Biogas Potential of Agriculture

Timur Nurgaliev^{1,2} · Joachim Müller¹ · Valery Koshelev²

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Abstract

The purpose of this research is to evaluate the biogas potential of agriculture in the typical Russian region. The design of this study was completed using the main kinds of agricultural production of the Tambov region as the feedstocks for biogas production. Average amounts of the feedstocks were calculated on the base of data for the period 2009–2018. The quantities and revenues of electricity, heat, and biofertilizers from biogas produced from various substrates were estimated and mapped for each of the twenty-three municipal districts of the region. Results revealed an average total monetary biogas potential of 88.52×10^9 RUB for the Tambov region per year, where 75.43% are provided by electricity and heat energy and the remaining 24.57%—by biofertilizers, therefore, biogas potential of the Tambov region is comparable with biogas potential of a European country. Such feedstocks as sunflower silage, cereal grain, and cereal straw were defined as the most attractive substrates in the region. At the same time, the most of feedstocks being the main farmers' commodity production are debatable to be used as substrates; as for Russian farmers, biogas production is a new and not well-known technology. Nevertheless, the developed calculation method can now be applied by local authorities of the Tambov region and other regions of the Russian Federation as the base to develop the biogas sector in the most promising areas by supporting farmers and business structures and attracting investments in biogas technology.

Keywords Renewable energy · Anaerobic digestion · Biofertilizer · Monetary potential · Russia

Introduction

Renewable energy sources are subject to debates and research in many countries due to the discussion of climate change and energy security. Regarding developments connected with renewable energies in the world, Russia is not learning from the world experience as fast and as effectively as it could do for its economy and energy industry. Despite Russia's formal commitment to the global climate change

regime with its new Energy Strategy 2030, Russia's enormous potential in renewable energy sources is poorly utilized due to the use of fossil energy sources [1].

The Russian power system is diversified regionally and consists of one unified power system (UPS) and multiple isolated power systems (IPSSs). Approximately 15 million people live outside the UPS and receive their electric power from IPSSs, which makes the electric power, mostly generated using diesel fuel, extremely expensive [2]. In Russia, the plans for a long-term development of the energy industry are based on the country's leading export positions. The industry is very energy and investment intensive, has a long investment cycle, and requires the development of new technologies and thus long-term and in-depth interdisciplinary research [3].

The Russian Government has developed an extensive legislation regulating the energy sector and national power supply [1, 4]. However, at the same time, in spite of this strong focus on the energy sector, the use of bioenergy in general and of biogas, in particular, is still neglected in the Russian policy and economy [1]. According [5], the analysis of the development of the Russian biofuel knowledge base

✉ Timur Nurgaliev
nurgaliev_timur@uni-hohenheim.de

Joachim Müller
joachim.mueller@uni-hohenheim.de

Valery Koshelev
vmkoshelev@gmail.com

¹ Institute of Agricultural Engineering, Tropics and Subtropics Group (440e), University of Hohenheim, Garbenstr. 9, 70599 Stuttgart, Germany

² Farm Management Department, Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, Timiryazevskaya str., 49, 127550 Moscow, Russian Federation

showed challenges for the diffusion of renewable energy that is not a priority for stakeholders within Russia. Nevertheless, the potential renewable resources in Russia are gaining EU interests as one of the alternative ways of diversifying of EU energy sources, especially in the North-West of Russia. The corresponding Directive 2009/28/EC on Renewable Energy allows member states to get electricity from non-EU countries [6].

Biogas is one of the renewable energy sources. The share of biogas in the world supply in 2016 was 1.7% [7]. The main biomass energy sources in Russia are organic agricultural waste with an energy content of up to 80 Mtoe a year, forest industry's organic waste—up to 1 Gtoe per year, urban (or municipal) waste, and peat (or turf)—in total 60 Gtoe per year and energy crops—a minimum of 270.9 Mtoe per year [8]. On the other hand, despite the fact that biogas is an important component for a sustainability transition in many countries, biogas production meets technical, economic, market, institutional, socio-cultural, and environmental barriers [7].

Regarding biogas produced by agriculture, a number of aspects connected with specificities of energy industry on rural territories should be mentioned. The energy sector of agriculture has its peculiarities in terms of the dispersion of rural consumers, low unit capacity, huge length of electrical, thermal, and gas networks, large sparsely populated territories. Moreover, in many cases, agricultural production has no centralized energy supply. These specifics imply requirements for energy supply systems and are the reason for such problems as substantial transition line wear off and low quality of supply, failures, and power losses [9].

Anyway, numerous works on renewable energies oriented to solve the problems connected with the energy industry by renewables were published on the topic of biofuels in general and biogas production in particular including recent literature review on new interventions in bio-energy research [10].

Being effective biogas production can become profitable for farmers in Russia. Rural population can improve its socio-economic situation by using biogas and by integrating it in productional structure. To evaluate it, technical and economic assessments using manure-based biogas in the agrarian sector are offered by Drusyanova [11].

It has been reported that the potential of biogas, which can be obtained from livestock and poultry waste, reaches 18.3 M m³. It is advisable to construct biogas plants at large livestock complexes and poultry farms of many municipal districts of the region [12].

Organizational and economic features to realize biogas production potential in agriculture were investigated for Lipetsk region. The analysis showed that in almost all municipal districts of the Lipetsk region, there are prerequisites for the introduction of bioenergy systems for the

production of pellets from straw and biogas from animal waste, and then, the production of electrical and thermal energy from them. Firstly, there is a shortage of traditional fuels and energy. Secondly, the prices of energies increase rapidly, which significantly outpaces the growth rate of prices for agricultural products. Thirdly, the agriculture of the region has reserves of raw materials in the form of straw and animal husbandry waste, sufficient for the organization of bioenergy production. These stocks, being unclaimed in recycling technologies, pose a serious environmental hazard. Fourthly, the organization of bioenergy production will provide additional jobs, which will help to reduce the unemployment rate in the region [13].

And, finally, it was stated that the potential production volumes of biofuels from biomass in Russia in the coming decades may amount to more than 800 M tons of equivalent fuel a year. That will not be less than the annual production of oil, coal, or natural gas, (excluding biotechnological recovery of oil production in old fields), as Russia's annual energy balance is more than 1600 M tons of equivalent fuel [14].

Speaking of estimating the biogas potential, it should be mentioned that the biogas potential was currently evaluated in many countries. But only one similar work on the subject can be found referring to the Russian Federation [15]. Preliminary results on topics of biogas potential in the Tambov region [16], biogas project on a Russian farm [17] and risk analysis of biogas projects in Russia [18, 19] have been published.

However, information about biogas from agricultural products is still scarce in the Russian Federation. Being the world oil and gas exporter, Russia is dependent on the fossil kinds of fuel. Nevertheless, biogas production can diversify energies, but the biogas potential in Russian regions is still not investigated, and, therefore, the authorities and farmers are still not informed about the abilities and opportunities they have referring to the biogas production. Therefore, this paper is the first study on the agricultural biogas potential performed for a typical Russian region to motivate interested parties to invest in the biogas technology and apply it to make energy and agricultural sectors of economy more effective.

Materials and Methods

The Tambov Region of the Russian Federation

Tambov was chosen as a model region, being one of the 85 constituent territories of the Russian Federation and including 23 municipal districts. The total population of the Tambov region is about 1 million people. The overall area spans 34.5 million ha. It is located in the temperate climatic zone

and is part of the black soil belt. Its general climatic conditions are characterized by an average temperature range from -11.5°C in January to 20.5°C in July. The maximum annual precipitation ranges from 450 mm in the southeastern part of the region and 500 mm in the northern part. The vegetation period lasts for 189 days [20].

On average, the electricity generated in the region from 2009 to 2018 was estimated at over 4048 TJ, the electricity imported from other regions at 10,273 TJ and the electricity exported from the region at 1936 TJ, while the mean electricity consumption of the region was estimated at 12,386 TJ [21].

The biogas potential of agriculture in the Tambov region is closely related to its main animal production resources, such as cattle, pigs and poultry, and to its crop production, such as maize, grasses of all kinds, sunflowers, all cereals (winter wheat, winter rye, spring triticale, spring wheat, spring barley, oat, millet, and sorghum) and sugar beet. Manure, produced by animals, and dung, produced by birds, can be used successfully as a substrate, as well as silage, which can be prepared from maize, grass, and sunflowers. Cereal grains can be used directly as a substrate, as well as straw, which is usually produced as a secondary product. Beet pulp and beet leaves, being secondary products of sugar beet production, are also commonly used as a feedstock to produce biogas.

Technically, the potential of AD production is limited by the capacities of biogas plants as well as by the capacities of substrate production. Unfortunately, we cannot refer to any known functioning biogas plants in the region. However, all the substrates that can be produced in the region, except beet pulp. Pulp production from beet is limited by the processing capacities of the sugar beet plants in the Tambov region. During the period under review, the overall mass of beet pulp produced in the region is estimated at 2368.50 kt per year in average [22].

Among others, the five largest sugar beet plants located in the region reach the following production capacities: Znamensky 6500 t per day, Zherdevsky 6000 t per day, Nikiforovsky 7000 t per day, Kirsanovsky 3600 t per day, and Uvarovsky 4000 t per day [23]. In calculating the theoretical potential, it is assumed that the plants are operated throughout the year. Therefore, a comparison of the theoretical biogas production potential from beet pulp as well as the beet pulp production capacities of sugar beet plants in the Tambov region is needed.

Quantities of the corresponding production are presented in Table 1 (average of non-zero values for the period from 2009 to 2018). Those non-published numbers were calculated by constructing linear trends by the least-square method (LSM) on the basis of published data. Data about quantities of the corresponding production for periods after 2018 for the municipalities are not published by the Federal

State Statistics Service of the Russian Federation (FSSS) so far as well as data on the electricity balance [21, 24].

The average approximate output of manure per animal is about 30 kg/day for cattle, around 4 kg/day for pigs and 0.189 kg/day for poultry [25]. Based on this information, from the number of animals in Table 1, the quantity of produced manure in the municipal districts of Tambov can be estimated. FSSS published quantities of maize produced for grain and green mass production. If the output of the green mass of maize can be utilized directly, the output of green mass of maize originally produced for grain can be calculated in the same way as the green mass of sunflower originally produced for grain. The average yield of maize produced for grain and for green mass during the period 2009–2018 in the Tambov region equals to 5.81 and 20.06 t per ha, respectively [26]. Therefore, the yield of maize green mass that can be produced from the crop originally intended for grain production, can be calculated as $20.06/5.81 = 3.45$ t per t of the maize grain production. Accordingly, the overall production potential of green mass of maize in the Bondarsky municipal district amounts to $7.04 \text{ kt} \times 3.45 + 4.02 \text{ kt} = 28.31 \text{ kt}$. It is known that the maximum mass losses in silage production can amount to 25% [27], and therefore, it is assumed that the average silage output equals 0.75 t per t of green mass. Based on this information, from the quantities of maize grain and maize green mass in Table 1, the quantity of maize silage in the municipal districts of the Tambov region can be estimated.

The same average silage output from green mass equal to 0.75 t of grass silage per t of grass green mass is applied to calculate grass silage output from grass produced in the municipal districts of the Tambov region presented in Table 1.

It is assumed that sunflowers produced for grain can be harvested for silage with a minimal yield of 21 t green mass per ha [28]. The average yield of sunflowers produced for grain for the period 2009–2018 in the Tambov region amounts to 1.84 t per ha [26]. As the yield of green mass from sunflower is not recorded for the region, it can be estimated from the yield of sunflower grain as $21/1.84 = 11.41$ t green mass per t of the sunflower grain production. Accordingly, the sunflower green mass production potential in Bondarsky municipal district is $39.96 \text{ kt} \times 11.41 = 455.94 \text{ kt}$. The same average silage output from green mass equal to 0.75 t of sunflower silage per t of sunflower green mass is applied to calculate sunflower silage output from sunflower produced in the region.

The grain/straw ratio can vary widely from cereal to cereal and from district to district due to differences in cereal kinds, production technology, and other factors [29], but for this study in the Tambov region, these differences are assumed to be negligible as all farms of the region are in the same climatic zone and the production technologies do

Table 1 Average production of resources available for biogas production in the Tambov region of the Russian Federation during the period 2009–2018 [24]

Municipal district	Cattle in 1000 animals	Pig in 1000 animals	Poultry in 1000 birds	Maize grain in kt	Maize green mass in kt	Grass in kt	Sunflower grain in kt	Cereal grain in kt	Sugar beet in kt
Bondarsky	3.15	52.76	36.71	7.04	4.02	5.58	39.96	60.23	15.49
Gavrilovsky	3.37	110.70	61.84	6.59	0.00	3.90	55.72	82.96	165.33
Inzhavinsky	6.87	5.37	4112.21	41.60	4.69	6.91	119.48	128.12	23.86
Kirsanovsky	3.17	3.42	28.19	8.05	1.06	3.81	74.40	101.60	275.48
Michurinsky	4.76	3.29	71.11	18.60	7.02	10.96	58.47	110.67	133.13
Mordovsky	6.75	7.31	54.33	11.51	22.53	14.02	113.05	150.05	337.81
Morshansky	7.00	3.26	89.01	38.48	8.68	7.48	50.57	82.46	0.00
Muchkapsky	3.46	4.00	44.46	21.96	0.00	1.68	81.99	88.78	151.51
Nikiforovsky	5.62	27.65	32.07	12.10	5.24	9.20	62.28	136.56	247.86
Pervomaysky	1.84	1.34	354.46	4.04	0.30	1.99	20.28	45.11	86.50
Petrovsky	3.23	3.27	65.68	24.38	0.02	3.32	134.14	205.68	145.58
Pichaevsky	3.99	1.52	46.43	3.14	8.53	12.59	35.25	56.16	37.91
Rasskazovsky	5.82	40.61	175.27	60.40	3.26	11.78	108.58	139.85	74.47
Rzhaksinsky	3.60	4.90	64.07	27.34	0.38	9.95	94.61	132.35	451.96
Sampursky	6.58	101.79	183.22	14.65	22.12	21.03	67.73	104.88	217.05
Sosnowsky	9.19	3.36	75.37	30.15	21.24	22.57	90.84	138.64	42.76
Staroyurevsky	6.05	7.34	87.34	27.23	0.72	5.68	51.77	106.77	23.74
Tambovsky	19.89	8.03	106.92	19.49	41.98	32.29	88.48	154.45	138.10
Tokarevsky	6.11	5.27	1394.84	16.74	2.40	10.50	96.20	144.03	267.05
Umetsky	3.55	3.45	33.63	8.37	0.00	3.99	58.63	76.93	84.08
Uvarovsky	5.27	3.95	41.68	11.18	14.59	34.65	75.05	108.66	316.88
Zherdevsky	6.52	131.88	74.14	19.35	1.67	5.24	98.61	139.91	368.59
Znamensky	4.84	93.68	49.14	20.92	11.09	6.67	74.44	102.86	315.85
Total	130.63	628.15	7282.12	453.29	181.56	245.78	1750.54	2597.68	3921.00

not differ dramatically. Therefore, the average approximate grain/straw ratio of all cereals is commonly assumed to be equal to 1:1.

The share of leaves in the overall yield of sugar beets is usually around 35% [27]; the output of beet pulp is approximately 80% from the original beet mass [30]. Therefore, it is assumed that the output of leaves is 0.35 t per t of sugar beet mass and the output of beet pulp is $0.65 \times 0.8 = 0.52$ t per t of the overall sugar beet yield.

Calculations

To calculate biogas potential of the Tambov region the following elements, their sets and subset were used. Outputs of biogas production, their sets and subsets are presented in Table 2.

Substrates produced from resources for biogas production and their set are described by the notation presented in Table 3.

Resources for biogas production produced in the municipal districts of the Tambov region and the set of these resources are presented in Table 4.

Table 2 Outputs of biogas production

Name of the product, set, or subset	Notation	Unit
Product of biogas production	$G = \{g\}$	
Biogas	g_1	m^3
Electricity	g_2	J
Heat	g_3	J
Biofertilizer	g_4	t
In-digestate N	g_5	t
In-digestate P_2O_5	g_6	t
In-digestate K_2O	g_7	t
Energies	$G_1 = \{g_2, g_3\}$	
In-digestate chemicals	$G_2 = \{g_5, g_6, g_7\}$	
Commodity biogas production	$G_3 = \{G_1, G_2\}$	

Municipal districts of the Tambov region and their sets are described by the notation presented in Table 5.

Potentials of biogas, electricity, heat, N, P_2O_5 , and K_2O production were calculated for each of the municipal districts of the Tambov region. The revenues B from the commodity biogas products g of biogas product, using

Table 3 Substrates

Name of the element or set	Notation	Unit
Substrates	$S = \{s\}$	
Cattle manure	s_1	t
Pig manure	s_2	t
Poultry dung	s_3	t
Maize silage	s_4	t
Grass silage	s_5	t
Sunflower silage	s_6	t
Cereal grain	s_7	t
Cereal straw	s_8	t
Beet pulp	s_9	t
Beet leaves	s_{10}	t

Table 4 Resources for biogas production

Name of the element or set	Notation	Unit
Resources	$K = \{k\}$	
Cattle	k_1	1000 animals
Pig	k_2	1000 animals
Poultry	k_3	1000 birds
Maize green mass	k_4	t
Grass green mass	k_5	t
Sunflower green mass	k_6	t
Cereal grain	k_7	t
Cereal straw	k_8	t
Beet pulp	k_9	t
Beet leaves	k_{10}	t

substrate s produced from resource k in district d is estimated in RUB as follows:

$$B_{gskd} = Q_{gskd} \times P_g; (g \in G_3; s \in S; k \in K; d \in D) \quad (1)$$

where P_g is price of biogas product g .

Total revenue potential B_{total} of the region is calculated as:

$$B_{total} = \sum_{g \in G_3} \sum_{s \in S} \sum_{k \in K} \sum_{d \in D} B_{gskd} \quad (2)$$

The production quantity of each output is calculated as:

$$Q_{gskd} = R_{gs} \times R_{sk} \times R_{kd}; (g \in G; s \in S; k \in K; d \in D) \quad (3)$$

g per unit of substrate s per unit of substrate (e.g., m^3 of biogas per 1 t of cattle manure), R_{sk} is the output of substrate s per unit of resource k (e.g., t of cattle manure per 1 cattle) and R_{kd} is the size of resource k per district d (e.g., number of cattle in a certain district).

Table 5 Municipal districts

Name of the element or set	Notation
Municipal districts	$D = \{d\}$
Bondarsky	d_1
Gavrilovsky	d_2
Inzhavinsky	d_3
Kirsanovsky	d_4
Michurinsky	d_5
Mordovsky	d_6
Morshansky	d_7
Muchkapsky	d_8
Nikiforovsky	d_9
Pervomaysky	d_{10}
Petrovsky	d_{11}
Pichaeovsky	d_{12}
Rasskazovsky	d_{13}
Rzhaksinsky	d_{14}
Sampursky	d_{15}
Sosnowsky	d_{16}
Staroyurevsky	d_{17}
Tambovsky	d_{18}
Tokarevsky	d_{19}
Umetsky	d_{20}
Uvarovsky	d_{21}
Zherdevsky	d_{22}
Znamensky	d_{23}

The conversion rates from substrate to methane as well as other substrate characteristics were taken from relevant sources and are presented in Table 6.

Total N, P_2O_5 , or K_2O potential of the region are calculated by the formula:

$$Q_{g,total} = \sum_{g \in G_2} \sum_{s \in S} \sum_{k \in K} \sum_{d \in D} Q_{gskd} \quad (4)$$

While outputs of biogas were taken directly from the referenced literature, the quantity of each chemical (N, P_2O_5 , or K_2O) as a production of commodity g is calculated as:

$$R_{gs} = \frac{DM_s}{100} \times R_{gs,DM}; (g \in G_2; s \in S; k \in K; d \in D) \quad (5)$$

where DM_s is the dry matter content (DM) of substrate s in % FM and $R_{gs,DM}$ is the content of chemical g in DM of substrate s in %.

Biogas substrate characteristics are presented in Table 6.

It was assumed that the substrate is loaded into the fermenters equipped with thermal insulation to reduce heat loss, as well as with integrated heaters and external heat exchangers to keep the uniform temperature inside the fermenters. This makes the AD process not sensitive to the

Table 6 Biogas substrate characteristics

Substrate	Substrate output per unit of resource in t per animal or in t per t of production	Biogas output in m ³ per t of substrate	Methane output in m ³ per t of substrate	DM in % FM	N content in % DM	P ₂ O ₅ content in % DM	K ₂ O content in % DM
Cattle manure	10.95	80.00	44.00	25	5.60	3.20	8.80
Pig manure	1.46	62.78 ^b	48.00 ^c	20 ^c	3.104 [*]	2.78 ^{d*}	3.10 ^{d*}
Poultry dung ^a	0.07	140	90	40	18.40	14.30	13.50
Maize silage ^a	0.75	200.00	106.00	33	2.80	1.70	4.30
Grass silage ^a	0.75	180.00	98.00	35	4.00	2.20	8.90
Sunflower silage	0.75	120.00 ^a	68.00 ^a	25 ^a	1.80 ^e	0.88 ^e	2.28 ^e
Cereal grain ^a	1	620.00	329.00	87	12.50	7.20	5.70
Cereal straw	1	275.42 ^b	170.00 ^c	84 ^c	0.60 ^{f*}	0.30 ^{f*}	1.19 ^{f*}
Beet pulp	0.52	68.00 ^a	49.00 ^a	24 ^a	2.33 ^{d*}	1.42 ^{d*}	1.81 ^{d*}
Beet leaves	0.35	175.00 ^g	105.00 ^g	15 ^g	1.46 ^{d*}	0.88 ^{d*}	2.48 ^{d*}

^aFNR [31], ^bDeublein [32], ^cWellinger [33], ^dZorg Biogas AG [34], ^eKWS [35], ^fPesticidy [36], ^gStarke [37]. *Average in-digestate N, P₂O₅ and K₂O content was taken in terms of % FM and converted to content in terms of % DM.

factors that cause temperature fluctuations inside the fermenter including extreme ambient temperatures in summer and winter [31]. It was assumed that the biogas is used in combined heat and power plants (CHPP) at an overall efficiency of 90% [38] that the energy output amounts to 21.6 MJ per m³ (or 6 kWh) and that approximately 1/3 of the energy produced is electricity while 2/3 are in the form of heat [39]. The average Russian prices for electricity, heat, N, P₂O₅, and K₂O were compiled for the period 2009–2018. Prices for electricity were set at 1.30 RUB/MJ and 0.27 RUB/MJ for heat. Prices of N, P₂O₅, or K₂O are given in RUB per t and are equal to prices of corresponding one-component fertilizers (ammonia in aqueous solution, ground phosphate rock, or potassium chloride) in terms of active material. Therefore, the price was set at 21,522 RUB/t for N, at 19,645 RUB/t for P₂O₅, and at 19,719 RUB/t for K₂O [40, 41].

MS Excel and Quantum GIS open source package (<http://www.qgis.org/es/site/>) were used to calculate the results and present the maps.

Results and Discussion

Electricity and Heat Production Potential of the Region

The overall biogas potential is estimated at 5040.43 M m³. Its distribution between districts and substrates is presented in supplementary material (Table A1). Biogas potential is closely related to the electrical and heat production potential. The overall electrical potential is estimated at 36.29 PJ. It was analyzed by ranking and sorted by substrates and districts. Results of ranking show that the first three substrates with an overall electrical potential of 81.82% are sunflower

silage (35.67%), cereal grain (31.95%), and cereal straw (14.19%). The summarized electricity potential of the first three districts in this ranking amounts to 19.11% of the total electricity potential. These are Petrovsky (7.00%), Inzhavinsky (6.13%), and Mordovsky (5.98%) municipal districts. Municipal districts were ranked in accordance to their electricity potential allocated by substrates. This ranking shows that sunflower silage in Petrovsky municipal district, cereal grain in Petrovsky municipal district and sunflower silage in Inzhavinsky municipal district have the highest potential with 2.73%, 2.53%, and 2.43%, respectively. As heat output in biogas CHPPs usually is approximately two times higher than the electricity output 2.43%, the overall heat potential of the region is estimated at an average of 72.58 PJ during the reporting period, while the distribution between districts and substrates for heat potential is the same. The distribution of electricity and heat potential according to municipal districts and substrates is presented in Fig. 1 and Fig. 2 respectively.

The biogas potential of agriculture in the Tambov region is compared with parameters of the region's actual electricity balance for the period under review. The electricity that could theoretically be generated by biogas could cover the overall electricity consumption of the region 2.93 times.

Potential of In-digestate N, P₂O₅, and K₂O Production

The overall nitrogen potential is estimated at 454.72 kt. It was analyzed by ranking after allocation by substrates and districts. Results of ranking show that the first three substrates with an overall N production potential of 85.08% are cereal grain (62.13%), sunflower silage (14.83%), and poultry dung (8.13%). The total potential of the first three districts in this ranking amounts to 22.56% of the

Fig. 1 Distribution of electricity potential in the Tambov region of the Russian Federation for the period 2009–2018

Fig. 2 Distribution of heat potential in the Tambov region of the Russian Federation for the period 2009–2018

total N production potential. These districts are Inzhavinsky (9.31%), Petrovsky (6.72%), and Tokarevsky (6.52%). Municipal districts were ranked in accordance to their nitrogen production potential allocated by substrates. This ranking shows that cereal grain in Petrovsky, poultry dung in Inzhavinsky and cereal grain in Tambovsky municipal districts have the highest potentials, namely 4.92%, 4.59%, and 3.69% respectively. The distribution of the nitrogen potential among municipal districts allocated by substrates is represented in supplementary material (Table A2).

The overall P_2O_5 potential is estimated at 264.97 kt. It was analyzed according to the ranking by substrates and districts. Results of the ranking showed that the first three substrates with a total of 83.30% in-digestate P_2O_5 production potential are cereal grain (61.41%), sunflower silage (12.44%), and poultry dung (10.84%). The combined potential of the first three districts in this ranking amounts to 23.99% of the total in-digestate production potential of P_2O_5 . These are Inzhavinsky (10.64%), Tokarevsky (6.86%), and Petrovsky (6.49%) municipal districts. Municipal districts were ranked according to their in-digestate P_2O_5 production potential allocated by substrates. This ranking shows that poultry dung in Inzhavinsky and cereal grains in Petrovsky and Tambovsky municipal districts have the highest potentials at 6.12%, 4.86%, and 3.65% respectively. The distribution of the P_2O_5 potential among municipal districts allocated by substrates is represented in supplementary material (Table A3).

The overall in-digestate K_2O production potential is estimated at 342.83 kt. It was analyzed by ranking after allocation by substrates and districts. Results of ranking showed that the first three substrates with a total in-digestate K_2O production potential of 71.67% are cereal grain (37.57%), sunflower silage (24.91%), and cattle manure (9.18%). The summarized potential of the first three districts in this ranking amounts to 22.02% of the total in-digestate K_2O production potential. These are Inzhavinsky (9.43%), Tokarevsky (6.37%), and Petrovsky (6.23%) municipal districts, which were ranked according to their in-digestate K_2O production potential allocated by substrates. This ranking shows that poultry dung in Inzhavinsky and cereal grains in Petrovsky and cereal grain in Tambovsky municipal districts have the highest potentials with 4.47%, 2.98%, and 2.23% respectively. The distribution of the P_2O_5 potential among municipal districts allocated by substrates is represented in supplementary material (Table A4).

Revenue Potential of the Region

The overall revenue potential is estimated at 88.52×10^9 RUB and was analyzed by ranking after allocation by substrates and districts. Results of ranking show that the first three substrates with a total revenue potential of 80.38%

are cereal grain (37.45%), sunflower silage (31.18%), and cereal straw (11.74%). The summarized potential of the first three districts in this ranking amounts to 19.73% of the total revenue potential. These districts are Inzhavinsky (7.00%), Petrovsky (6.88%), and Tokarevsky (5.85%). Municipal districts were ranked according to their revenue potential allocated by substrates. This ranking shows that cereal grains in Pichaevsky municipal district, sunflower silage in Pichaevsky municipal district, and cereal grain in Tokarevsky municipal district have the highest revenue potential, namely 0.81%, 0.63%, and 2.08% respectively. The distribution of the revenue potential among municipal districts is presented in Fig. 3.

Despite cereal grain has the highest biogas potential in the region, it should be mentioned that after numerous discussions with stakeholders, it was apparent that not all farmers would agree to use cereal grain for AD production, which is usually considered to be a cash-crop—very often the main one. On one side, farmers fear to lose their existing sales channels, and on the other, they have doubts about the new, not well-tested technology. In other words, all potential participants (farmers and the state) would welcome the application of AD technology mainly associated with the utilization of wastes and secondary products to generate “green” energy, especially if this is profitable. However, they would not prefer to use grain and fodders to produce biogas.

The revenue potential allows the estimation of the available biogas production in universal financial terms. Moreover, the revenue potential takes different variables into account. Factors such as resource volume in each municipal district, substrate output per resource unit, and prices for each product make this estimate more comprehensive and multi-faceted and offer the possibility to consider not only the financial side of AD but also the properties of substrates.

To start with, it should be mentioned that it is not possible to produce in-digestate N, P_2O_5 , and K_2O separately from the digestate; therefore, the revenue that can be derived from selling biofertilizer (or used by farmers for their own needs) should be considered as “unified whole”. Distribution of the revenue potential between the crop production sector, the animal production sector, and poultry sector has rather precise tendencies.

The crop production sector generates more than 81×10^9 RUB of its biogas production revenue from energy (electricity and heat). The crop production sector (including such substrates as cereal grain, cereal straw, all kinds of silage, beet pulp, and beet leaves) makes up 92.41% of the overall revenue potential, the animal production amounts to 4.39%, and the poultry production has 3.19% of the overall revenue potential (supplement material, Table A5).

The revenue potential of the ten substrates in the 23 municipal districts is presented with the ranks 1–230 in supplementary materials (Table A6). It shows for example, that

Fig. 3 Distribution of revenue potential in the Tambov region of the Russian Federation for the period 2009–2018

highest singular revenue potential is found for cereal grain in Petrovsky. Looking at the overall ranking of all substrates, cereal grain also has the highest value of 1. Looking at the overall ranking of all municipal districts, Inzhavinsky shows the highest revenue potential.

Among others, poultry dung has the lowest substrate output per unit of resource but has the highest resource volume in Inzhavinsky municipal district. In addition, poultry dung with a biogas output of 140 m³ per t substrate reaches the highest concentrations of N, P₂O₅, and K₂O. All these factors make Inzhavinsky municipal district one of the most advantageous districts for investments in the region due to the poultry dung.

These substrate production trends and capacities determine the position of each region in the matrix, which indicates the energy and biofertilizer production potential in monetary units (Fig. 4).

In general, all regions can produce substrates for AD that can generate revenue mostly by selling energy. The average share of energy of the overall regional sales potential is estimated at 75.43%, and the share of biofertilizers at 24.57%. Due to the enormous amount of poultry dung produced in the Inzhavinsky district and its high potential to produce N, P₂O₅, and K₂O, this district has a significant offset compared to other districts on the right side of the graph (Fig. 4).

In spite of the fact that renewable energy resources have been slow to penetrate the Russian energy market [42] and

use of them is still neglected in Russia [1], Russia has a huge potential of renewable resources in general and biogas production in particular [1, 6, 43]; the current situation in Russia referring to renewable energy sector needs urgent action oriented to the development of this industry [44].

Biogas potentials were evaluated for such countries as Albania [45], Turkey [46], Serbia, [47], Sweden [48], Poland [49], and China [50], and this paper is one of the first to evaluate biogas potential of a typical Russian region. Results in this study show that the biogas potential of the Tambov region is comparable with the biogas potentials of some European countries, e.g., total amount of energy that could be obtained from biogas in Poland is 39.44 PJ [49] which is close to the biogas electricity potential in the Tambov region of the Russian Federation (36.29 PJ).

Russia is a world oil and gas exporter, and hence, it depends on these kinds of fuel, but renewable energies can considerably diversify energies. Moreover, renewable energy potential of the North-West could help the EU decarbonize its electricity supply at least cost due its geographic proximity to the EU [6]. Making the country less dependent on this sector of economy biogas production can make farmers less dependent on the state energy policy and green Europe's energy supply through developing Russia's renewable energy potential [6]. This study is to motivate farmers and authorities to diversify energy production by biogas to make energy and agricultural sectors of economy more flexible.

Fig. 4 Distribution of municipal districts by their potential to produce energy and biofertilizer in 10⁹ RUB

Conclusion

The overall biogas technology potential for the Tambov region of the Russian Federation was evaluated by the offered methodology. The potentials of biogas, electricity, heat, nitrogen, phosphorus pentoxide, and potassium oxide outputs in physical and financial terms were calculated. The distribution of the potential according to substrates, districts, and production types was illustrated by a ranking.

This calculation method can be applied to any region by local authorities to develop the biogas production sector or by businesses to invest in biogas technology.

The elaborated and applied methodology allows the evaluation of the region's revenue potential but does not consider investments and operating costs. So far, it also does not take into account specific farm conditions of the region. Therefore, further studies should focus on the economic analysis of specific biogas projects.

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