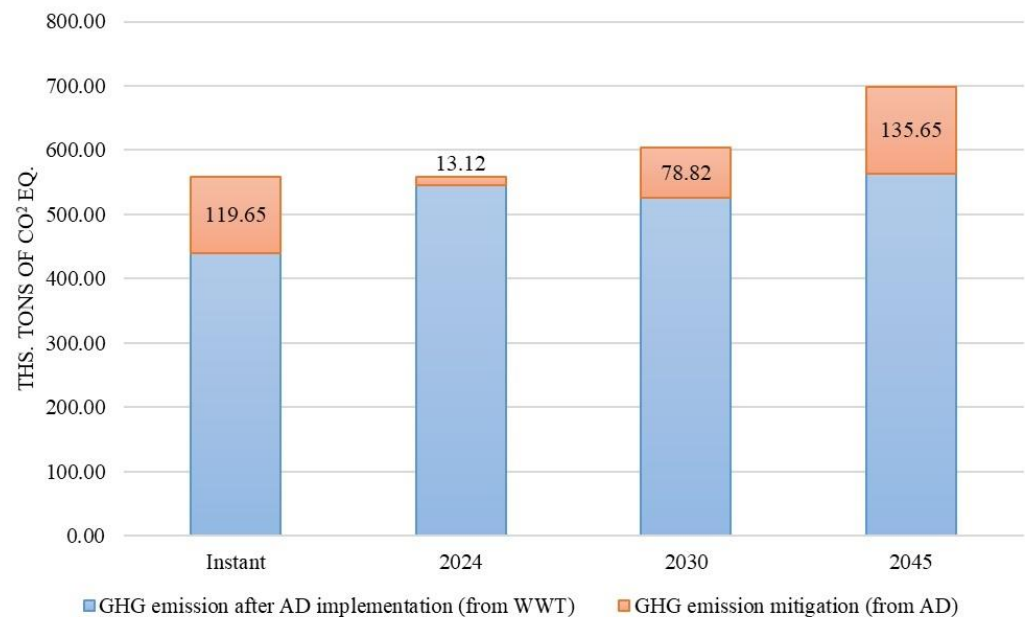


Figure 3. The benefits for GHG emission mitigation.

The diagram, presented in Figure 3, is based on the GHG emission values in the WWT category, as published in the report on the national inventory of anthropogenic emissions [56]. For the Sverdlovsk region, the values were obtained by extrapolation of the country's population to the populations of the cities under consideration within the case study. The values of GHG emissions up to 2045 for the development scenario forecast are based on the inertial scenario of the strategy of socio-economic development of the Russian Federation with low GHG emissions until 2050 [57].

Based on the data presented in Figure 3, the total share of GHG emission mitigation under the instant forecast is projected to be 21.4%, while the development scenario forecast assumes a gradual increase in the indicator up to 19.41% of the total GHG emissions, considering the abovementioned conditions. It is worth noting that the instant forecast takes into account only the actual state of GHG emissions. Consequently, in contrast to the energy potential benefits, the development scenario forecast exhibits a comparatively lower effect on GHG reduction.

Considering economic efficiency, it is worth noting that the implementation of biogas projects in countries with significant fossil fuel reserves has poor profitability with respect to the low prices for electrical energy, a lack of administrative preferences for the implementation of biogas projects in the form of tax breaks, grants and incentives, and limited availability of equipment, technology and qualified personnel [58].

A comparison of the features of the proposed methodological approach for the widespread implementation of biogas projects' forecasting benefits with the findings of similar studies from the literature review is presented in Table 6.

According to a comparative analysis of methodological approaches to forecasting benefits from the widespread implementation of biogas projects, presented in Table 6, the proposed methodology allows for a comprehensive assessment of benefits in the categories of energy and ecology, considering basic economic metrics. The framework has a clear cause-and-effect relationship and is based on relevant international research, including laboratory tests for the specific case study being considered.

However, the present approach has some limitations. The first one is associated with the use of averaged indicators for the volume of SS generation rate per person, depending on the number of residents in the locality, as the basis of the methodology. This decision was

made based on the proportion of city residents covered by centralized sewerage services, as well as a higher level of application of WWT and SS treatment technologies, which is typical for the Sverdlovsk region and the countries of the post-Soviet region. The specific indicator value adopted in the methodology is equal to 10 kg of DM per person per year for cities with a population under 1 million inhabitants. This value is likely to be less accurate than the actual value in developed countries.

Table 6. Comparison of methodological frameworks for AD widespread implementation forecast.

Scope	Framework of EEA [10]	Framework of WBA [24]	Proposed Framework
Boundaries	Global territory of EU-27 and EEA-32	Global territory (world)	Local territory (administrative region within the country)
Data of SS generation	Eurostat data of actual SS generation volumes	Predicted by specific value SS/person/day	Predicted by specific value SS (DM)/person/year
Evaluation of biogas yield	No	Predicted by specific value liter of biogas/person/day	Predicted by specific value Nm ³ of biogas/mass of SS (VS/DM)
Considering self-energy consumption for AD process	Yes	No	No
Evaluation of energy generation	Predicted by specific value energy/mass of SS. Considers combined energy potential (electricity + thermal)	Yes, but the value is unclear	Predicted by specific value kWh/Nm ³ of biogas; considers electricity and thermal energy separately
Evaluation of GHG emissions	No	Predicted by specific value mass of CO ₂ eq./person/year	Calculated by GHG emission equation
Forecast	Instant	Development scenario	Instant and development scenario

A further limitation is associated with the use of CHP generation as an exclusive technique for biogas utilization. This state of affairs is preferable for countries with significant natural gas reserves and/or inexpensive energy, for example, in the Russian Federation. At the same time, the deployment of alternative solutions at various administrative territories may prove advantageous in terms of the number of benefits compared to CHP generation.

Finally, the methodology does not take into account a comprehensive range of sludge pre-treatment and co-digestion techniques [59,60] for increasing biogas yield, which will ultimately affect the quantitative forecast of the benefits.

The potential development of the methodology includes the following actions:

- exploration of the average volumes of SS generation rates within different case studies, including Africa and Asia;
- determination of factors influencing the DM per capita specific indicator;
- proposing a set of DM per capita specific indicator values, based on a set of influencing factors;
- consideration of alternative solutions for biogas utilization and specification of the conditions for choosing the appropriate option.

Maintaining the principle of simplicity for conducting research in a specific case study is of great importance both in the context of the present methodology and in relation to its future development.

5. Conclusions

The transition towards the principles of CE was shown to enable us to turn the issue of WWT waste by-products from a pressing environmental problem into a potential source of benefits. The proven and long-established technology of AD of organic waste was regarded as the most efficient tool within the considered paradigm. Widespread implementation of biogas projects at WWTPs was demonstrated to offer a range of benefits, including the following:

- The development of distributed generation system of electrical and thermal energy;
- Disinfection and stabilization of waste for subsequent safe disposal;
- The reduction in GHG emissions by retaining methane originated as a result of waste biodegradation;
- The attraction of capital investments and development of intellectual technological capital in the territory under consideration.

The maximum effect can be achieved at the territories with extensive coverage by a centralized sewerage system, in conditions of high energy prices and rates of payment for environmental pollution. At the same time, the widespread implementation of AD technologies in countries with significant fossil fuel reserves enables us to transition towards the principles of a circular economy, as elucidated in the findings of the case study. Consequently, the implementation of a similar scenario in the Sverdlovsk region could yield up to 20.8 and 24.8 million kWh*y of electrical and thermal energy, respectively, while the GHG emission mitigation potential could reach 120 thousand tons of CO₂ equivalent.

However, the use of AD technologies is currently hampered by a number of factors from technological limitations to administrative barriers and a lack of incentives for its implementation. To overcome these existing difficulties, it is advisable to evaluate the benefits from the implementation of biogas projects not only qualitatively but also quantitatively.

This study contributes to the development of existing forecast models and presents a comprehensive tool for managers that provides a clear and comprehensive vision of the resulting effect both in terms of both instant assessment and scenario development of the territory's economy. The methodological approach is based on the relationship "resident → waste → biogas → benefits", which employs recognized average specific values to obtain the desired research result, while these values are differentiated depending on the type of population and considering the results of laboratory tests.

The results of this study will provide managers at various levels, including local authorities and directors of enterprises, with information to make informed management decisions to create the prerequisites for the widespread implementation of biogas technologies in the territory, which will contribute to sustainable development of the regions.

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