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Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

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Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

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Contents

Issues of Rational Energy Supply to Specially Protected Natural Areas and How to Resolve Them with the Example of the Khuvsgul National Park

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Abstract — **The paper addresses the issues of applying solar plants and solar heating systems for energy supply to the facilities located in specially protected natural areas (SPNA). The findings of the research into the existing energy systems and possible strands of their development, given the installation of reactive power compensators and the adoption of photovoltaic cells (PVCs), are presented. A comparative analysis of the modernized system functioning with the existing power grid is carried out. To this end, a special algorithm for multi-criteria optimization of the locations and generating capacity for solar plants is used, which involves sequentially checking the feasibility of additional capacity to be installed at consumers' of each considered substation. The possibility of using solar heat supply to a specific facility is investigated and economic indicators are calculated for it. A heating system layout has been developed and proposed for the school building, which makes it possible to provide it with thermal energy throughout the year.**

As a case study, the paper considers the problem of electricity and heat supply to consumers in the cross-border recreational area "Baikal-Khuvsgul." At present, power supply to this region is provided from the Central electric power system (CEPS) of Mongolia from the Muren substation along the 35 kV power transmission line (TL) to the substation in the center of the Alag-Erdene sum, and from it, through the 35kV, 15kV and 10 kV distribution networks, further to consumers. At the same time, due to the weak energy infrastructure, significant remoteness and inaccessibility of the area, as well as low population density, the development of this system does not seem effective in most of the territory and does not ensure the conditions for the creation of a reliable fuel and energy supply. According to modern requirements, including the growing loads and the development of ecotourism in the region, it is time to reconsider the concept and approaches to the energy supply and determine the most appropriate ways to implement them. First of all, it is necessary to assess the possibility of using local renewable and other energy resources. The findings of the study on the local energy resources, given the characteristics and environmental vulnerability of protected areas, as well as the seasonal nature of changes in the electrical and thermal loads of most consumers, suggest that the most feasible way is to introduce solar energy.

Index Terms: **Local energy resources, annual solar radiation, the number of "degree-days" of heating, solar heating, thermal energy storage, solar photovoltaic, local system, backup source, solar power plant, power quality, power supply reliability, multi-criteria optimization.**

I. Introduction

The issue of energy supply in the light of the contemporary energy and environmental problems is resolved by using special, so-called sustainable, methods, technical solutions, and production processes. This strand is essential and decisive, when it comes to power supply to consumers located in specially protected natural areas.

The foregoing seems to be especially relevant for the northwestern zone of the Specially Protected Natural Area (SPNA) of Lake Khuvsgul, which includes the protected areas of Khordil-Sardik, the Darkhad Basin, and the Tsagaan Taiga, where, along with a relative increase in the number of indigenous people in recent years, there is an intensive flow of tourists staying all year-round and seasonally. In this regard, the electricity and heat consumption of the area increases significantly. Study [1] considers the fundamental issues and the current state of power supply to the Baikal-Khuvsgul transboundary territory as prerequisites for research into the possibility of using renewable energy for the purposes of power

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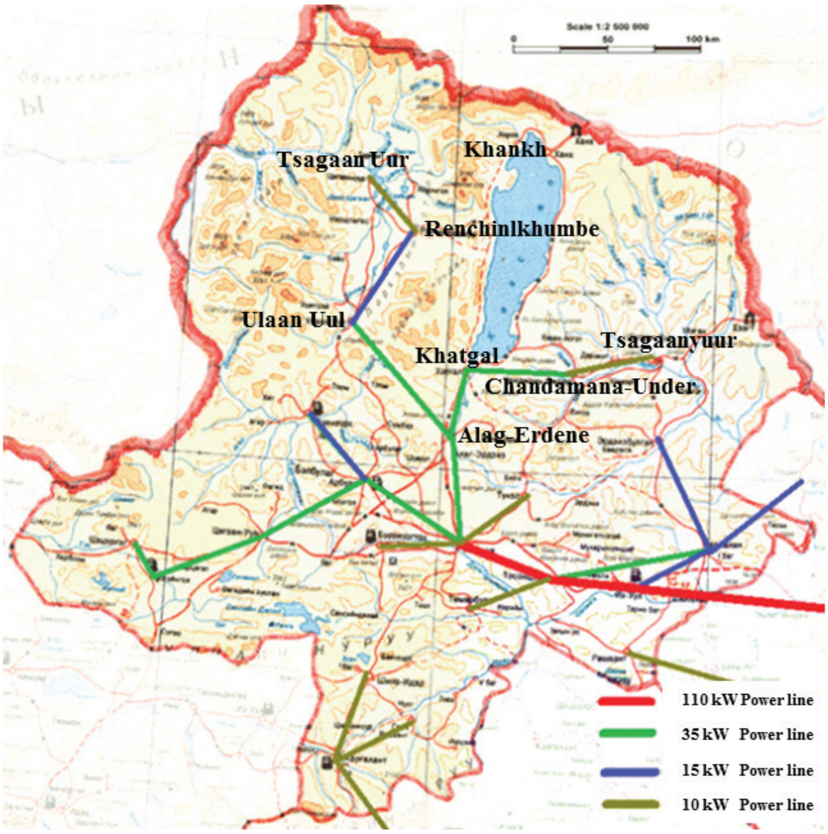

Fig. 1. A scheme of electricity supply to the territory.

supply to consumers. The current power supply system from the EPSs of Mongolia and Russia is analyzed and it is noted that the state of the power supply does not meet the existing controllability and reliability requirements. A further growth in electricity consumption in the region in question exacerbates the situation with energy supply to consumers, as the expansion of electrical networks to cover this territory is complicated due to its remoteness and inaccessibility. Studies by the Russian side to improve the efficiency, quality and reliability of power supply to these areas, including the Khankh sum of Mongolia, show the possibility and sufficient potential to attract distributed generation (DG) through the installation of solar power sources [2].

In Mongolia, the territory located on the right side of Lake Khuvsgul (Fig. 1) is supplied with electricity from the Mongolian CEPS from a substation in the city of Muren through a 35 kV power line of the local power grid through a substation in the center of the Alag-Erdene sum to a substation in the center of the Ulaan-Uul sum, and from it along a 15 kV power line to the center of the Renchinlkhumbe sum and further along a 10 kV power line to the Tsagaan-Uur sum. The left coast of Lake Khuvsgul is also supplied with power from Alag-Erdene via a 35 kV power line through Khatgal to Chandaman-Under and from there via a 15 kV power line to Tsagaan-Uur sum (Fig. 1). Work similar to that presented in [2] was carried out to analyze and assess the efficiency of the local distribution

Table 1. Indicators of population and energy consumption of the area.

Sum	Total population number	Population in the sum	Rural population density,	Annual electrical load,
Tsagaan-Uur	1 950	916/1 034	0.19	341 065
Renchinlkhumbe	4 907	781/4 126	0.49	426 984.33
Ulaan-Uul	4 259	1 400/2 859	0.28	561 083
Tsagaan-Uur	2 650	1 040/1 610	0.18	518 047.8
Chandamana Under	3 058	980/2 078	0.46	545 507.13
Khatgal (city)	3 195	1 195	-	1 810 527.64
Alag-Erdene	3 331	1 001/2 330	0,52	465 989.85
Moron	40 770			33 213 309.42
Khankh	2 783	1 604/1 159	0,21	603 923.44

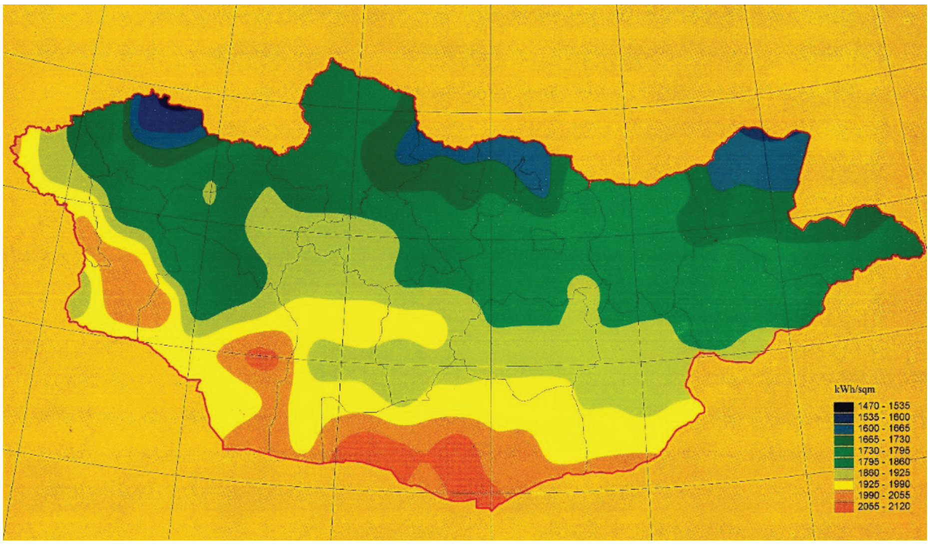

Fig. 2. Annual total solar radiation on a horizontal surface, kWh/m^2 per year.

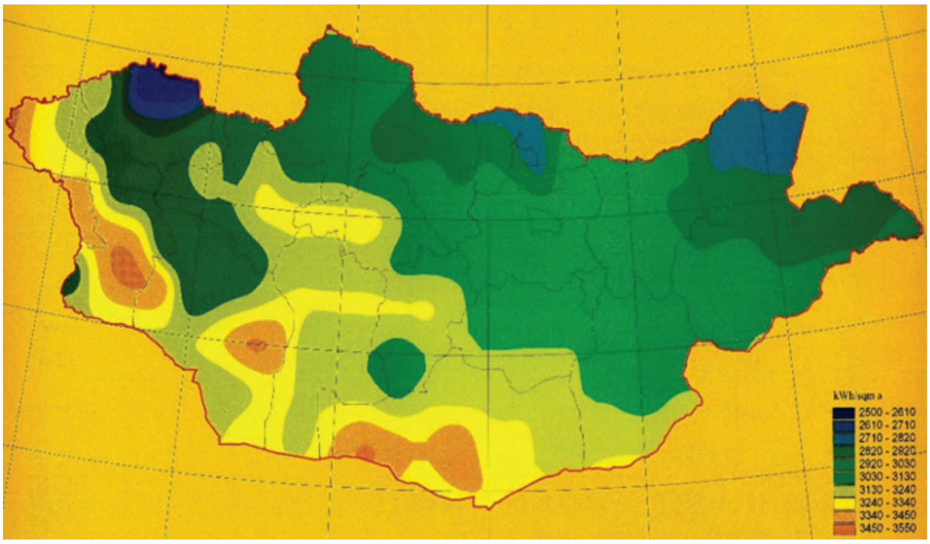

Fig. 3. Annual direct solar radiation on a perpendicular surface, kWh/m^2/year.

electrical network operation, and to ensure the quality and reliability of power supply to the sums. The results of the present studies are given below.

When solving the issues of energy supply to consumers in the sums of Khuvsgul aimag, located in remote mountainous taiga regions, it is important to pay attention to population density and types of economic activity developed. The population density in the areas at issue is 0.4–0.7 person/km^2, which is relatively low compared to the average values for both the aimag (1.3 person/km^2) and the country (2.0 person/km^2) [3]. The main economic activities are cattle breeding and tourism. Due to the vast territory and small population of the sums, the density of the rural population in these areas is low (Table 1).

Not all coastal areas of Khuvsgul, except for the centers of sums and some of their settlements and individual consumers, are located within effective distances from the route of power transmission line connected to the country's EPS [1]. Some rural consumers are supplied with electricity from various individual and distributed low power sources (diesel generators and other micro sources). A specific feature of Khuvsgul aimag is the increased number of rural residents living on its territory, 47.2% on average for the aimag. This must be taken into account when addressing the issues of energy supply to the settlements.

When choosing heat supply methods, one should also bear in mind that the majority of centers in the sums have an insignificant heat load. The outcomes of our studies on the heat supply to 23 sums of the Khuvsgul aimag indicate that the heat load of 10 sums is in the range of 0.2–0.4 Gcal/h (232.7–465.2 kW). With such a heat load, given the remote location of consumers across the territory and with respect to one another, the use of a centralized heating system has no competitive advantages over individual heating or the connection of closely located consumers to one heat source (decentralized and group heat supply). Alternative energy

Table 2. Assumed electrical load values.

No.	Substation	Load condition 1		Load condition 2	
		Active power	Reactive power	Active power	Reactive power
		kW	kVar	kW	kVar
	Consumers in the eastern territory of Lake Khuvsgul				
	Substation “Tsagaan-Uur”				
1	Tsagaan-Uur	113.48	23.04	123.48	36.02
	Substation “Chandman-Under”				
2	Chandmana-Under (1)	37.40	7.59	47.40	15.58
3	Khukhkhuu bug (1)	50.00	3.03	65.00	3.94
	Substation “Khatgal”				
4	Khatgal (1)	87.93	5.33	277.93	16.84
	Khatgal ATP-1	67.65	4.10	96.76	5.86
5	Altanmuren goal	45.14	2.74	65.14	3.95
6	BZS “Magniterde”	31.25	1.89	21.25	1.29
7	“Gundalai” holiday center	40.00	2.42	52.00	3.15
8	Alagtsar	50.00	3.03	40.00	2.42
	Consumers in the western territory of Lake Khuvsgul				
	Substation “Tsagaan-Uur”				
9	Tsagaan-Uur	62.86	12.76	72.86	21.25
10	Renchinlkhumbe Substation				
11	Renchinlkhumbe	44.79	2.71	44.79	2.71
	Substation “Ulaan-Uul”				
12	Ulaan-Uul (16)	91.41	5.54	71.41	4.33
	Substation “Alag-Erdene”				
13	Alag-Erdene	66.00	9.40	56.00	7.98
14	Sumber (36)	40.00	2.42	40.00	2.42
	Substation “Muren”				
15	Muren 35-1	200.00	– 28.50	51.00	– 9 613.09
16	Muren 6-1	2 400.00	145.45	1 329.00	80.54
17	Muren 6-2	3 168.00	191.99	2 390.00	144.84

Table 3. Assessments of voltage levels and voltage deviation angles at substation buses.

	Substation	Load condition 1			Load condition 2		
		Ul,	u,	U, angle	Ul,	u,	U, angle
		kV	p.u.	degree	kV	p.u.	degree
	Erdenet 110 kV	114.00	1.01	0	113.00	1.00	0
	Bulgan 110 kV	110.32	0.98	– 4.22	112.06	0.99	– 2.56
	Tosontsengel 110 kV	103.11	0.91	– 19.45	112.81	1.00	– 10.86
1	Muren 110 kV_1	101.61	0.90	– 23.29	112.34	0.99	– 12.64
2	Muren 110 kV_2	101.61	0.90	– 23.29	112.34	0.99	– 12.64
3	Muren 35 kV_1	37.41	1.01	– 33.46	38.62	1.04	– 18.19
4	Muren 35 kV_2	37.41	1.01	– 33.46	38.62	1.04	– 18.19
5	Alag-Erdene 35 kV	36.06	0.97	– 33.84	37.04	1.00	– 18.52
6	Sumber 35 kV	36.06	0.97	– 33.84	37.04	1.00	– 18.52
7	Khatgal	35.79	0.97	– 34.42	37.57	1.02	– 11.87
8	“Gundalai” holiday center 35 kV	35.75	0.97	– 34.46	36.61	0.99	– 19.29
9	Alagtsar 35 kV	35.68	0.96	– 34.54	36.54	0.99	– 19.36
10	Chandamana-Under	35.64	0.96	– 34.58	36.50	0.99	– 19.40
11	Khukhkhuu bag	35.64	0.96	– 34.58	36.50	0.99	– 19.40
12	Ulaan-Uul	35.70	0.96	– 34.26	36.72	0.99	– 18.85

Table 4. Calculated values of load and active power losses for power transmission lines of the electrical network.

Power transmission line		Load condition 1		Load condition 2	
		Loading	Losses (total)	Loading	Losses (total)
		%	MW	%	MW
	Erdenet-Bulgan	45.82	1.38	26.16	0.44
	Bulgan-Tosontsengel	38.85	3.75	23.99	1.17
	Tosontsengel-Murun	34.98	0.83	17.86	0.21
4-5	Muren-Alag-Erdene	9.22	0.02	10.89	0.02
5-6	Sumber	0.36	0.00	0.32	0.00
5-6	Sumber_a	0.00	–	0.00	–
5-7	Alag-Erdene-Khatgal	3.70	0.00	4.94	0.01
7-8	Khatgal - “Gundalai” holiday center	2.54	0.00	2.57	0.00
8-9	Altantsar - “Gundalai” holiday center	2.21	0.00	2.18	0.00
9-11	Altantsar - Khukhkhuu bag	1.79	0.00	1.89	0.00
10-11	Khukhkhuu bag-Chandamana-Under	0.43	0.00	0.49	0.00
11-10	Khukhkhuu bag-Chandamana-Under_a	1.37	0.00	1.41	0.00
5-12	Alag-Erdene-Ulaan-Uul	1.74	0.00	1.48	0.00

sources can be used in addition to traditional heating boilers for decentralized and individual heating. The main consumers in the centers of sums and small settlements are first-aid posts, hospitals, schools, kindergartens, local administration buildings and houses of culture, which are financed from the local budget. The issue of heat supply to such consumers can be resolved within the framework of the master plan for the development of rural energy using renewable energy sources that do not violate the environmental requirements of specially protected natural areas.

This paper deals with the issues of improving the electricity and heating systems distributed over hard-to-reach mountain-taiga areas in terms of the environmental aspect dictated by the requirements of the special protected areas. The possibility of establishing local systems for electricity and heat supply to consumers by using local renewable energy resources is shown on the example of solar energy.

II. The use of solar energy

Solar energy is one of the most environmentally friendly natural energy resources. Therefore, it can be considered as the primary one for the protected area at issue. Although this area is located in Mongolia’s northernmost territory, the solar radiation it receives is not inferior to most of territories in the country [5] and is quite acceptable for the use in energy supply to its consumers. As follows from Fig. 2, the annual incoming total solar radiation of the Khuvsgul region lies in the range of 1600 to 1800 kWh/m^2 per year.

Direct solar radiation on a surface perpendicular to the sun’s rays, which is of major importance for the calculation and use of solar power plants (Fig. 3), is in the range of 2800–3000 kWh/m^2 per year. These data are quite consistent with the estimates previously published in [1], corresponding to 1600–1720 kWh/m^2 per year.

III. Transformation and rationalization of power supply

It is obvious that solar energy can be used for both power supply and heat supply to autonomous consumers, agricultural facilities, and settlements. Recently, solar photovoltaic plants have become widespread in Mongolia. Almost all settlements in rural areas use photovoltaic cells for domestic needs. The use of solar photovoltaic cells (PVCs) in power generation is not particularly difficult, except for the need to provide the initial funding of the plants, the cost of which is constantly decreasing. Solar cells seem to be an effective solution for small disparate consumers (households, tourism facilities, schools, hospitals, administrative and public buildings in settlements) in the specially protected area. The solar plants with solar photovoltaic cells constructed in the centers of sums have increased the reliability and improved the operating conditions and voltage stability of 10–35 kV transmission lines in the settlement of Khankh.

The performed computational studies of the power transmission lines operation made it possible to assess the efficiency of the power systems under the existing conditions. To comprehensively present the situational behavior of operating parameters of the substations (Table 1) in this system, the substations of all sums in the Khuvsgul aimag, which are connected via a 110 kV transmission line from the city of Erdenet through the city of Bulgan, were included in the calculated diagrams.

The Power Factory software Toolbox was used to conduct computational studies of the operating conditions of electrical networks. The calculations were performed for two initial conditions, namely, for the winter maximum (load condition 1) and summer minimum loads (load condition 2). Tables 2, 3 and 4 present the assumed values of electrical loads and the results of assessing voltage levels, voltage deviation angles at substation buses, loading and losses of active power in power transmission lines, respectively.

Table 5. Comparison of voltage level and voltage deviation angle for the buses of substations with compensators and with a 5 MW renewable energy source.

Number	Substation	Winter maximum						Summer minimum					
		Load condition 3			Load condition 5			Load condition 4			Load condition 6		
		Ul, kV	u, p.u.	U angle degree	Ul, kV	u, p.u.	U angle degree	Ul, kV	u, p.u.	U angle degree	Ul, kV	u, p.u.	U angle degree
1	Muren110 kV_1, 2	119.51	1.06	– 26.31	123.67	1.09	– 21.89	105,10	0,93	– 11,09	105.97	0.94	– 7.94
2	Muren 35kV_1, 2	36.01	0.97	– 28.25	37.00	1.00	– 23.68	105,10	0,93	– 11,09	37.00	1.00	– 9.69
3	Alag-Erdene 35kV	34.71	0.94	– 29.83	35.61	0.96	– 23.87	35,37	0,96	– 13,39	35.22	0.95	– 10.68
4	Sumber 35kV	34.71	0.94	– 29.83	35.61	0.96	– 23.87	35.37	0.96	– 13.39	35.22	0.95	– 10.68
5	Khatgal	34.59	0.93	– 30.65	35.30	0.95	– 24.43	35.04	0.95	– 14.27	34.89	0.94	– 11.70
6	Gundalay 35kV	34.55	0.93	– 30.70	35.26	0.95	– 24.47	35.00	0.95	– 14.32	34.84	0.94	– 11.75
7	Alagtsar 35kV	34.48	0.93	– 30.78	35.19	0.95	– 24.55	34.92	0.94	– 14.39	34.76	0.94	– 11.84
8	Chandamana-Ulziy	34.43	0.93	– 30.83	35.15	0.95	– 24.6	34.87	0.94	– 14.44	34.71	0.94	– 11.89
9	Khukhkhuu bag	34.43	0.93	– 30.83	35.15	0.95	– 24.6	34.87	0.94	– 1.44	34.70	0.94	– 11.89
10	Ulaan-Uul	34.65	0.94	– 30.82	35.21	0.95	– 24.26	35.08	0.95	– 13.83	34.98	0.95	– 11.29
11	110 kV SPP	–	–	–	123.69	1.09	– 21.87	–	–	–	105.99	0.94	– 7.92
12	35 kV SPP	–	–	–	39.34	1.06	– 20.38	–	–	–	33.70	0.91	– 5.89

The voltage level for the maximum load conditions ranges from 0.90 to 1.01 in per units, and for the minimum load conditions, it varies from 0.99 to 1.04 p.u. The voltage deviation angle at the substation buses reaches 34.58º under the maximum load condition, and 19.40º – under the minimum load condition.

Power losses in power transmission lines are at an acceptable level, and the load of Erdenet-Bulgan transit double-circuit lines reaches up to 45.82% at the winter maximum load and only 26.16% – at the summer minimum load.

The computational studies show that the distribution of active and reactive power, overloads of lines and substations, and voltage levels by node change within the allowable limits outlined by regulatory documents, which confirms the admissibility and feasibility of the planned load conditions. Power quality can be assessed by using the indicators such as the voltage deviation in the network from its nominal values. They must be within acceptable limits. The cost-effectiveness of the load condition can be determined by the values of power and electricity losses in the electrical network. To this end, we identified eight local calculated nodes, for which the following indicators were analyzed:

Minimization of the total voltage deviation on the low side of substations supplying consumers

$$\delta U_{\Sigma} = \sum_{i=1}^{n} \left| \delta U_i \right| , \quad (1)$$

where δU_i is voltage deviation from the nominal value on the low side of the i-th substation, %.

Minimization of total active power losses in the network

$$\Delta P_{\Sigma} = \sum_{j=0}^{k} \left| \Delta P_j \right| , \quad (2)$$

where ΔP_j is active power losses in the j-th component of the electrical network, kW.

Maximization of the power supply reliability index for the consumer, which was estimated by the share of the essential consumers load covered with the help of RES at each substation

$$R = \sum_{k=0}^{n} \frac{1}{n \cdot L_i} \left(\min \left(L_i ; \frac{P_{res}}{n \cdot P_i} \right) \right), \quad (3)$$

where n is the number of substations; L_i is share of the i-th substation load corresponding to essential consumers, p.u.; P_{res} is power of renewable energy source installed at consumers of the i-th substation, kW; P_i is the load of the i-th substation, kW.

To improve the power grid operation with an increase in power consumption in winter and summer, computational studies were conducted for the installation of reactive power compensators and the usability of photovoltaic cells. The analysis of the initial conditions allowed identifying the sites for installing compensators according to the largest deviations of the voltage angle on consumer buses, including 35 kV and 15 kV buses of substations. The substations mentioned above are Khatgal, Tsagaan-Uul, Ulaan-Uul and Muren. The Muren substation was chosen to adopt RES.

For illustration, Table 5 shows the results of a computational study for the winter maximum load conditions in the power grid with compensating devices connected in the above places (Load condition 3) and with a renewable source at the Muren substation (Load condition 5) for all substations that belong to the Khuvsgul sums. Here, for comparison, the calculation results are also given for the summer conditions (Load conditions 4 and 6).

For clarity and comparison of the initial winter conditions (Load condition 1) with the data of the calculated conditions given in Table 5, Figure 4 indicates

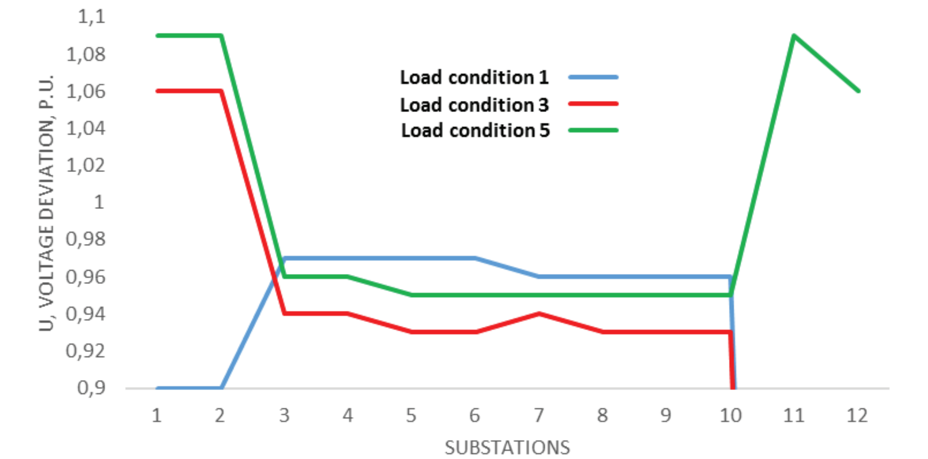

Fig. 4. Voltage deviation (in p.u.) at substations for the winter maximum conditions with respect to steady state with and without compensators and a 5 MW renewable energy source.

Fig. 5. Voltage deviation (in p.u.) at substations for the summer minimum conditions with respect to steady state with and without compensators and a 5 MW renewable energy source.

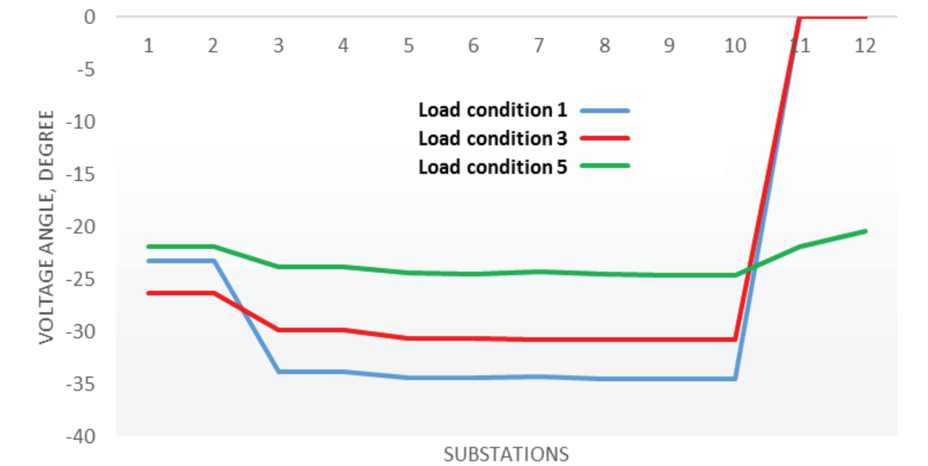

Fig. 6. Voltage angle deviation for the winter maximum at the substations with and without compensators and a 5 MW renewable energy source.

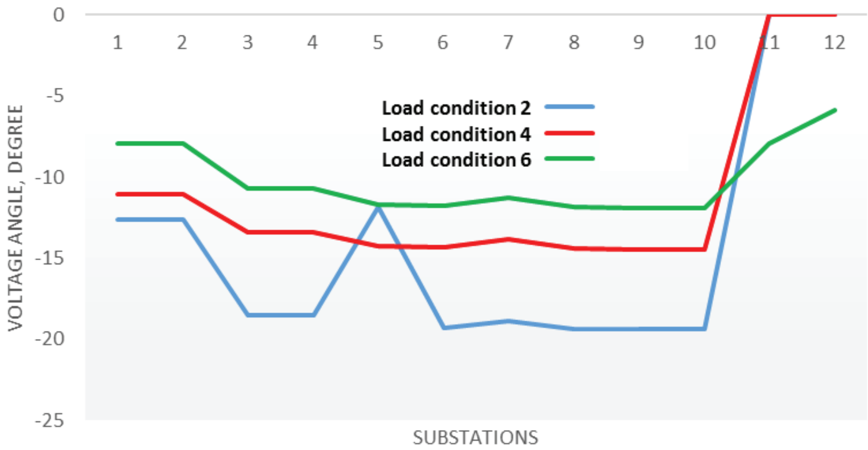

Fig. 7. Voltage angle deviation for the summer minimum at the substations with and without compensators and a 5MW renewable energy source.

Table 6. The assessment results for the loading of power transmission lines and active power losses with compensators and 5 MW solar plants at the Muren substation.

No.	Power transmission line	Winter maximum				Summer minimum			
		Load condition 3		Load condition 5		Load condition 4		Load condition 6	
		Loading	Losses (total)	Loading	Losses (total)	Loading	Losses (total)	Loading	Losses (total)
		%	MW	%	MW	%	MW	%	MW
1	Erdenet-Bulgan I	47.91	1.49	44.13	1.26	25.32	0.42	24.45	0.39
2	Erdenet-Bulgan II	47.91	1.49	44.13	1.26	25.32	0.42	24.45	0.39
3	Bulgan-Tosontsengel	49.23	5.67	43.51	4.22	19.86	0.9	14.1	0.42
4	Tosontsengel-Mörön	41.97	1.16	35.18	0.8	17.12	0.2	12.54	0.1
5	Moron-AlagErdene I	11.69	0.03	10.16	0.02	12.08	0.03	13.52	0.03
6	Sumber	0.37	0	0.36	0	0.33	0	0.36	0
7	Sumber_a	0	–	0	–	0	–	0	–
8	Khatgal-Gundalai amralt	2.63	0	2.58	0	2.69	0	2.98	0
9	Alagtsag-Gundalai	2.28	0	2.24	0	2.29	0	2.53	0
10	AlagErdene-UlaanUul	2.31	0	1.81	0	1.52	0	1.71	0
11	Khukhkhuu bag-Chandmani Undur	0.44	0	0.43	0	0.51	0	0.57	0
12	Khukhkhuu bag-Chandmani Undur_a	1.42	0	1.39	0	1.48	0	1.64	0

their combined graphs constructed to show the distribution of voltage deviations at the substations of the Khuvsgul sums and the Muren substation.

Following the objectives set in this work, all data given in Tables 2–5 and Figures 4 and 5, represent only the findings related to the diagram of the grid supplying power to the Khuvsgul sums that are part of the protected area.

The remoteness from the power generation center and the length of the local power grid significantly affect the values of its operating parameters, especially the voltage level. The reactive power compensators reduce the voltage deviation and, consequently, make corresponding operating conditions of the power grid more stable and resilient. As seen in Tables 2–5, compensators are to be purposefully installed to maintain the required voltage level and other operating parameters.

Detailed studies on the choice of parameters and sites for placement of compensators have shown that the achievement of the desired results can be facilitated through the reasonable use of RES.

The cost-effective energy supply solutions obtained in these studies became possible due to a comprehensive

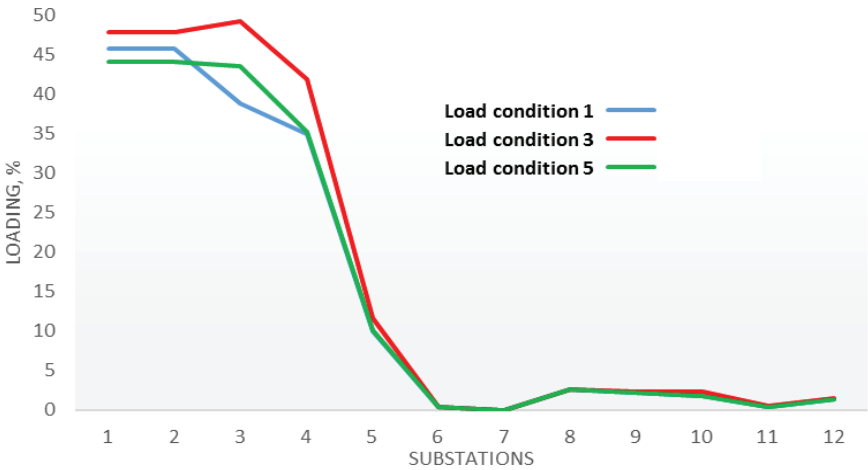

Fig. 8. Change in the level of loading of power lines at maximum loads.

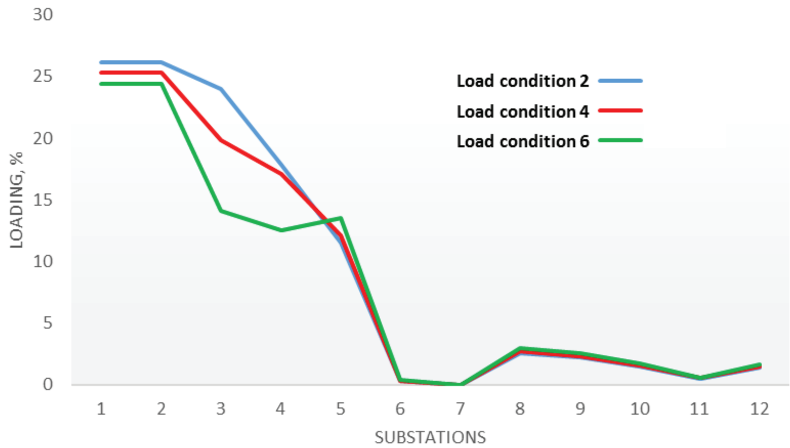

Fig. 9. Change in power loss in power transmission lines for the winter maximum load with compensators (1), without them (3), and with a 5 MW renewable energy source (5).

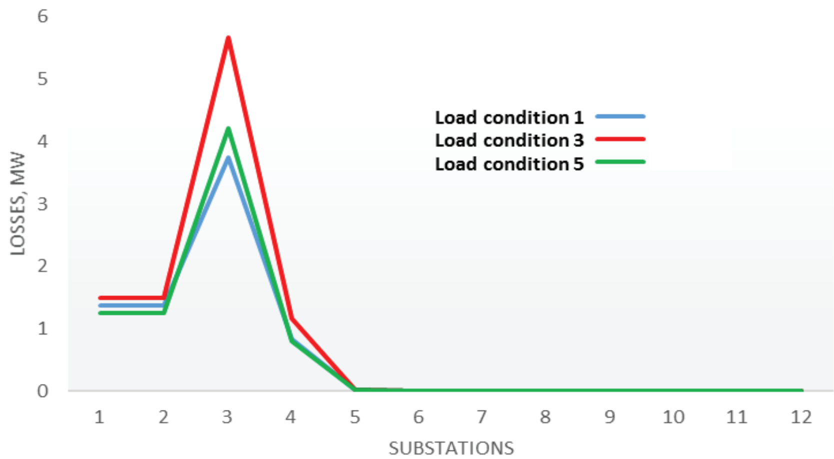

Fig. 10. Change in active power losses in power lines at maximum loads.

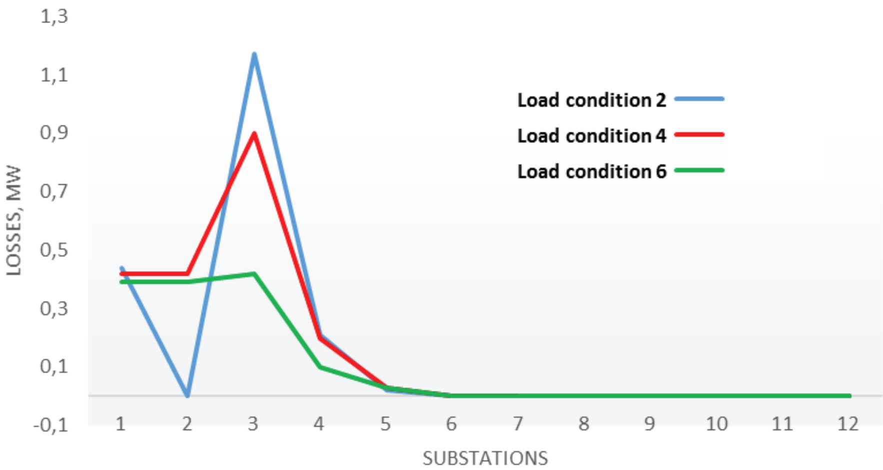

Fig.11. Change in active power losses in transmission lines at minimum loads.

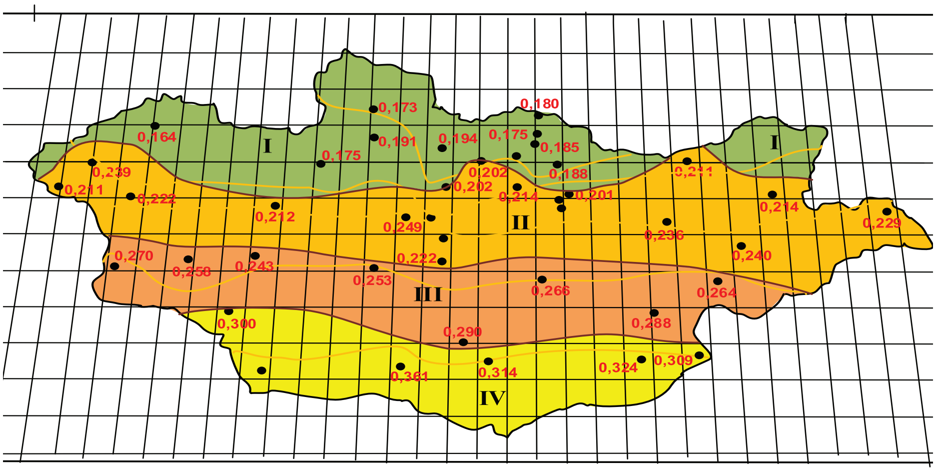

Fig.12. Zoning map of Mongolia's territory for the use of solar energy for heating buildings.

Fig.13. View of the school building for 320 students.

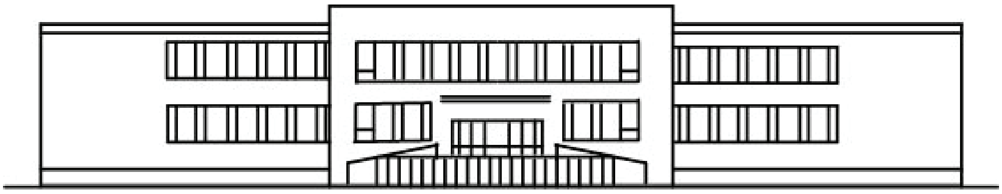

Fig. 14. General view of the building of the secondary school for 320 students.

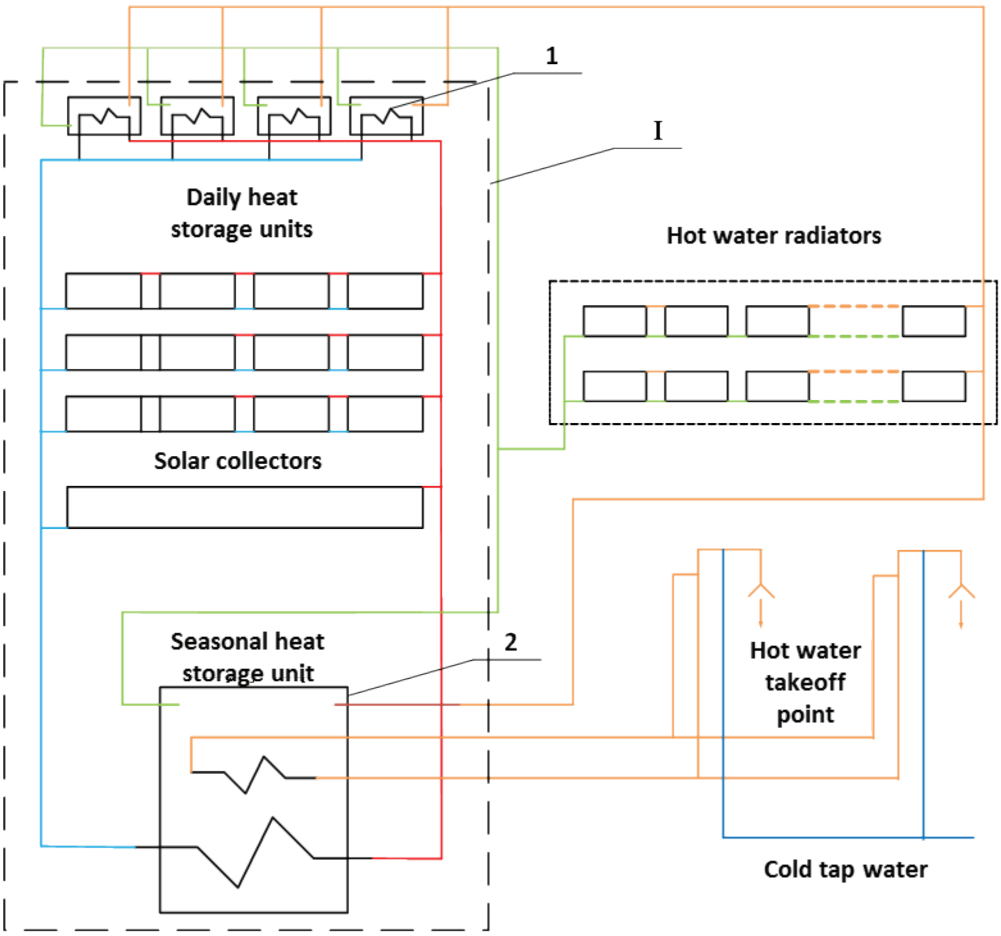

Fig. 15. Diagram of the solar heating system of the building.

consideration of this issue, taking into account the reasonable combination of centralized energy supply and distributed generation with renewable energy sources, as well as the use of advanced power grid equipment. These solutions are shown in Fig. 6 in the form of operation plots for voltage deviation for all substations in the Khuvsgul aimag power grid. Substations and nodes in this Figure are represented by conventional numbers from 1 to 12. According to the initial conditions, the considered power flows correspond to those given above and have the same numbering. The system stability effects obtained for low summer loads were more pronounced (Fig. 7).

In winter, the main 110 kV transit transmission line is loaded up to 45.82% of the installed capacity, and in summer, the load is 26.16% of the installed capacity. The transfer capability decreases with the use of compensators and increases with the introduction of new capacities of renewable energy sources. Power losses in transmission lines go up with the use of compensating devices and go down with the renewable capacities added, which happens due to the reduction of long transmission lines.

Thus, with the compensators, the voltage deviation in relative terms approaches unity. With reactive power compensation at the substations Khatgal (21), Tsagaan-Uul (16), Ulaan-Uul (23) and Muren (8), voltage deviations and active power losses decline, and the reliability of power supply and the stability of the electrical network operation increase.

Calculations confirm that in order to maintain the required voltage level and other operating parameters, compensators should be placed not only on the buses of these substations but also at some other nodes. The calculations also show that compensating devices can minimize the total voltage deviations on the low side of the substations supplying power to consumers. The additional input of RES represented by a solar plant of PV-type proves to be an effective solution to maintain voltage stability in the networks.

The expected addition of new potential electricity consumers may lead to unacceptable voltage deviations on the low side of substations in sums and settlements, as well as to high active power losses in the electrical network. In this regard, for the sustainable socio-economic development of the Baikal-Khuvsgul transboundary recreational area, it is necessary to ensure an environmentally sound and reliable power supply to existing and prospective consumers according to the electricity requirements.

Thus, the calculations show (Figures 8, 9, 10, and 11) that compensators and renewable energy generation can minimize the total voltage deviations on the low side of substations that supply consumers under the growing electrical loads on the territory of Khuvsgul aimag.

IV. Solar heating

The use of solar energy in heat supply (hot water, heating, cooling, and others) faces structural and technological problems arising when it is integrated into existing or newly established systems. Let us dwell on these aspects in more detail.

Previous studies on the use of solar energy for heat supply focused on technological solutions for generating heat [5] and zoning the territory of Mongolia in terms of its efficiency for heating buildings, depending on the climatic conditions of the area [5, 6]. According to the findings of these studies, four solar heating efficiency zones were identified in the direction from north to south of the country. In Fig. 9, they are shaded in different colors. In green zone I, located at the top of Fig. 10, year-round (including the entire heating period) use of solar heating is associated with considerable financial costs, i.e., initial capital investment. This zone includes the Khuvsgul aimag, which is part of the protected area. This is due to the relatively low solar activity.

A thin yellow line on the map of Mongolia (Fig. 10) shows the isolines of total solar radiation on a horizontal surface, dividing the country's territory according to its values of 1200, 1300, 1400, 1500 and 1600 kWh/m^2 per year. They can serve as a basis for assessing the integral indicator of the natural thermal energy coming to the studied area. The heat consumption of a building for its heating under specific climatic conditions of the area can be characterized by its integral indicator, the so-called "heating degree-day" (HDD). It represents the total time of the difference between the standard (normative) room temperature and the outdoor air temperature for the heating season, calculated following its daily variation [6]. The average indoor air temperature value, called the "standard temperature," was assumed to be equal to 18.33°C (65°F) when determining the HDD index. Based on the ratio (θ) of the annual total solar radiation coming on a horizontal surface (ASRHS) and the number of heating degree-days, the country's territory was divided into the above 4 zones. In actuality, when moving from north to south and with a decrease in HDD, the ASRHS rises, which indicates the enhancement of the efficiency of solar heating in buildings. Dots on the map mark the calculated values of θ = ASRHS/HDD [kWh/(m^2·°C·day)].

V. Solar energy for heating school

The design outdoor air temperature for heating in the centers of 23 sums in the territory of Khuvsgul aimag is between – 24.5 and – 43.2°C. The main thermal energy consumers in the centers of sums, along with the population, are a secondary school, a hospital, houses of culture and local administration, as well as trading and public service facilities. The research carried out by IT&IE (Institute of Thermal Engineering and Industrial Ecology at Mongolian State University of Science and Technology, Ulaan Baator, Sukhbaator district.) shows that for the centers of Khuvsgul aimag sums, the annual total heat load ranges from 296.6 Gcal/year (the Erdenebulgan sum) to 2 114.0 Gcal/year (the Tarialan sum) and the maximum hourly loads are 0.103

Table 7. Heat output of the solar system and heat balance of the building (for the months of heating season), kWh.

Month	X	XI	XII	I	II	III	IV
Heat output of the solar system	1 373.3	1 064.7	947.0	1 031.7	1 275.6	1 537.2	2 103.7
Heat consumed by the building for heating	398.5	732.9	968.2	1 030.8	923.6	645.8	356.6
Hot water supply	282.9	282.9	282.9	282.9	282.9	282.9	282.9
Total heat demand of the school	681.4	1 015.8	1 251.1	1 313.7	1 206.5	928.7	639.5
Daily heat balance (+/–)	+691.9	+48.9	–304.1	–282.0	+69.1	+608.5	+1 464
Monthly heat balance (+/–)	+20 797	+1 516	–9 123	–8 742	+2 142	+17 038	+43 920

Gcal/h and 0.743 Gcal/h, respectively [7]. This indicator for the centers of sums considered here ranges from 0.2 to 0.4 Gcal/h. The possibility of using solar heating in these areas (for example, centers of the sums) was assessed on the example of a secondary school for 320 students, which has a standard building design (Fig. 11).

The use of solar energy for heating and hot water supply to housing stock, buildings of educational and public institutions, tourist and health facilities, and holiday homes usually operating in the warm seasons of the year, is a relevant objective, especially in the light of environmental protection measures and development of ecotourism in specially protected areas. The efficiency of these technologies is quite high, despite the rich resources of fuel biomass obtained by cleaning forest areas of the Khuvsgul taiga and the preparation of firewood for household needs. Large solar water heating systems on the beaches of Lake Khuvsgul can be an example of solar plants. High-capacity water heaters designed to provide hot water and water procedures, and meet sanitary needs have been used and have demonstrated successful operation in holiday centers, sanatoriums (Terelzh, Sugnogor and Under-Dov), a summer camp for Selbe school students, at a remote railway siding (52-nd siding of the UBRW), and other facilities of the country.

We will consider the possibilities of using solar heating for consumers of zone I (Fig. 10) in the case of a school building for 320 students. These studies have made it possible to get some general results of a computational experiment on providing year-round heat supply to buildings, which can be extended to other projects [6]. The general view of the building is shown in Fig. 12, and the schematic diagram of the solar heating system adopted for it is demonstrated in Fig. 13. The system includes daily and seasonal heat storage units. According to the standard project, the construction volume of the school building is 16 065 m^3, the total area of all floors is 3 662.1 m^2, the dimensions of the base area in the plan are 48.0 m × 48.0 m (there is a free area in the center of 18.0 m × 18.0 m), and the height of the building is 7.75 m. The building must meet the requirements of energy efficiency. For this reason, annual heat loss is calculated per unit floor area, and has to be reduced to a value of the specific indicator of less than 100 kW/m^2 per year. This should be done by increasing thermal resistance of external enclosing structures through the measures reducing heat losses, for example, by using triple glazing and double-glazed windows and doors of the REHAU type, equipment for the southern facade of the building, which structurally combines a wall fence with flat solar collectors of the FT-FP-2M*1M type, ventilated air heat recovery, and others [8]. Vertical installation of solar collectors on the southern facade of the building is the most effective for solar systems primarily used in the cold seasons in northern latitudes, where the sun's height is low [5].

For the Darkhad basin, where Renchinlkhumbe sum is located, the total annual heat consumption for heating a building under the climatic conditions of the region can be 250 583.0 kWh/year, which corresponds to a specific heat loss indicator of 68.4 kWh/m^2 per year.

The adopted thermal diagram of the solar system includes flat solar collectors located on the front facade of the building and on its roof for heating the non-freezing liquid heat carrier of the first closed loop (I). The system is composed of daily heat storage units in the form of separate tanks (1) and a seasonal heat storage unit in the form of a large concrete tank (2). They are equipped with a heat exchange surface through which the heat carrier heated in solar collectors flows. The system is provided with heating devices (for example, water radiators), hot water takeoff points that have cold tap water mixing lines for temperature control, measuring instruments, and others. For the climatic conditions of the region where the minimum temperature reaches –40°C, the primary loop of the system must have a heat carrier that does not freeze up to a temperature of –50°C, for example, TYFOCOR L, which is an odorless hygroscopic liquid based on propylene glycol, which is not harmful to health. It is actively used as a cooling brine or heat transfer fluid.

Table 7 summarizes the results of a computational study relying on climatic data of the area, indices of the solar system heat output, thermo-engineering characteristics of the building envelope and heat consumption by the school building.

Table 7 shows that in October and April, the solar system produces more heat than required. Consequently, the excess energy is stored in daily storage systems for later use. From November to March, daily output becomes insufficient to meet the building's demand for heat and the lack of heat is replenished from the seasonal storage. The seasonal storage facility accumulates excess heat produced by the solar system throughout the year, primarily during warm periods. This is the basic principle of year-round continuous operation of the solar system, which ensures complete thermal independence of the school. The objective of providing autonomous heat supply can be achieved by choosing an optimal combination of daily and seasonal storage capacities based on mathematical modeling and calculation, and economic criterion. If necessary, a supplementary heat source can be used.

Capital investment in the school building for 320 students, aimed at the measures to reduce heat losses by enclosing structures and equipment of the solar heating system, is about MNT 170 million (at the rate of 2014). This value roughly corresponds to 10% of the capital investment in the school project. The payback period for additional capital investments, associated with a decrease in heat losses relative to the design value and equipment of the solar heating system for the building in question due to savings in fuel costs, is 7.3 years. The discounted payback period is 9 years.

To provide a convincing illustration of the possibility of using local environmentally friendly energy resources to supply energy to consumers in the specially protected areas, we considered the case of solar heat supply to the largest consumer in the sum center – a secondary school. In addition, the choice of solar heating for the school is of paramount importance for the environmental education of children.

In most cases, small consumers can apply simpler methods and schemes of solar heating systems without much difficulty. These systems work reliably on clear days at any time of the year.

Thus, the use of solar energy is an urgent issue that contributes to comfortable living and helps tackle other social and economic problems, primarily for remote regions of Mongolia. At the same time, if buildings are equipped with photovoltaic cells, they become energy-independent eco-facilities that meet the energy supply requirements.

VI. Conclusion

1. The Mongolian-Russian transboundary Baikal-Khuvsgul specially protected natural area is a unique ecosystem, which is of great scientific importance not only for studying natural diversity, but also for exploring the impact of human economic activity on the natural formation. Therefore, special attention should be paid to potential consequences of any activities carried out in this area. Energy supply to local consumers and that related to a sharp increase in touristic activities in the region are no exception.

2. A specific feature of the specially protected natural areas is an underdeveloped system of fuel and energy supply due to the remoteness of settlements and low density of the population. In this situation, the issue of energy supply can be addressed by involving local renewable energy sources. The territory under consideration has a high solar energy potential.

3. Increase in the reliability and continuity of centralized power supply together with improvement in the electricity quality are possible by the use of distributed generation sources (solar photovoltaic cells) at specific local electrical network nodes mainly corresponding to the centers of sums and settlements. The Power Factor Software can be employed to identify and obtain the options for ranking the weak nodes, placement of compensators, the required capacity and location of solar plant, which ensure the permissible voltage deviations for consumers, low total losses of active power, and high reliability of power supply.

4. The centralized system is not advisable for heat supply to the centers of small settlements with their small and often dispersed load. Therefore, the issue of their energy supply can be resolved through an individual and/or group system based on solar or other renewable energy. The real possibility of using a solar heating system (heating and hot water), even for fairly large facilities, is shown by the example of a typical secondary school. Based on modeling and calculation of the school's energy supply, it was determined that additional funds (10% of the total capital investment in the project) would be required. Apart from solar heating to be used in the building, another important strand is the implementation of measures to reduce heat losses to meet the requirements of energy-efficient buildings. It is worth noting that the solar system receivers installed on the southern wall structure reduce heat loss. All the listed measures to enhance energy efficiency made it possible to bring the annual rate of heat loss through the building envelopes (reduced to the floor area) to 60 kWh/m^2 per year.

5. The use of solar plants to provide hot water to meet the domestic needs of the population, the needs of sanitary-resort and tourist facilities, and their heating, as well as the use of solar cells to generate electricity for consumers in remote areas are an effective and advantageous direction of energy supply to the Khuvsgul National Park and specially protected natural areas in general.

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A Method to Aggregate Schemes of Gas Systems for an In-Depth Study of Their Expansion

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***Abstract* — There are about 30 natural gas production and transmission companies operating currently in the Russian Federation. The vast majority of them are interconnected and form the Unified Gas System. It includes gas production, processing, transmission, and underground storage facilities. Various problems in the gas system are solved relying on multilevel modeling and indicators of varying degrees of detail. This generates the need for and relevance of the development of methods for multilevel modeling and aggregation of gas systems. The paper presents an analysis of methodological approaches to the aggregation of schemes of gas systems and their facilities, which are currently available in the world. A method is proposed to aggregate gas systems, which encompasses a procedure for aggregating a real-world gas system, i.e., its representation as a calculated scheme of a smaller size. The study employs the methods of graph theory and aggregation procedures. The proposed method is illustrated by an example of a gas system covering three territorial entities, including 20 consumer nodes, 8 fields, and 14 compressor stations. The proposed methodology is applied to create a database for comprehensive studies of the Unified gas system expansion.**

***Index Terms*: aggregation, gas system, main gas pipelines, fields, gas consumers, calculated scheme, real-world system.**

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I. Introduction

The Unified gas system (UGS) of the Russian Federation is a complex, multi-line, extended system that integrates gas systems of the CIS, Eastern and Western Europe. It interacts with gas producers in Central Asia, and supplies gas to the countries of Northeast Asia. The UGS has a huge number of components and connections. It is virtually impossible to create an accurate model that adequately describes all UGS facilities (linear sections, main gas pipelines (MG), compressor stations (CS), gas compressor units (GCU), fields, underground gas storages, gas consumers, and others) in a comprehensive study of the system expansion. In this regard, the aggregation of a real-world gas system, i.e., its representation by a smaller calculated scheme, is of great importance. This is why this research is relevant.

The UGS of the Russian Federation is a unique natural monopoly structure. Given various factors and properties of the gas system, we can distinguish the following main levels of its investigation and mathematical modeling [1]:

1) A subsystem of a more general system of the energy sector (in general energy, economic, environmental and other intersectoral problems);

2) The industry as a whole, in technical and economic terms (natural monopoly);

3) A functionally integral system (for the cases of gas flow control in normal situations, for seasonal and emergency control) in the problems of planning and phased expansion, reconstruction and operation of gas systems, as well as in the analysis and synthesis of their reliability;

4) A set of production and technological facilities and subsystems (determination of parameters during their design for gas systems).

Aggregation of gas systems (GS) is relevant at all levels of the hierarchy, but especially at the first three. It includes the following steps: 1) building an aggregated calculated gas system scheme; 2) identifying aggregated technical and economic characteristics (TEC) of new and existing gas transmission and gas production companies (GTC and GPC), which also includes demand projection in the wholesale natural gas markets; and 3) aggregating the gas systems in quasi-dynamics by year of the calculation period. This paper focuses on the construction of an aggregated calculated scheme of a gas system.

The construction of an aggregated gas system is understood as the transformation of a real-world gas supply diagram into another, a simpler one, but corresponding to the original one with a certain accuracy, while maintaining the required properties of the primary system in the resulting scheme [2]. The resulting aggregated scheme, being simpler than the original one, is characterized by a smaller number of nodes and links, which facilitates the analysis and use of the results to generate the necessary solution.

II. Analysis of Methodological Approaches to Aggregation of Calculated Schemes of Gas Systems and Their Facilities

The increase and complication of gas systems in Russia and their integration into the UGS led to the need to create enlarged calculated schemes to comprehensively examine and identify the optimal path for their expansion.

Currently, there are various aggregated schemes of the UGS as a whole and its individual parts. These schemes differ because they are designed for different objectives, based on different initial information available, and intended for different levels of the hierarchy.

For example, the existing General plan for the Development of the Russian Gas Industry until 2030 [3] makes it possible to determine economically sound strategic directions for the development of the gas industry. It presents projections for the development of consumption, transport and production of natural gas in Russia as a whole and in the federal districts. Study [4] describes the stages of the general plan development. The first stage employs a systems approach to plan the development and reconstruction of the UGS; the second stage suggests fundamental technical solutions at the level of individual sections of the UGS. It also substantiates the need to consider a large number of expansion options. The study also accentuates that at present, medium- and long-term planning relies on an aggregated flow diagram, which was once adopted in an unnecessarily enlarged form because of the capabilities of computers.

There is an approach to the construction of enlarged calculated schemes, which is based on an expert method. According to this method, the main gas transport corridors are marked on the map of the Russian Federation and the main intersections of gas flows are marked following the opinion of a decision maker or a group of experts [5]. Such a scheme is too enlarged and does not sufficiently reveal the nature of gas supply to some regions and constituent entities of the Russian Federation (small entities are discarded), meanwhile accuracy is lost.

Although, in the world, there is no analogue to the UGS of Russia, which is a unique large-scale system, still researchers from other countries conduct the studies on the expansion of large gas systems [6–9]. For example, they consider gas systems of different European countries, where gas supplies from the UGS of the Russian Federation are also taken into account [10–12]. The expansion of gas systems is modeled in gas models. Papers [13, 14] provide a review and comparison of gas models developed in different countries.

The main downsides of such models are as follows: gas production and liquefaction are linked into one production; it is assumed that the country has a single gas producer, i.e., aggregated source nodes are characterized by aggregate cost and performance; the real market is segmented along the boundaries of the network companies, while in the models, the network has no clear boundaries; only few models can take into account gas storage.

Some models consider networks of varying degrees of aggregation (countries, cities, territories) [15]. When calculating gas transfers between countries, gas exporting countries are designated as source-nodes, and one country can be designated by one or more source-nodes. Similarly, importing countries can be designated by one or more consumer-nodes on the scheme. Source-nodes and consumer-nodes are interconnected by gas transport arcs. Such networks require the aggregated performance to be determined, however, these calculations are not described. According to [14], the lack of transparency in obtaining an aggregated network is a common modeling problem.

Authors of [16] propose iterative aggregation, which involves examining the features of the system, statistical data, and, on this basis, building mathematical models that describe the development and functioning of the system. Further, the main indicators of the system are determined, their weight coefficients are set to calculate the aggregated characteristics. A heuristic algorithm is also proposed for iterative aggregation, which suggests that the weight coefficients are given by experts, not by a fixed number, but by a range. The use of this method is complicated due to the impossibility of collecting a huge amount of detailed initial information on the system, and due to the existence of a large number of random factors that cannot be taken into account and described.

In [5, 17], approaches to the aggregation of indicators from the lower level of the hierarchy to a higher one are described. An attempt is also made to switch from expert aggregation to formal mathematical modeling (the method of convolutions of particular values of indicators is used).

Gas exports are calculated based on an analysis of global trends in the development of gas systems and an assessment of the gas market situation following the materials given in the general plan for the development of the gas industry. Retrospective information is collected for each country consuming Russian gas, including purchase volumes and information on long-term contracts for the sale of gas to these countries. Based on this information, export volumes are projected. The average gas export values are detailed and distributed among the nodes of the calculated scheme in accordance with the capacity of the export corridors.

New natural gas consumer-nodes "appear" in the calculated gas supply scheme when considering prospective hydrocarbon markets for the constituent entities of the Russian Federation. The studies examine the feasibility and efficiency of investment projects for the development of natural gas resources, rationale for the long-term goals for the development of industry, agriculture, and for the improvement of the welfare of the people.

World's scientific and practical experience shows that the issue of aggregation of gas systems is neither sufficiently studied nor systematized. There is no algorithmic description of the methods for aggregating the gas system scheme. The following aspects of aggregating the system components are poorly investigated:

– Demand for natural gas is most often projected to be overall for the country or a district;

– Aggregated source nodes are represented in the scheme by large fields, disregarding small fields and independent gas producers;

– Aggregation of the main gas pipelines identifies the main gas transmission corridors, which have a single-line representation with a total throughput capacity. Other main gas pipelines are often ignored.

The scientific novelty of this work is related to a gas system aggregation method including an algorithm for building a model calculated scheme of a gas system to the level of entities, which allows formalizing this process.

III. A Method of Aggregating the Gas Supply Calculated Scheme

A method is proposed to aggregate the gas system to the level of the entities of the Russian Federation but not to the level of the federal district (as in the General Plan), which allows clarifying and detailing information on gas consumption, transmission and production to a lower level.

Gas system is considered at three levels: 1) main gas pipelines, fields, underground gas storages; 2) gas transmission and gas production companies (GTCs and GPCs); 3) Unified gas system of the Russian Federation. Solving the problems of the optimal gas system expansion, we firstly analyze technical and economic characteristics of the lower level components (main gas pipelines, fields), then use these data to determine the characteristics of GTCs and GPCs, and consider the entire UGS, determining the optimal flows, gas transmission directions and cost. In reverse order, the obtained data is checked for the agreement with the lower levels. If discrepancies occur, the next cycle of calculations is performed until a solution acceptable for all levels is found.

The gas system is represented as a directed graph and is considered as a set of three subsystems: gas sources, main transmission networks and consumers. Source facilities include all facilities that deliver gas to the main transmission network: complex gas treatment plants, gas chemical complexes and underground gas storage facilities (UGSFs), if at the considered time point the UGSF is working for gas extraction. The main gas transmission facilities consist of sections of the main gas pipelines, including the linear part and compressor stations located on it. Consumers include consumer groups that take gas from main gas pipelines and UGSFs, if the time under consideration coincides with the period of gas injection into them.

The construction of the gas system model network graph is based on the following principles:

the network configuration reflects the directions of the main gas transmission systems, the location of large gas transmission interconnectors, the points of connecting the main gas pipelines of source facilities to consumers;

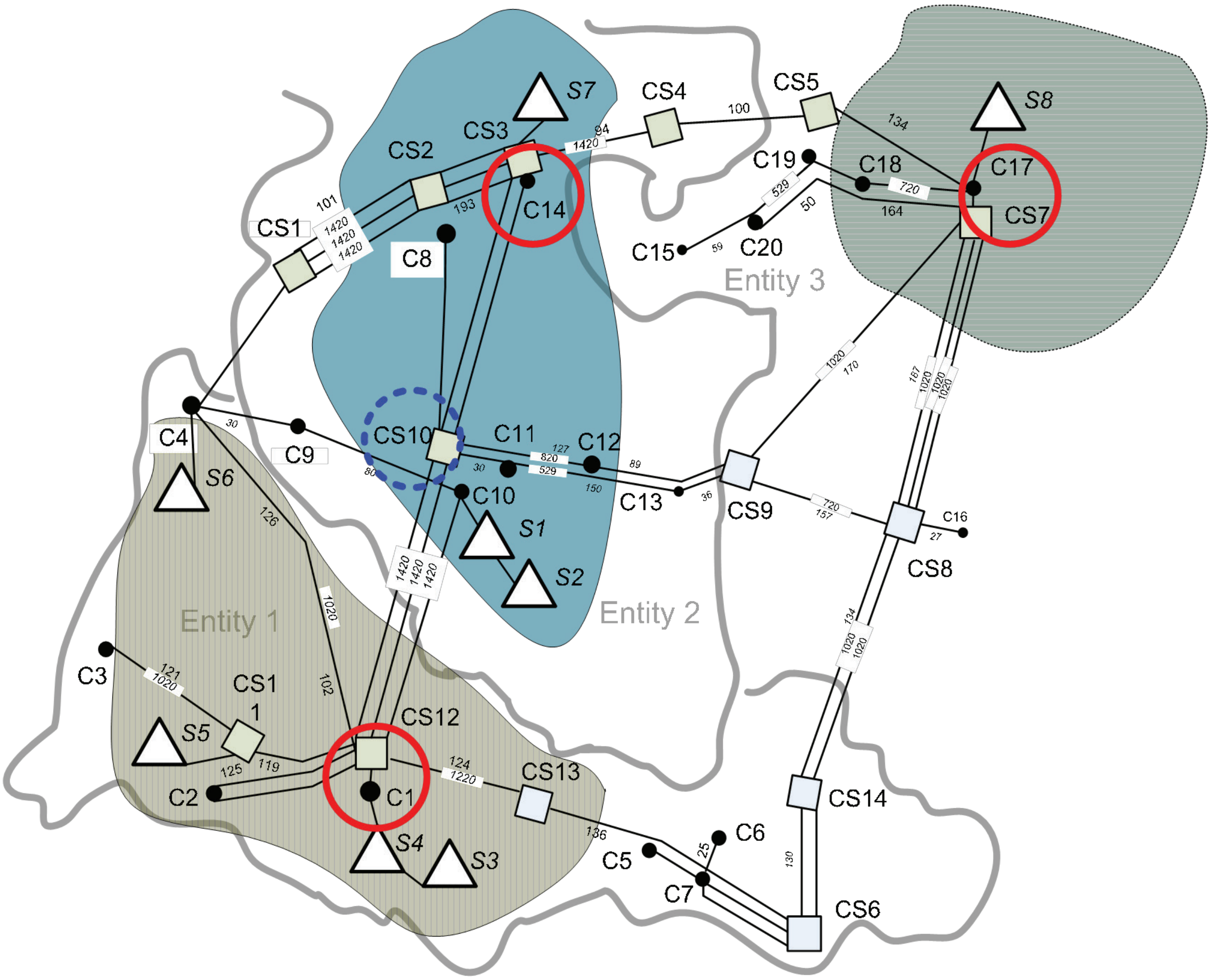
network nodes include the points of connecting gas transmission mains to the production, storage, and consumption facilities, as well as branching points of gas flows (at the locations of nodal CSs); the sections of main gas pipelines located between two network nodes stand for branches of the model network;

technical and economic indicators of the aggregated network components are obtained by summing or averaging the corresponding indicators of the detailed scheme components

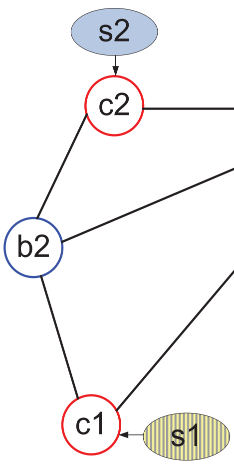
The nodes to be investigated include a region, an autonomous republic, and a territory with focus on large industrial consumers (if necessary).

The initial data used in the study are:

- ***for sources***: maximum annual gas production at all fields and gas producing companies in general, operating costs and gas loss at the GTCs. Information used is from the Main Directorate of Natural Resources of the Ministry of Natural Resources of the Russian Federation and the JSC "Gazprom;"
- ***for UGS gas mains***: diameters, the number of lines, lengths, connection points of all compressor stations, operating costs and the share of gas losses of the gas transmission company (auxiliary gas consumption and leaks). UGS maps and collected statistical information used are from JSC "Gazprom;"
- ***for consumers***: projections of future gas demand for constituent entities of the Russian Federation, various industries, gas exporting countries, which are obtained by studying with the models of the energy sector of the Russian Federation, and the data from the General Plan for the development of the gas industry and other sectors of the economy.
- Let us consider an algorithm for scheme aggregation by using a conventional example of a gas system consisting of three territorial entities (for example, entities of the Russian Federation), including twenty



(a)



(b)

Fig. 1. Schemes of a conventional gas system: (a) detailed scheme of the gas system, C – consumer nodes; CS – compressor stations; S – source nodes; (b) aggregated gas system scheme, c – consumer nodes; s – source nodes; b – branching nodes.

consumer nodes (C1, C2, ..., C20) and eight fields (S1, S2, ..., S8), Fig. 1a.

1. Identification of adjacent nodes.

The proposed conventional scheme is an undirected graph.

Adjacent nodes are nodes connected to each other by one or more arcs. For example, CS10 is connected to C8, CS3, C11, C12, C10, and CS12 (6 adjacent nodes). Thus, the branching nodes in the presented scheme are CS3, CS7, CS8, CS9, CS10, CS12, C4, and CS11. In the aggregated scheme, for each entity, we take one main branching node, from which gas pipelines with the highest total throughput capacity (CS7, CS10, CS12) run.

We identify the branching nodes, i.e., the nodal components of the scheme (most often CS), with at least three adjacent nodes.

2. Identification of aggregated consumer nodes and branching nodes.

The aggregation of the detailed gas scheme in this case is proposed to the level of the constituent entities of the Russian Federation, which will act as consumer nodes.

In each entity, a node with the maximum demand is identified. If the entity has two or more nodes with the same maximum demand, then the node closest to the main branching node is selected.

In our example, the largest consumers are C1 – in entity 1, C14 – in entity 2, and C17 – in entity 3. We place the aggregated consumer nodes at the nearest branching nodes with which they are connected by the gas main: C14 ≡ CS3, C17 ≡ CS 7, C10 ≡ CS10, C1 ≡ CS12, and designate them as consumers on the aggregated scheme. In entity 2, the branching node CS10 does not coincide with the maximum consumer node C14 ≡ CS3. In this case, both nodes are marked on the aggregated scheme, one as a consumer node, the other as a branching node designated as b2. Such a node is necessary to correctly indicate the main gas flows on the scheme. The total demand of the entity is summed up to be the demand of the consumer node, and the demand of the branching node is assumed to be zero.

Each consumer (entity) is a collection of all consumer nodes included in it. Thus, the first consumer entity (c1) includes the demand of seven consumer nodes: C1, C2, ..., C7; c2 – (C8–C14), c3 – (C15–C20).

The nodes in the detailed scheme (Fig. 1a) are numbered in an end-to-end manner for clarity, while the nodes in the formulas proposed below to obtain the technical and economic characteristics of the aggregated scheme are numbered by entity.

The natural gas needs of an aggregated consumer are obtained from the condition of equality of needs for the original and aggregated schemes. In general, the need of the *j*-th entity Q_j^C and the total demand in the system Q_Σ^C are determined as follows:

$$Q_j^C = \sum_{i=1}^{I_j} Q_{ij}^C, \; j = \overline{1, J},$$

$$Q_\Sigma^C = \sum_{j=1}^{J} Q_j^C,$$

where *j* is a number of entity of the RF, $j = \overline{1, J}$, J is the number of entities; *i* is a number of consumer node of the initial scheme, which refers to the *j*-th entity; $i = \overline{1, I_j}$, I_j is the number of consumers in entity *j*.

3. Aggregation of source consumers with respect to gas production companies.

In the aggregated scheme, the source is a gas production company that can operate several fields located in one entity. The operation areas of GPCs in Fig. 1a are shown with hatching areas. We designate each GPC as an aggregated source node (s1, s2, s3) connected to the consumer node of the entity where the GPC is located. The production in the aggregated entity is the total production of the GPC fields. For convenience, the numbering of source nodes coincides with the numbering of entities. In this algorithm, the scheme is aggregated to the level of entities. If it is necessary to introduce a new gas field into the calculated scheme, and there is uncertainty to which source node it should refer to, it is important that the aggregated source node include sources from one entity. If it covers two or more entities, then the gas flows along the arcs of the aggregated scheme will be very different from the real-world ones.

$$Q_j^S = \sum_{k=1}^{K_j} Q_{kj}^S, \; j = \overline{1, J},$$

$$Q_\Sigma^S = \sum_{j=1}^{J} Q_j^S,$$

where *k* is a number of source node of the initial scheme, which refers to the *j*-th entity; $k = \overline{1, K_j}$, K_j is the number of sources in entity *j*.

4. Aggregation of main gas pipelines.

In the aggregated scheme, multi-line main gas pipelines are represented as single-line ones. The aggregated arc of the graph between two nodes is characterized by the total capacity of gas pipelines at the boundary between two entities and the length of all gas pipelines going from one node to another. For example, the throughput capacity of arc c1–c3 will be equal to the throughput capacity of section CS8–CS14, Fig. 1a. If a branching node is introduced in the entity in addition to the consumer node, then additional aggregated arcs are specified for the other entities. For example, the throughput capacity of the additional arc b2–c3 is equal to the throughput capacity of the section CS10–CS9.

Many methods exclude gas pipelines through which gas does not flow from one entity to another (such as CS12–C2, CS10–C8, etc.) when aggregating the scheme. As a result, the costs allocated to such gas pipelines may be lost. To prevent this, we distribute the unconsidered lengths along the arcs coming from the entity proportionally to the capacities of these arcs. Thus, the length of the aggregated

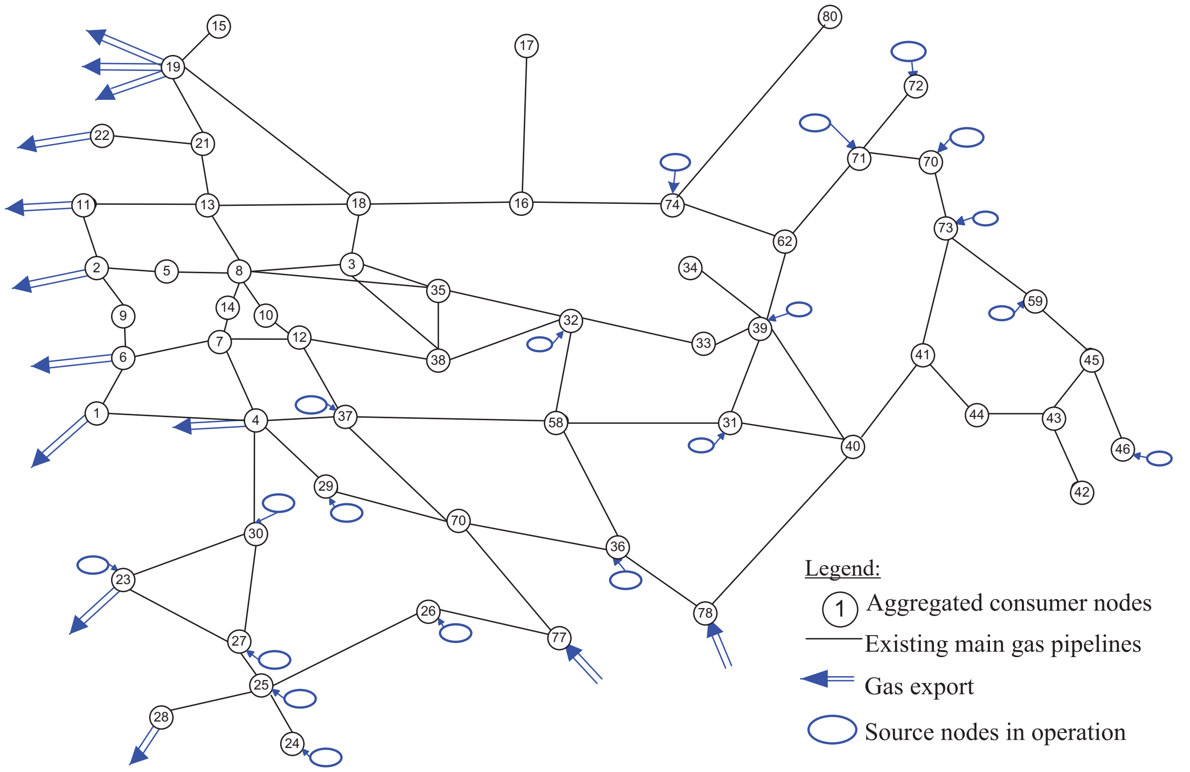


Fig. 2. Aggregated calculated scheme of the gas system of the Russian Federation.

arc, (1), is determined by summing the lengths of the gas pipelines running from the main consumer node of the original scheme of one entity to the consumer node of a neighboring entity or to a branching node, if it exists in the entity (term 1), and the lengths of all excluded gas pipelines located in the entity, including gas pipelines running from sources, in proportion to the throughput capacity of this arc (term 2):

$$L_{j-j'} = \sum_{m^B=1}^{M^B} \sum_{m=1}^{M} L_m \cdot n_m + L_j^{ex}, \qquad (1),$$

$$j \neq j';\ j = \overline{1,J};\ j' = \overline{1,J};\ n_m = \overline{1,N_m}$$

where j, j' are consumption or branching nodes of the aggregated scheme; $m^{\hat{A}} = \overline{1, M^B}$; M^B is the number of main gas pipeline branches at the boundary of the entities; $m = \overline{1, M}$; M is the number of sections between the compressor stations of the detailed scheme; L_m is the length of the m-th section; $n_m = \overline{1, N_m}$; N_m is the number of lines on the m-th section; L_j^{ex} is the lengths of unconsidered gas pipelines in entity j of the detailed scheme.

According to the above method, the scheme of each gas transmission company is aggregated.

5. Integration of aggregated schemes into one along the boundaries of the gas transmission company area.

The final step of building the calculated scheme is "gluing" all aggregated schemes into one (when considering the unified gas system). "Gluing" is performed along the boundaries of the operation areas of gas transmission companies. For example, a complex multi-line unified gas system is represented by an aggregated calculated scheme (Fig. 2).

6. Construction of a redundant scheme.

The existing large-scale projects of gas transmission systems under design or implementation are superimposed on the existing aggregated gas system scheme. Additionally, links corresponding to projects and scientific developments, carried out in research and design organizations, by year of planned periods, are placed on the calculated scheme. Thus, a redundant aggregated calculated scheme reflecting the stages of gas system expansion is provided for the time horizon under study (Fig. 3).

The proposed gas system scheme aggregation method is verified by a conventional example (Fig. 1). Calculations for various options (lack of gas at source nodes, bottlenecks along arcs, and others) indicate that, with the aggregation principles observed, the resulting calculated scheme clearly reflects gas flows among the entities.

Analysis of calculations for the detailed and aggregated schemes has shown that the gas needs of all consumers is 100% satisfied. In the detailed scheme, the reserve equal to 2.96 billion m^3/year remained only in field S8 (with the highest production price). In the aggregated scheme, there is a reserve of 2.98 billion m^3/year in S3, which includes S8 (calculation error was 0.7%). In the detailed scheme, the amount of gas transmitted from node 1 to node is 21.99 billion m^3/year, in the aggregated

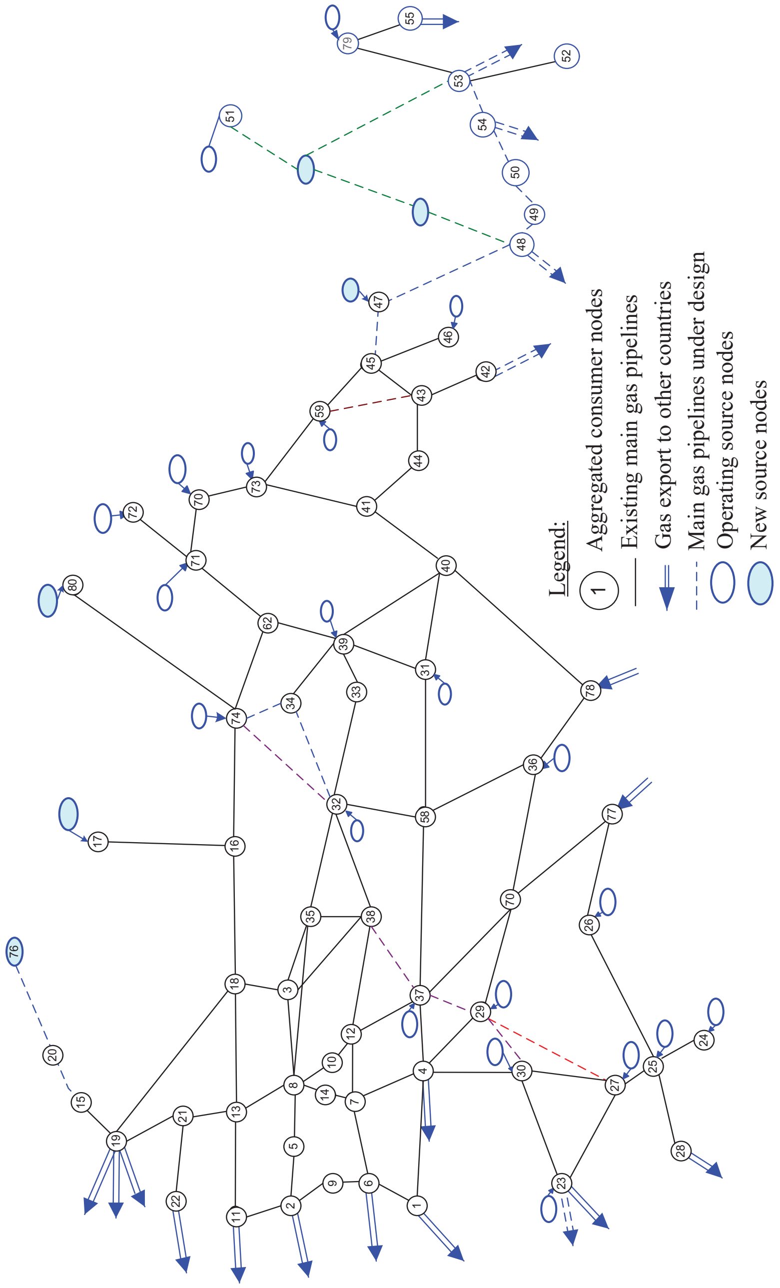
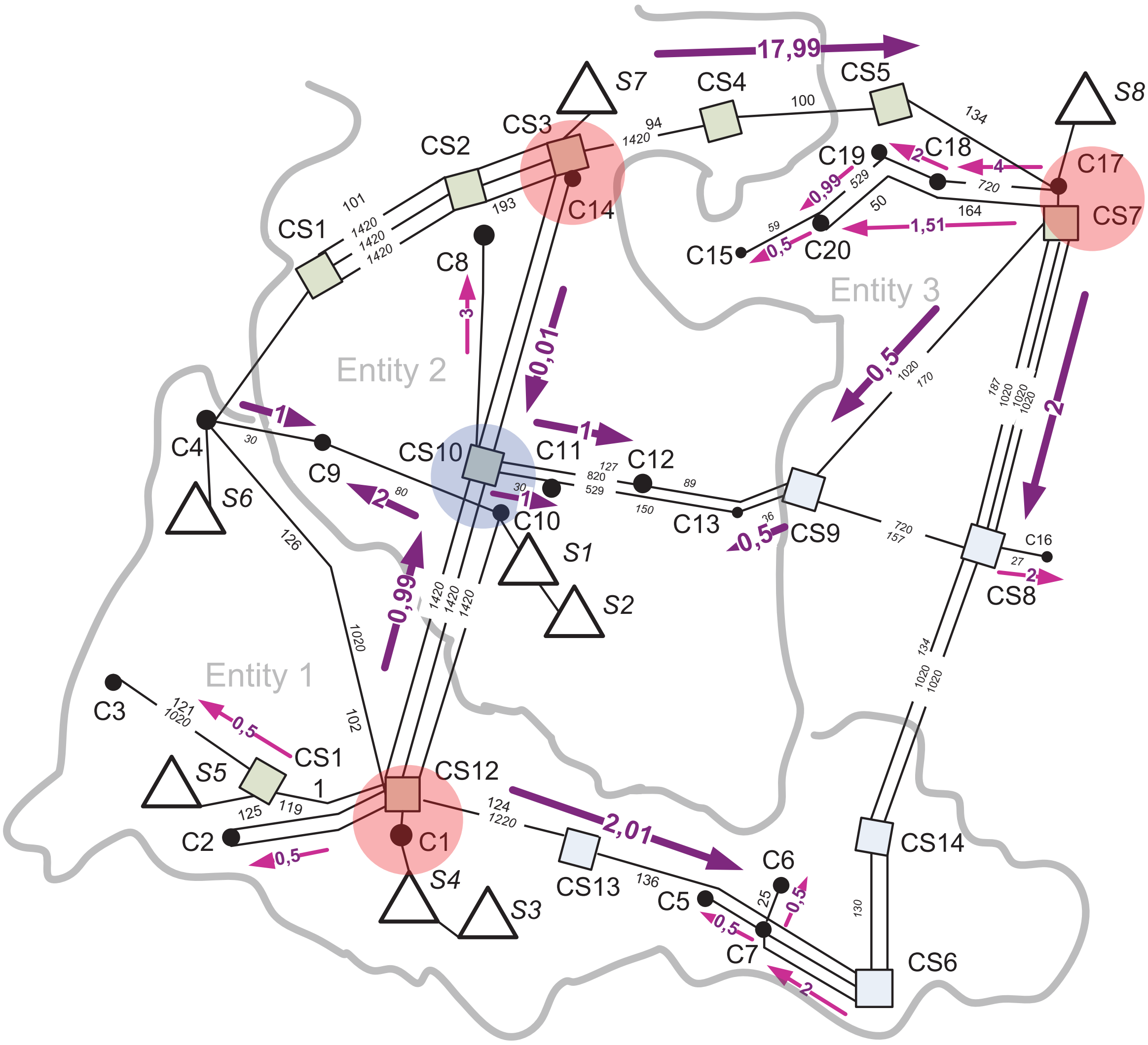


Fig. 3. Redundant aggregated calculated scheme of the gas system of the Russian Federation, 2030.



(a)

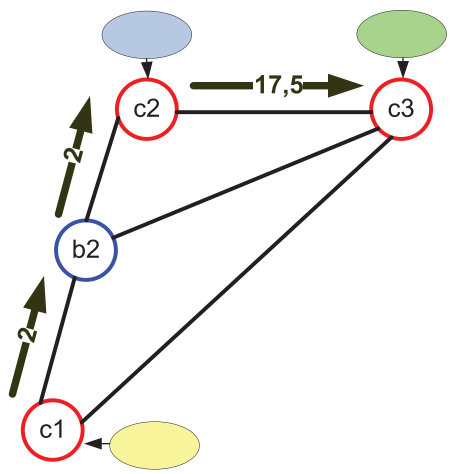


Fig. 4. Flow distribution in the detailed (a) and aggregated (b) schemes.

scheme – 2 billion m^3 / year (0.5%). In the detailed scheme, gas transmitted from node 2 to node 3 amounts to 17.99 – 0.5 = 17.49 billion m^3/year, in the aggregate scheme – 17.5 billion m^3/year (0.06%).

Thus, the maximum difference or calculation error between the calculated indicators, in particular, gas flows and production volumes of the detailed (Fig. 4a) and aggregated (Fig. 4b) schemes is about 1% (Fig. 4a, b) [18]. The difference comes from rounding off the data.

The proposed method was applied to create an information base for multi-level modeling of the gas system expansion in Russia until 2030; analyze the current state of the Russian gas industry with a focus on gas production, transportation and the demand for gas in different industries; aggregate the scheme of Russia's gas system (Fig. 3); identify the technical and economic characteristics of its facilities; and to investigate the prospects for the gas supply development in the constituent entities of the Russian Federation [1].

IV. Conclusion

1. The paper proposes a method for aggregating a real-world gas system, i.e., its representation by a simpler calculated scheme characterized by a smaller number of nodes and connections, which facilitates the analysis and use of the results to generate the necessary solutions. The aggregation approach is based on the consistent simplification of gas transmission and gas production companies and their integration into a single calculated scheme.
2. The proposed method for aggregating the scheme of the gas system factors in small fields, independent gas producers, and minor gas mains both among entities and within them.
3. The verification of the method presented in the paper has shown that the main characteristics (gas production and consumption volumes, wholesale prices) are in a fairly close and comparable range with actual indicators.
4. The research was carried out under State Assignment Project (no. FWEU-2021-0002) of the Fundamental Research Program of the Russian Federation for 2021-2030.

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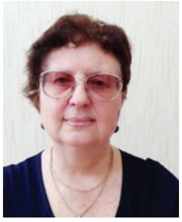

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Simulation and Optimization of Entrained-Flow Air-Steam Gasification of Brown Coals

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***Abstract* — A mathematical model was used to estimate the achievable efficiency of brown coals gasification in air-steam atmosphere. The optimal conditions for gasification were determined, the values of the cold gas efficiency and the produced gas composition were obtained. The dependence of the incompletely burned carbon yield on the conversion conditions was established. The results obtained can be used to evaluate the engineering and economic performance of thermal power plants with integrated gasification combined cycle (IGCC) fed by brown coals.**

***Index Terms*: gasification, brown coal, mathematical modelling, optimization.**

I. Introduction

Prospects for the use of coal in the energy sector are currently ambiguous. On the one hand, coal is considered as a «fuel of the past» (due to its high specific emissions), and the recent energy projections indicate its gradual replacement with more environmentally friendly fuels [1, 2]. On the other hand, despite the decline in the share of total energy consumption, the coal consumption is still huge. The advantages of coal as a fuel are large reserves and low cost. Reducing fuel costs will make it possible to use power equipment to improve the efficiency of energy production and purification of combustion products. In this case, coal may be more attractive than fossil hydrocarbons (especially under the current circumstances of political and economic turbulence).

Clean coal technologies traditionally include combustion technologies (low-temperature combustion, Rankine cycle with higher values of parameters) and gasification technologies (combined cycle, CO_2 capture). In this paper, we address the latter way to improve the efficiency of coal fuel use. Until now, coal gasification has been used mainly in chemical technology (primarily for the production of cheap hydrogen). There have been several major projects aimed at the energy application of coal gasification but most of them were closed or put on hold after government subsidies were used up (e.g., the Wabash River) or for economic or technological reasons (e.g., the Kemper power plant). Few of them are currently operating (e.g, Nakoso IGCC [3] and Taean IGCC [4] plants). The slow development of gasification-based energy technologies in the area of high-capacities is primarily due to competition with coal combustion technologies, for which average efficiency of power production has increased almost to the level of IGCC [5]. The specific capital costs for the construction of IGCC plants are high, and their reliability is lower than that of conventional plants [6]. The advantages of coal-fired IGCCs are their values of environmental metrics: low nitrogen and sulfur oxides emission, lower costs for CO_2 removal [7, 8], and the possibility of combining the production of energy and chemical products [9]. The increase in gasification capacities is mainly concerned with the chemical industry, where coal is a source of cheap hydrogen and synthesis gases.

The reserves of brown coals exceed those of black coals but the thermochemical conversion of brown coals is, as a rule, more complicated from the technological standpoint. This is due to the lower calorific value of brown coal (low carbon content and higher moisture content) and the peculiarities of the physicochemical transformations of the organic and mineral parts under high-temperature conditions. The process of brown coal gasification discussed in this work is not considered from the point of view of the transformation of the mineral part (slagging and fly ash formation). The aim of the work is to assess the energy characteristics of the gasification process, which are determined by the composition of the organic part and moisture content.

For a reliable evaluation of the engineering and economic performance of IGGC plants, a method for calculating the characteristics of the gasification process is needed. The cold gas efficiency largely determines the

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thermal efficiency of the plant as a whole, as well as the choice of equipment for gas treatment and cooling. In some cases, experimental data are available [10]. However, that is not the case for new processes which have not been used in industry. In this regard, mathematical models of different levels of detail are also employed: from semi-empirical schemes and equilibrium approximations [11, 12] to complex multidimensional thermohydrodynamic codes [13]. When choosing the level of detail, first of all, it is necessary to take into account the application of simulation results: the optimization of the flow and heat transfer features requires the use of computational fluid dynamics models but the optimization of the gasifier operation modes as part of a power plant inevitably leads to the use of the simplest (empirical and thermodynamic) models.

In this work we study the single-stage process of pulverized coal gasification in air-steam mixtures numerically. To this end, a one-dimensional stationary fuel conversion process model is used. Despite simplifications and assumptions made, this model allows one to obtain more reliable estimates of the gasification process efficiency than the widely used chemical equilibrium models, while achieving it at a much lower computational cost than detailed thermohydrodynamic models. The proposed model can be used for a full-fledged engineering and economic optimization of the gasifier operation modes as part of an IGCC plant.

II. Mathematical Model and Input Parameters

A detailed description of the mathematical model and the results of its partial validation can be found in [14, 15]. The model was used earlier in the computational optimization of the parameters of entrained-flow gasification of various fuels with various gasifying agents [16, 17].

$$Uc_p \frac{d\left(m_p T_p\right)}{dz} = \alpha S_p\left(T_g - T_p\right) + \varepsilon\sigma S_p\left(T_w^4 - T_p^4\right) + \sum_j Q_j r_j \,. \qquad (1)$$

Eq. (1) includes the spatial coordinate z (reaction zone length), m; particles velocity U, m/s; particle mass m_p, kg; particle temperature T_p, K; particle heat capacity c_p, J/(kg·K); heat transfer coefficient α, W/(m^2·K); particle surface S_p, m^2; particle emissivity ε; Stefan-Boltzmann constant σ, W/(m^2·K^4); gas temperature T_g, K; wall temperature T_w, K; physicochemical processes rates r_j, kg/s (drying, pyrolysis, heterogeneous reactions); their thermal effects Q_j, J/kg.

Drying rate r_{dr} depends on the temperature range:

$$r_{dr} = \begin{cases} \dfrac{\beta S_p M_{H_2O}}{R_g T}\left(P_{H_2O}^{eq} - P_{H_2O}\right), \; T_p \le T_b, \\ \dfrac{\alpha S_p\left(T_g - T_p\right) + \varepsilon\sigma S_p\left(T_w^4 - T_p^4\right)}{\left|Q_{dr}\right|}, T_p > T_b. \end{cases} \qquad (2)$$

Here T_b is water boiling point, K; β is mass transfer coefficient, m/s; P_{H_2O} is partial water vapors pressure, Pa; R_g is gas constant, J/(mol·K).

Pyrolysis rate r_{pyr} depends on the temperature in Arrhenius law:

$$r_{pyr} = k_{pyr} \exp\left(-\frac{E_{pyr}}{R_g T_p}\right) m_V \,. \qquad (3)$$

Here k_{pyr} is a preexponential factor, 1/s; E_{pyr} is activation energy, J/mol; m_V is volatile matter content in particle, kg.

The heterogeneous reactions rate is determined by the diffusional kinetics equation:

$$r_g = \frac{S_p C_g}{\dfrac{1}{k_g e^{-\frac{E_g}{R_g T}}} + \dfrac{d_p}{Nu_D D_g}} \,. \qquad (4)$$

Here C_g is gasification agent concentration (O_2, CO_2, H_2O); k_g is a preexponential factor, m/s; E_g is activation energy, J/mol; Nu_D is diffusional Nusselt number; D_g is diffusivity, m^2/s; d_p is average particle diameter, m. Reaction heat Q_j was calculated from thermochemical data [18]. Arrhenius parameters of heterogeneous reactions were estimated using correlations proposed in [19]. The particle velocity is considered equal to the gas velocity as determined by the continuity equation. The gas composition in each section is at equilibrium given a fixed degree of fuel conversion (i.e., the equilibrium problem is solved for the gas phase). An iterative scheme is used to search for a stationary solution: the fuel conversion rate is calculated using a system of ordinary differential equations for changing the mass of particles at a given temperature distribution; using the thermodynamic model, the heat release and the composition of the gas phase in each calculation element are calculated; then the stationary problem of heat transfer is solved under fixed heat sources. The iterations are completed when the temperature distribution ceases to change perceptibly.

The gas phase equilibrium problem is as follows [20]: find

$$\mathbf{n}^{eq} = \operatorname{argmin} G(\mathbf{n},T)$$

subject to constraints:

$$G(\mathbf{n},T) = \sum_{j=1}^{N_g} n_j^g \left(\mu_j^g(T) + R_g T \ln \frac{n_j^g}{\sigma^g}\right) + \sum_{k=1}^{N_c} n_j^c \mu_j^c(T),$$

$$\mathbf{A}(\mathbf{n} - \mathbf{n}^{in}) = 0,$$

$$\mathbf{n} \ge 0.$$

Here G is Gibbs free energy, J/K; $\mathbf{n}$ is composition vector, mol ($\mathbf{n}^{in}$ is a vector of initial composition, $\mathbf{n}^{eq}$ is equilibrium composition), indices g and c correspond to gaseous and condensed phases; μ_j is the chemical potential of j-th component, J/mol; σ^g is gas phase molar sum, mol; $\mathbf{A}$ is element balance matrix. The enthalpy of coals is determined through the calorific value and enthalpies of combustion products. Properties of coal matter are modelled by pure carbon. The solution to the equilibrium problem in this form exists and is unique, which follows from the convexity of the thermodynamic functions for such systems [21, 22].

Table 1. Characteristics of coals.

	Berezosvky	Mugunsky	Urtuysky
C^{daf}, %	70.95	73.72	76.01
H^{daf}, %	4.98	5.61	4.86
O^{daf}, %	23.11	17.63	17.83
N^{daf}, %	0.64	1.44	0.81
S^{daf}, %	0.32	1.44	0.49
W^r, %	33	22	29.5
V^{daf}, %	48.0	56.4	39.1
A^d, %	7.0	20.0	8.8
HHV, MJ/kg	16.01	16.84	17.81
m_{air}, kg/kg	5.59	6.12	6.27

The composition of the coals used in the calculations is given in the table (data originate from the handbook [23]). These three coals are quite similar in composition: Mugunsky coal contains 2–3 times more ash and less moisture; Urtuysky coal contains more carbon in the organic mass and therefore has a higher calorific value. The stoichiometric amount of air required for complete combustion varies for the coals in the range of 5.5–6.3 kg/kg. The moisture content of coals is 22–33%, which does not quite correspond to the fuel milling and transport conditions (moisture content of pulverized coal can hardly exceed 10%): we use this assumption to simplify the calculations and partially take into account the costs of drying.

Calculations are carried out for a cylindrical reactor with a diameter of 3 m and a length of 9 m. The operating pressure is about 15 atm. The fuel consumption is about 50 kg/s. The average particle size is 0.1 mm. The gasification agent is a mixture of air and water vapor (initial temperature is 655 K). Variable parameters are specific air consumption (1–6 kg/kg of fuel), specific steam consumption (0–0.1 kg/kg of fuel), and fuel load (from 80 to 120% of the nominal flow rate). The characteristics of the gasification process are the temperature and composition of the produced gas, the incompletely burned carbonyield and the cold gas efficiency, which is equal to the ratio of the heating values of the produced gas and raw fuel:

$$\eta = \frac{q_{CO}n_{CO} + q_{H_2}n_{H_2} + q_{CH_4}n_{CH_4}}{Q_f}100\%.$$

Here Q_f is coal heating value, q_j is heating value of j-th gaseous component, n_j is the yield of j-th component, kg/kg$_{\text{fuel}}$. Produced gas heating value is calculated based on the main combustible components: CO, H_2 и CH_4. Cold gas efficiency is usually a function of stoichiometric parameters and temperature. In the present paper, we study the effect of fuel composition and air/fuel ratio.

III. Calculations Results and Discussion

A typical dependence of the produced gas composition on the air/fuel ratio is shown in fig. 1a. In the range of air-fuel ratios up to 2.5 kg/kg, the fraction of combustible components (CO and H_2) increases and the concentration of gasification agents (CO_2 and H_2O) decreases. Fig. 1b shows the corresponding growth of cold gas efficiency (Fig. 1b). With a further increase in the air/fuel ratio, combustible components are oxidized, and the cold gas efficiency decreases. In qualitative terms, this dependence is the same for all coals (Fig. 2), with slight deviations, which are explained away by the differences in the chemical and proximate composition. The curve shown in Fig. 1b has its extremum, approximately at the same level for all selected coals (corresponding cold gas efficiency is 67–69%). Unreacted oxygen appears in the reaction products below the stoichiometric air/fuel ratio. This is because an increase in air-fuel ratio (given a constant reaction zone length) reduces the dwell time of fuel particles in the reactor. At an air/fuel ratio of about 5 kg/kg, a significant incompletely burned carbon yield and a sharp temperature decrease are observed (Fig. 3). Interestingly, the maximum cold gas efficiency and the minimum incompletely burned carbon yield do not coincide: for a more complete conversion of the fuel, a small excess of air above the optimum is required. Commonly used thermodynamic models tend to make these extrema equal.

The fuel load slightly affects the per-unit indicators. Figure 4 shows the dependencies of the main combustible components yield (CO and H_2) in absolute units (mass flow rates) and below – in relative units (per-unit mass of the fuel from which they were obtained). Fuel consumption fluctuates within the 20% range, either above or below. As can be seen, the dependencies of the specific yields of the components practically coincide, at least in the region most interesting from a practical point of view (near the efficiency maxima).

Calculations were carried out to assess the effect of the fuel load and steam-fuel ratio on gasification efficiency. As expected, an increase in the steam-fuel ratio leads to a decrease in the incompletely burned carbon yield and a slight decrease in cold gas efficiency. Note that gasification reactions also involve moisture evaporating from the fuel and forming during the oxidation of volatile substances. An increase in fuel consumption leads to both an increase in incompletely burned carbon and a decrease in cold gas efficiency by 2–3 percentage points (Fig. 5).

Thermodynamic models of gasification processes usually underestimate the final equilibrium temperature, which is due to an overestimation of the fuel conversion [20]. Long dwell times are needed to achieve final equilibrium at temperatures below 900–1000°C. Therefore, in practice, the gasification reactions occur, as a rule, above the thermodynamically optimal temperature. The model used in this work takes into account the kinetic features of heterogeneous reactions; therefore, the estimates obtained with its help will be more realistic than the equilibrium approximation. The heating value of brown coal, as can be seen in Table 1, is 16–18 MJ/kg. Therefore, to maintain

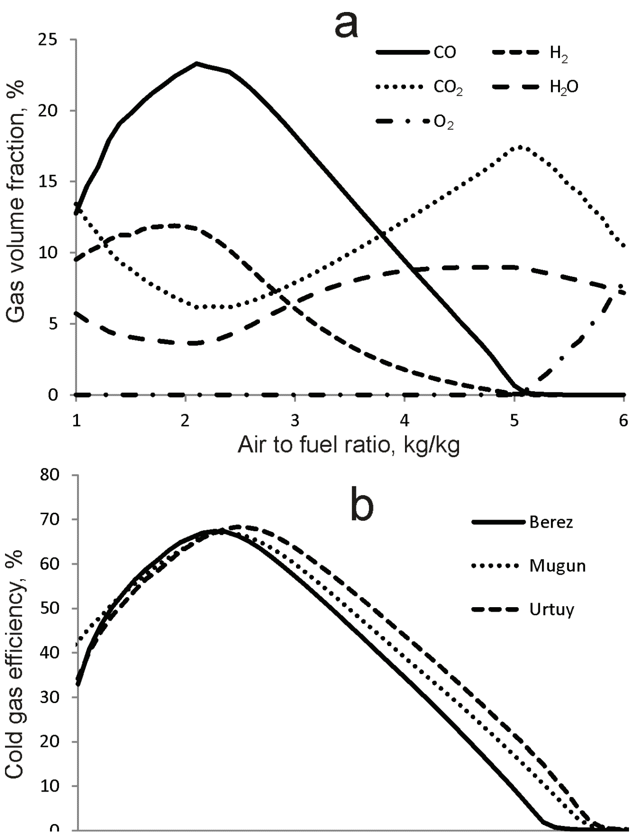

Fig. 1. (a) Dependence of the produced gas composition on the air-fuel ratio (Berezovsky coal, steam-fuel ratio 0.05 kg/kg); (b) Dependence of the cold gas efficiency on the air-fuel ratio and coal composition.

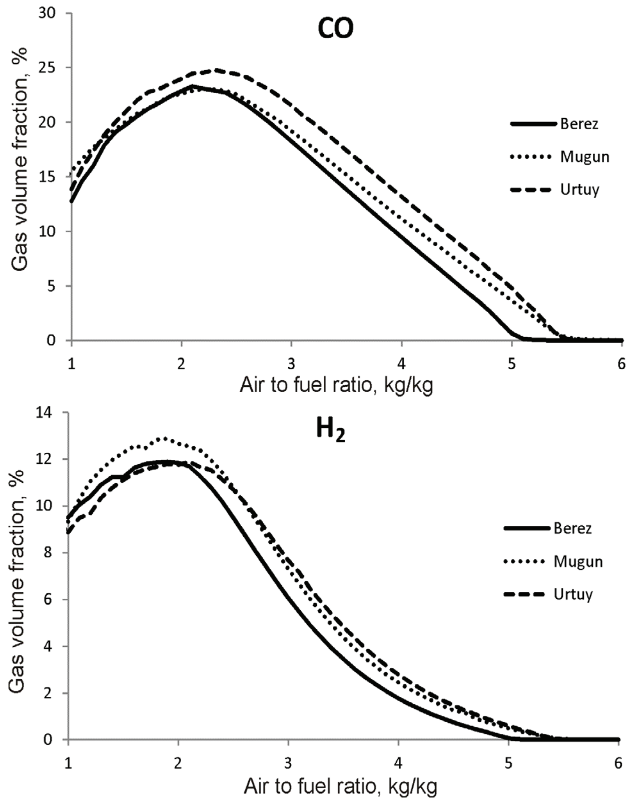

Fig. 2. Dependence of the volume fraction of CO and H_2 in produced gas on the air-fuel ratio and coal composition (steam-fuel ratio 0.05 kg/kg).

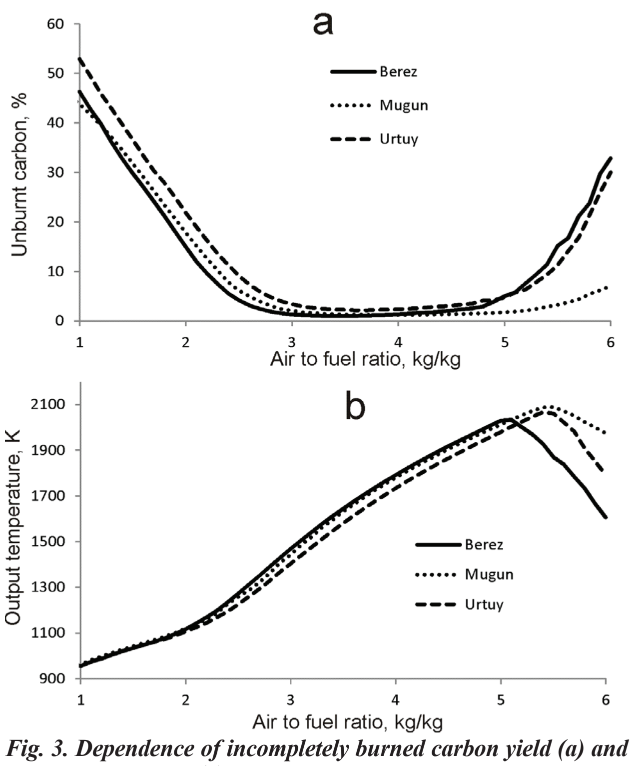

Fig. 3. Dependence of incompletely burned carbon yield (a) and output temperature (b) on the air-fuel ratio and coal composition (steam-fuel ratio 0.05 kg/kg).

a stable process, it is necessary to spend about 25% of this heating value to achieve a temperature at which gasification reactions will proceed at a sufficient rate. These losses along with incompletely burned carbon lead to low cold gas efficiency (60–70%). They can be reduced, for example, by heating the air [24].

As mentioned above, the relationship between the cold gas efficiency and the fuel conversion degree is, in general, non-monotonic. Figure 7 shows the calculated dependencies: the air-fuel ratio there increases from right to left. It can be seen that the higher values of the cold gas efficiency correspond to a rather high level of incompletely burned carbon yield. To reduce incomplete combustion to an acceptable level, it is necessary to increase the air-fuel ratio, reducing the cold gas efficiency. Similar problems in choosing the parameters of the gasification process were considered earlier, for example, in [16], where an increase in temperature was required to ensure conditions for liquid ash removal.

Gasification of Urtuysky coal has the highest cold gas efficiency due to its higher heating value. It is followed by Berezovsky coal and, finally, Mugunsky coal. The last two coal blends, however, differ little, and given the assumptions made, the characteristics of their gasification can be considered almost identical.

In total, 300 regimes were obtained for each coal

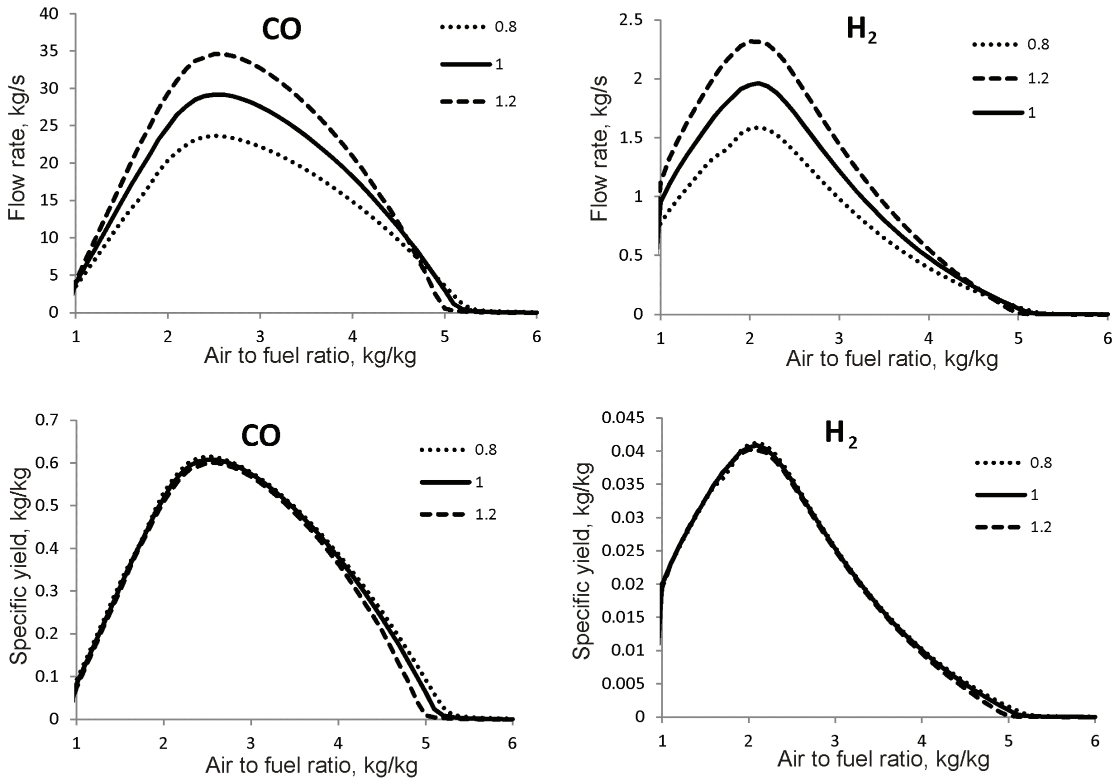

Fig. 4. Dependence of the output flow rates and specific yields of the main combustible gases on the air-fuel ratio and coal composition.

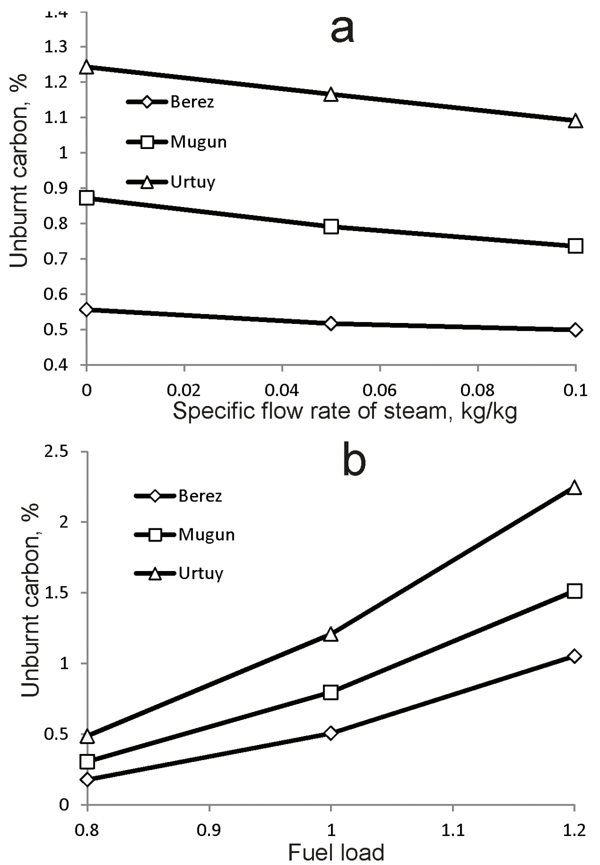

Fig. 5. Dependence of the minimum incompletely burned carbon yield on the steam-fuel ratio (a) and fuel load (b).

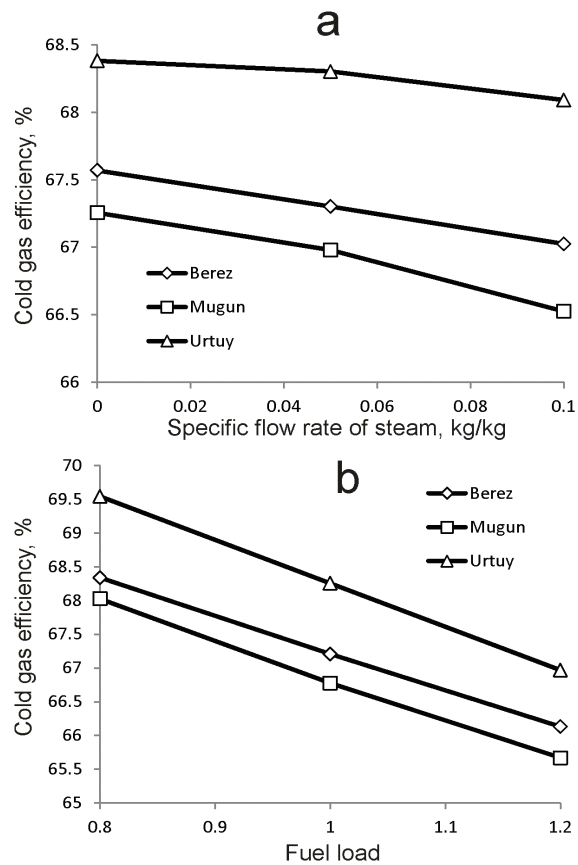

Fig. 6. Dependence of the maximum cold gas efficiency on the steam-fuel ratio (a) and fuel load (b).

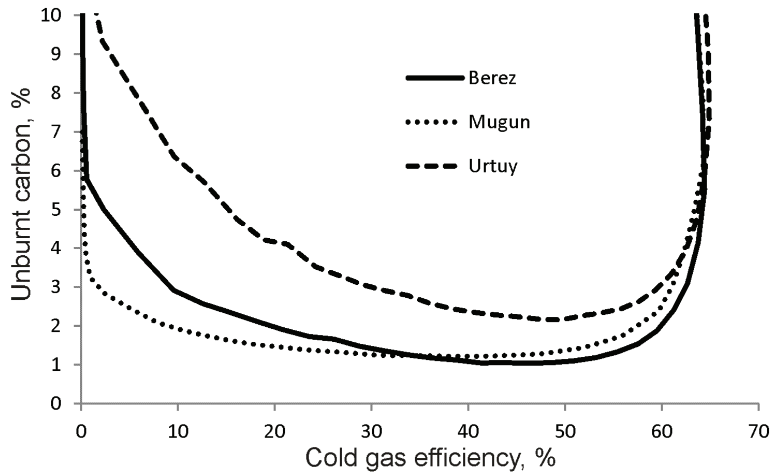

Fig. 7. Relationship between the incompletely burned carbon yield and the cold gas efficiency for different coals.

composition with varying fuel, air and steam flow rates. The results of calculations presented in the form of tables can be used to optimize parameters of power and chemical plants with brown coal gasification. In this case, numerical tables can be used to evaluate the characteristics of the gasification process with a discrete range variables but estimates show that interpolation between nodes allows one to transition to continuous variables.

In future studies, it will be possible to further reduce the computational costs in several ways: (1) to narrow down the intervals for air-fuel ratios; (2) to sparse the grid of parameters in areas where the change in efficiency and product yield is sufficiently close to linear; (3) to use the dependence of the incompletely burned carbon yield on temperature as a constraint in the thermodynamic model.

Conclusion

The paper presents the findings of a computational study of entrained-flow air-blown gasification process characteristics for different brown coals. Constraints imposed on the process efficiency that are due to the reactivity and fuel heating value are shown. The maximum values of the cold efficiency for the selected coals reach 66–68%. However, to achieve sufficiently deep fuel conversion, it is necessary to increase the air-fuel ratio and to reduce cold gas efficiency. The results of the calculations will be used to conduct optimization studies of combined-cycle plants with integrated gasification of brown coals.

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Integrated Methanol and Power Production Based On the Coal of the Tavan Tolgoi Coalfield

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***Abstract* — Mongolia has significant resources of high-quality coals. Because of the coalfired TPP at the Tavan Tolgoi coalfield currently being designed, of greatest interest is the coal of the fourth seam of the Tavan Tolgoi coalfield with recoverable reserves of 6,500 million tons. The TPP is expected to offset the power shortage in the southern region of Mongolia as well as Tavan Tolgoi itself and the nearby Oyu Tolgoi mine. In light of the environmental requirements of today, new coal-fired power plants must be environmentally friendly and, if possible, produce additional marketable products along with electricity. For Mongolia, which imports all its liquid motor fuel, this could be methanol, which serves as a fuel for vehicles and the energy industry. This article investigates the issues involved in studying the competitiveness of the integrated production of methanol and electricity based on the coal of the Tavan Tolgoi coalfield in Mongolia.**

***Index Terms*: co-generation, mathematical modeling, methanol, power generation.**

I. Introduction

Mongolia has significant resources of high-quality coals. Of most interest is the coal of the fourth seam of the Tavan Tolgoi coalfield that has recoverable reserves of 6 500 million tons. In terms of strategic importance, the Tavan Tolgoi coalfield is of great importance to the Mongolian economy, both for exports and for the creation and development of the coal processing industry and processing by coal chemical means.

There are plans to build a new coal-fired thermal power plant at the Tavan Tolgoi coalfield, which should offset the power shortage in the southern district and Tavan Tolgoi itself and the nearby Oyu Tolgoi mine [9]. In light of the environmental requirements of today, new coal-fired thermal power plants must be environmentally friendly and, if possible, produce on-spec fuels with high added value along with electricity. For Mongolia, which is a net importer of liquid motor fuel, this could be methanol, which is a fuel for the energy industry serving the transport sector and the generation of heat and electricity This article investigates the issues involved in studying the competitiveness of the integrated production of methanol and electricity based on the coal of the Tavan Tolgoi coalfield in Mongolia.

The conventional technology of methanol production from fossil fuels consists of two main steps: production of synthesis gas and synthesis of methanol from this gas. Both stages are characterized by the release of large amounts of heat, which is usually used to produce medium-pressure steam that is sent to the turbines that drive the compressors of the plant, as well as for the needs of other production facilities. This method of heat utilization is accompanied by significant losses during the operation. The combination of two processes – methanol synthesis and electricity generation at a single plant (combined-cycle gas turbine with integrated coal gasification and methanol synthesis, hereinafter referred to as CGMS-CCGT) – is a more efficient way to utilize the heat of gasification, as well as thermal and chemical energy of purge gases in the synthesis process. This combination improves energy efficiency, reduces investment by integrating the functions of some of the equipment, and streamlines the plant process flow diagram by eliminating the return flow of synthesis gas.

CGMS-CCGTs are characterized by high complexity of process flow diagrams, a variety of physical and chemical processes occurring in their components, as well as virtually no significant experience designing them. Mathematical modeling and modeled feasibility studies are the main way to study such plants.

A great deal of attention in the world is paid to research on technologies for converting fossil fuels into synthetic fuels [1, 2, 7]. The above studies have significant

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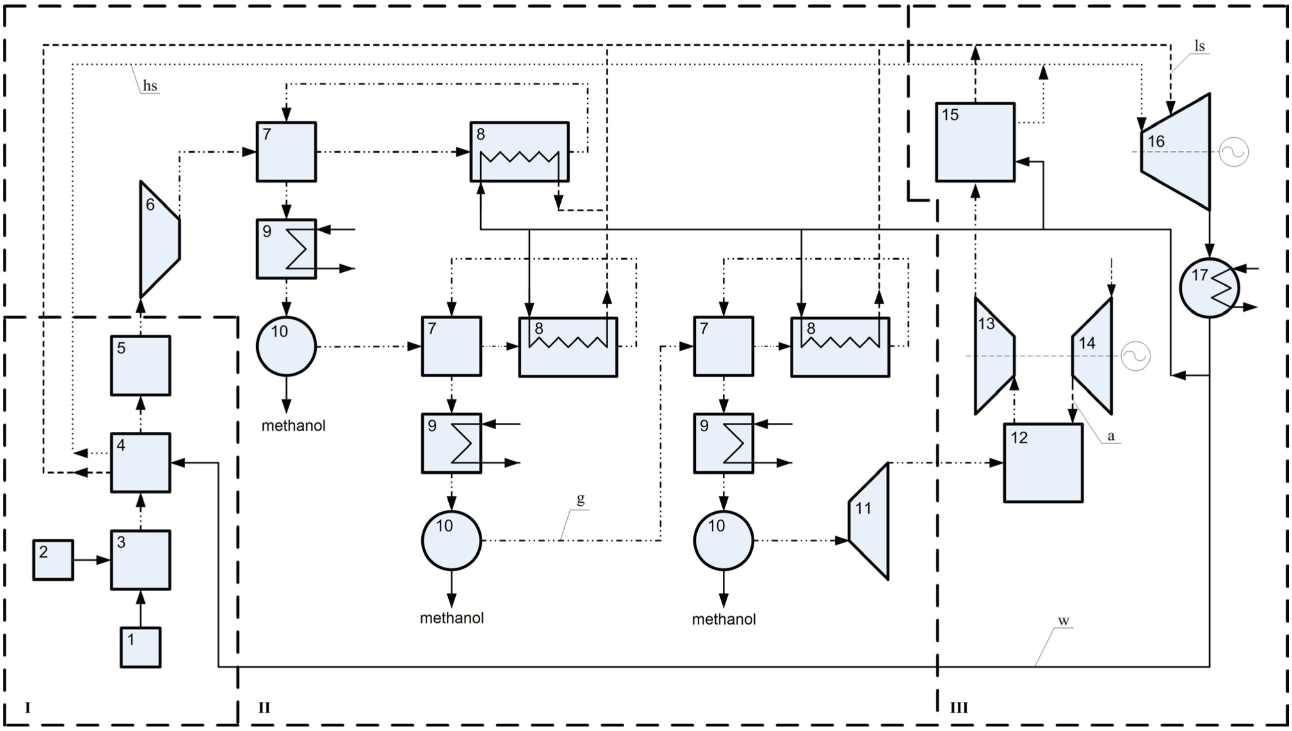

Fig. 1. CGMS-CCGT process flow diagram; g – gas, a – air, w – water, ls – low pressure steam, hs – high pressure steam; I – gasification unit, II – methanol synthesis unit, III – power unit; 1 – fuel preparation and supply system, 2 – oxygen generation system, 3 – gasifier, 4 – cooling system of gasification products, 5 – gasification product treatment system, 6 – synthesis gas compressor, 7 – regenerative gas-gas heat exchanger, 8 – methanol synthesis reactors, 9 – condenser, 10 – methanol separator, 11 – expansion turbine, 12 – gas turbine combustion chamber, 13 – gas turbine, 14 – air compressor, 15 – heat recovery steam generator, 16 – steam turbine, 17 – steam turbine condenser.

differences, for ex-ample, in the layout of process flow diagrams, use of feedstock, conditions of plant operation, and methods for determining efficiency. This study is based on the methodology of systems re-search of complex fuel co-production power generation systems, based on comprehensive optimization studies backed by detailed mathematical models of the plant and its constituent elements.

II. A Methodological Approach to Cgms-Ccgt Studies

The process flow diagram of the CGMS-CCGT was developed on the basis of state-of-the-art technologies. The process of fuel gasification is carried out in the reaction chamber of the gasifier in a fluidized bed at a pressure of 2 MPa. The optimal process flow diagram of methanol synthesis, with once-through synthesis reactors and intermediate cooling of synthesis products in heat exchangers by low-pressure steam was selected as a result of preliminary studies of various process solutions: with an isothermal reactor, with a primary synthesis reactor, with cooling of synthesis products by fresh synthesis gas, etc. The power generation unit provides for integrated gas-steam cycle, which is deemed the most promising for power plants (Fig. 1).

The CGMS-CCGT under consideration is a hybrid engineering system that includes both process and power generation components of equipment with a complex layout of heterogeneous process links. The main way to study such plants is mathematical modeling and modeled numerical experiments. The models were developed using the SMPP software package developed at the Melentiev Energy Systems Institute, SB RAS [3]. This software package, based on information about the mathematical models of the individual elements of the units, the process links between them, and the purpose of calculation automatically generates a mathematical model of the unit in the form of a calculation program in the Fortran programming language.

The mathematical model of the gasification unit includes models of reaction chambers of gasifiers, freeboard, convective gas-water heat exchangers, and synthesis gas treatment system. The mathematical model of the methanol synthesis unit includes models of synthesis-gas compressors, catalytic reactor, regenerative gas-gas heat exchangers, and condensers. The mathematical model of the power unit includes models of the expansion and gas turbines, air compressor, purge gas combustion chamber, steam turbine compartments, steam turbine condenser, extraction stage heater, and heat recovery steam generator. The mathematical model of the CGMS-CCGT as a whole contains more than 2 000 parameters and hundreds of algebraic and transcendental equations. When developing mathematical models, various methods of mathematical

Table 1. Characteristics of the coal of the Tavan Tolgoi coalfield.

No.	Proximate analysis		Result	Limit value
1	Moisture content W^r, %		10.5	4–17
2	Ash yield A^r, %		24.8	10–33
3	Volatile matter V^r, %		25.1	18–30
4	Sulphur S^r_{total}, %			0.6–1.0
	Ultimate analysis			
1	Carbon C^{daf}, %		85.9	84–87
2	Hydrogen, %		5.15	2.0–6.7
3	Nitrogen, %		1.97	1.7–2.3
4	Sulphur, %		0.96	0.8–1.4
5	Oxygen, %		6	4.5–7.6
6	Chlorine, %		0.02	0.01–0.03
7	Calorific value Q^r_H	kcal/kg		5 000–6 300
8		MJ/kg	22.6	18.5–26.0
	Temperature points, ^0C			
1	Initial deformation temperature		1.08	1 050–1 600
2	Softening temperature	Sphere	1.11	1 100–1 600
3		Hemisphere	1.2	1 300–1 600
4	Flow temperature		1.35	1 300–1 600

programming were used [1, 3, 5, 6].

On the basis of the mathematical model of the CGMS-CCGT such engineering and economic performance metrics as the amount of methanol and electricity produced (at a given consumption of coal), plant efficiency, the mass of the catalyst for the synthesis, the area of heating surfaces of heat exchangers, capital expenditures, operating costs, etc. are determined.

In order to find the optimal options of the CGMS-CCGT structure it is necessary to solve the problems of non-linear programming, the purpose of which is to calculate the parameters of the plant so as to provide the minimum cost of methanol at a given internal rate of return, fuel and electricity price, while taking into account the physical and engineering constraints.

Mathematical problem statement

$$\min C_m(x,y,B,K,M,E,C_e,C_f,IRR_z)$$

subject to the following conditions

$$H(x,y) = 0,$$

$$G(x,y) \geq 0,$$

$$x_{min} \leq x \leq x_{max},$$

where C_m is the price of methanol, x is the vector of parameters to be optimized, B is the annual fuel consumption, K is capital expenditures of the CGMS-CCGT, M is the annual methanol production, E is the annual electricity production, C_e is the electricity price, C_f is the coal price, IRR_z is the internal rate of return, H is the vector of equation constraints, G is the vector of inequality constraints, x_{min}, x_{max} are vectors of boundary values of the parameters to be optimized.

III. Engineering and Economic Optimization of CGMS-CCGT Parameters

The purpose of research conducted with the aid of mathematical models of the CGMS-CCGT is to determine the optimal parameters of the plant and the sensitivity of its economic performance to changes in external conditions. This is required to assess the prospects for large-scale application of this method of processing the coal of the Tavan Tolgoi coalfield.

The ratio between methanol synthesis and electricity generation has the greatest effect on the engineering and economic performance of the plant. The main parameters affecting this ratio are the composition of the blast into the gasifier, which determines the composition of the synthesis gas, and the number of reactors in parallel in the stages of the synthesis unit, which determines the degree of conversion of the synthesis gas into methanol. Note that the amount of oxygen for gasification was determined assuming that the required gasification temperature for a given steam flow rate is ensured. In this paper, we consider different options of the CGMS-CCGT with different values of the above parameters.

The main input data, which were taken for the analysis of the CGMS-CCGT process flow diagram and calculation of its engineering and economic performance metrics, were assumed on the basis of cost estimates of CCGTs and chemical plants for methanol synthesis, taking into account the uncertainty of capital expenditures [9].

Table 1 shows the characteristics and composition of

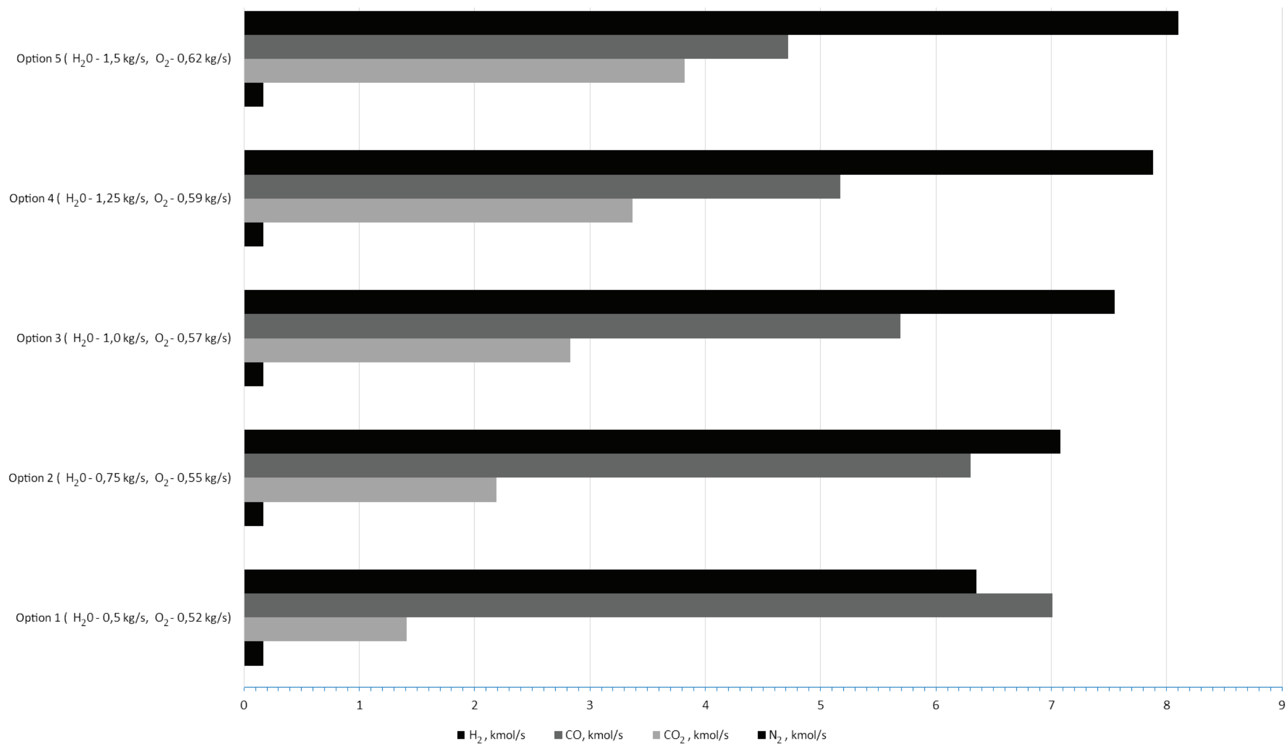

Fig. 2. Compositions of synthesis gas for each CGMS-CCGT option.

Table 2. Optimal values of engineering and economic performance metrics of the fuel co-production power generation system.

Metric	Option 1	Option 2	Option 3	Option 4	Option 5
Annual consumption of oil equivalent, thousand t.c.e.			3 500		
Methanol synthesis catalyst consumption, tons/year	450 441.5	392 435.2	338 558.0	302 170.7	280 904.0
Capacity, MW:					
air compressor	399.6	314.0	261.8	226.5	237.1
oxygen compressor	37.6	39.4	41.0	44.2	42.5
synthesis gas compressor	61.2	61.2	60.6	58.8	59.8
Gas turbine capacity, MW	681.5	541.0	455.6	397.3	415.1
Steam turbine capacity, MW	362.1	357.2	360.4	385.5	370.7
Expansion turbine capacity, MW	16.4	13.7	12.2	11.1	11.4
Net capacity, MW	408.9	340.2	303.3	293.3	291.6
Auxiliary capacity, MW	651.1	571.8	524.9	500.7	505.7
Annual electricity generation, mln. kWh	2 862.4	2 381.1	2 123.1	2 051.1	2 042.8
Annual methanol production, thousand tons (thousand t.c.e.)	1 709.3 (1 231.9)	1 878.5 (1 353.8)	1 947.9 (1 403.9)	1 951.1 (1 406.2)	1 920.9 (1 384.4)
Capital expenditures of the plant, thous. US dollars.	1 404.82	1 344.13	1 320.09	1 339.65	1 341.35
inclusive of the following:					
gasification unit	439.91	454.72	467.80	480.55	494.06
synthesis unit	479.87	458.61	452.03	472.04	461.63
power unit	485.05	430.80	400.26	387.06	385.66
Thermal efficiency, %	0.620	0.650	0.657	0.653	0.644
Methanol price, US doll. /t.c.e.	416	377	368	375	382

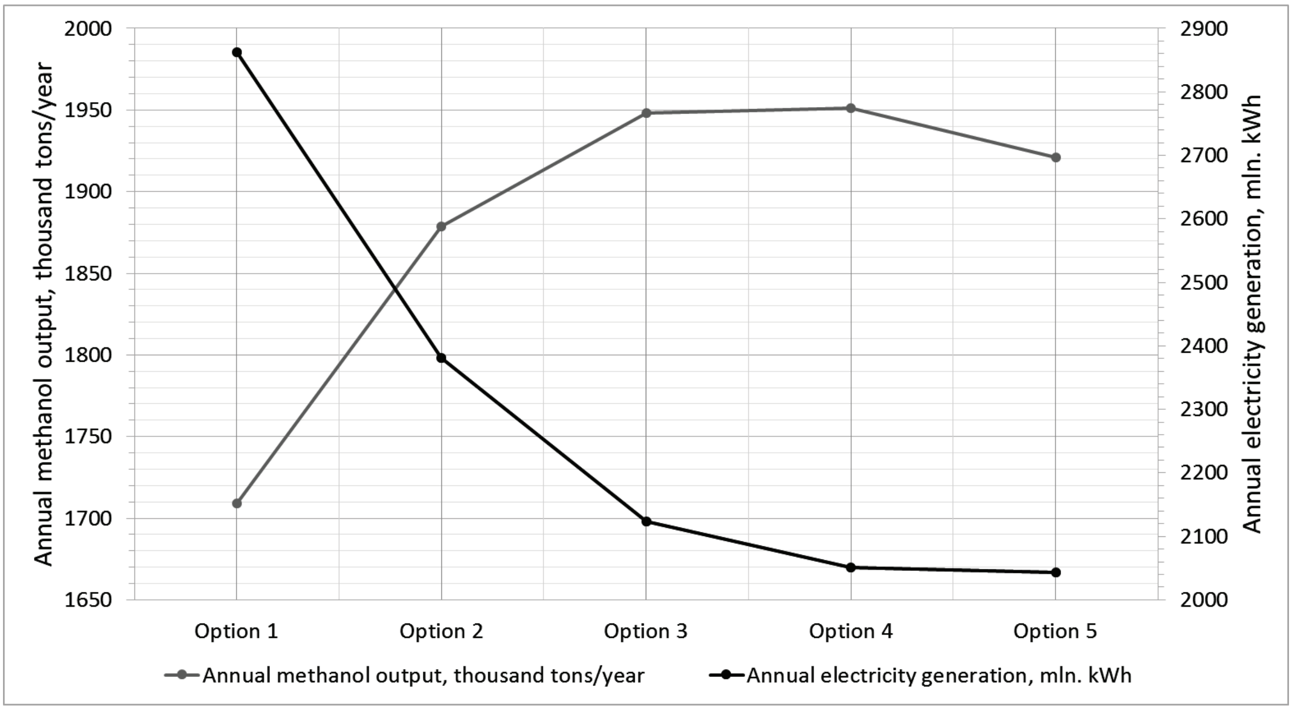

Fig. 3. Annual output of methanol and electricity.

the coal of the Tavan Tolgoi coalfield of Mongolia. Figure 2 shows the investigated options of the CGMS-CCGT that are characterized by different composition of the gasifying agent and compositions of synthesis gas obtained as a result of gasification of coal of the Tavan Tolgoi coalfield.

The optimal values of engineering and economic performance metrics for the options under study are presented in Table 2.

Figure 3 shows the ratio of annual electricity to methanol output for each option.

IV. CONCLUSION

In terms of economic performance (minimum price of produced methanol) and energy efficiency (maximum thermal efficiency of methanol production) it is Option 3 that proves optimal.

It can be seen that the CGMS-CCGT has a high thermal efficiency: up to 66% as com-pared to 55% for conventional coal-fired methanol synthesis plants. Option 1 having the lowest specific steam consumption for blast is characterized by minimum methanol production and maximum electricity generation. This is due to the lack of hydrogen in the synthesis gas, which is necessary for the formation of methanol. Significant amounts of CO remaining after the synthesis reactions enter the combustion chamber of the gas turbine, resulting in increased power generation. However, the increase in revenue from electricity production fails to offset the growth of capital expenditures, and the price of methanol is at its maximum. Option 5 that comes with the highest steam consumption is characterized by the lowest electricity production and sufficiently high methanol output.

Option 3, which is deemed optimal, is characterized by a significant deviation of the composition of fresh synthesis gas from the one required stoichiometry-wise (the H_2:CO ratio is lower). Working with this composition reduces energy losses, and all excess CO is burned off in the power plant. This circumstance makes it possible to abandon the expensive CO conversion unit, reduce the supply of water steam into the gasifiers (compared to dedicated methanol synthesis plants), which increases the energy efficiency of the use of chemical energy of coal. It should be noted that due to greater slip stream of gas from the synthesis unit (significantly greater than that for methanol synthesis process units), the productivity of synthesis reactors increases dramatically (approximately twofold), because they operate on synthesis gas with a more favorable composition.

Another important defining feature of the CGMS-CCGT is its environmental friendliness. This is due to the following circumstances. Hydrogen sulfide content in the synthesis gas entering the synthesis unit must not exceed 0.2 mg/nm^3 (as per the requirements imposed by the catalyst) and ash content must not exceed 5 mg/nm^3 (as per the requirements of preventing erosion of the flow channel part of gas compressors and turbines). As for nitrogen oxides, their only source is the combustion chamber of the gas turbine of the power unit. This is hundreds of times less in terms of SO_2, 2 times less in terms of ash, and 4 times less in terms of NO_x than the environmentally friendly thermal power plants.

In the range of methanol prices from 416 to 368 US dollars / t.c.e., obtained for each CGMS-CCGT option while taking into account the projections of changes in world oil prices and trends in the ratio of oil prices to prices of other fuels, we can conclude that methanol produced from the coal of the Tavan Tolgoi coalfield can successfully compete with methanol produced at conventional dedicated methanol synthesis plants.

There is a fairly large set of plausible combinations of economic conditions under which methanol and electricity production plants prove economically viable. Therefore, these plants are promising and require more detailed study, primarily through the construction of pilot plants.

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Bibliometric Analysis of 2019–2021 Conference Proceedings on Artificial Intelligence and Energy Indexed in Scopus

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***Abstract* — The article presents a bibliometric analysis of 2019–2021 conference proceedings indexed in Scopus and dealing with the subject of Artificial Intelligence and Energy. The relevance of the subject is considered in the context of the energy transition and the application of artificial intelligence to the rational use of energy resources. A comparative analysis of the publication activity of researchers from Russia, China, India, the United States, and Indonesia on the subject in question is given. Methodology-wise, the emphasis for the purpose of identifying the subject is not on the co-occurrence of keywords but rather on the clustering of documents, which rests on the hypothesis that the titles of research contributions most concisely and fully reveal the content of the research paper and allow the subject matter expert to make a relevant choice of such contributions to facilitate their research. The study made use of two software tools: Carrot2 and Clustering App (CSV Explorer). It is shown that Russian contributions are characterized by the tendency of having engineering issues prevail while insufficient attention is paid to environmental, economic, and social issues of using AI in the energy sector. Studies originating from China and the United States are of the greatest interest in terms of the information presented, both with respect to the relevance of their topics and the cutting-edge nature of their content. Studies from India and Indonesia are more general in nature; of interest are the efforts of these countries to engage in global scientific activities.**

***Index Terms*: bibliometric analysis, artificial intelligence, energy, documents clustering, Carrot2, Clustering App (CSV Explorer).**

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I. Introduction and Objectives

The subject of the energy transition is largely related to the efficient and rational use of energy resources. Such a statement of the problem is actively promoted by leading international institutions. Thus, the International Energy Agency supported the policy “National Program for Rational and Efficient Use of Energy” (2007–2017) designed to support the efficient use of energy in energy production, transportation and distribution, storage and consumption, to achieve the highest sustainable development with the available technologies, minimizing the impact on the environment and optimization of energy saving and cost reduction.

Since 2010, there has been an expansion of this program to introduce energy efficiency measures into national public buildings, standardize management systems, develop recommendations and implement energy efficiency measures. The report [1] states that in 2021, global energy intensity – a key measure of the economy’s energy efficiency – is expected to improve by 1.9% after improving by only 0.5% in 2020.

The Russian Federation is characterized by a high level of energy intensity of its GDP [1–3], the current situation requires reducing the specific consumption of fuel, heat, and electricity by increasing their rational use.

The main reasons behind this situation taking place are the wear-and-tear and obsolescence of process equipment and energy equipment, along with high energy losses in buildings and structures.

In this regard, the Ministry of Economic Development of the Russian Federation is working to fulfill the task set by the President of the Russian Federation to reduce the energy intensity of the GDP, including as part of the implementation of a comprehensive plan of measures to improve the energy efficiency of the Russian economy, approved by Order No. 703-r of the Government of the Russian Federation of April 19, 2018.

The report “Energy Efficiency in Russia: Untapped Reserves” [4] presents a comprehensive, practical analysis of energy efficiency in Russia: its potential, benefits, and recommendations for making full use of this resource.

To solve the above tasks, relevant structures are created: the Center for Expert and Analytical Support in the Field of

Energy Saving and Energy Efficiency Improvement of the Ministry of Economic Development of Russia, Department of Competition, Energy Efficiency, and Environment.

The International Energy Agency also emphasizes that energy transitions require innovation in power system planning.

Achieving these goals is possible only on the basis of in-depth data analysis in making both organizational and engineering decisions.

Advances in AI technology make it possible to explore vast amounts of monitoring data, optimize processes, predict anomalies, identify objects, and extract meaning from disparate data sources. Enriching reality with a digital twin, providing verification and trust through distributed ledgers fundamentally changes operational activities.

Leading oil and gas companies are well aware of this, to take one example, there is an opinion voiced by Shell as cited in the article "Digitalization accelerates the energy transition," and it is clear that digitalization is based on artificial intelligence [5].

A variety of issues related to this matter can be found in the report [6].

The above brief summaries were to define the main objective of this study: how the issues of AI applications in the energy sector are mapped in the proceedings of scientific conferences of 2019–2021.

Materials

The choice of abstract databases for bibliometric analysis is quite subjective, the indexing of conference papers and the forming of queries in the databases differ significantly. The arguments in favor of the choice of Scopus for this author were the following results of queries to the two main abstract databases:

WoS: for Conference Proceedings Citation Index – Science (CPCI-S); 2019–2021; Topic=Energy, one gets **73 560** results as of 2022-02-19. When refined by Countries= RUSSIA the query returns **4 545** results.

Scopus: the query PUBYEAR > 2018 AND SUBJAREA (ener) AND (LIMIT-TO (DOCTYPE, "cp")) returns **159 249** results. When refined by AFFILCOUNTRY, "Russian Federation" the query returns **14 667** results.

Since one of the goals of this study was to identify possible areas for further research in the field of energy for Russian academic institutions, the significantly higher representation of Russian conference proceedings on energy-related topics in Scopus influenced the choice in favor of this abstract database.

The second selection factor was the classification system used by these abstract databases, while they are comparable to some extent for energy-related topics: WC=Web of Science Categories Energy & Fuels and Scopus SUBJAREA Energy, including: Energy (all); Energy (miscellaneous); Energy and Energy Technologies; Fuel Technologies; Nuclear Energy and Engineering; Renewable Energy Sources, it is harder to compare them with respect to topics related to Artificial Intelligence.

Scopus has All Science Journal Classification Codes (ASJC) and the code 1702 – Artificial Intelligence, while in WoS a similar result can only be achieved by forming a query with Topic = Artificial Intelligence, which is not a built-in filter in the system.

When analyzing the topics of conference papers, additional keywords are important: Keyword Plus in WoS (Key Words Plus are index terms automatically generated from the titles of cited articles) and Index Keywords (Index Terms) in Scopus (Description: Controlled vocabulary terms assigned to the document). The advantage of the Scopus platform appears to be in the controlled vocabulary of terms (uniform description of entities) and the fact that Index Keywords reflect the content of the document, not the titles of references. And this study aims to work with the content of the conference proceedings themselves, rather than identifying topics from the titles of references.

The reasoning behind choosing conference proceedings over journal articles to form the main query was as follows: of the total 31 058 research contributions written in English and indexed in Scopus for 2019–2021 for SUBJTERMS (1702) AND SUBJAREA (ener), 29 160 are articles from conference proceedings and 1 252 are journal articles. Contributions by Russian authors are 1 585 conference papers and 113 journal articles, respectively. Moreover, 112 articles by Russian authors were published in the International Journal of Engineering Research and Technology, which is no longer indexed by Scopus since 2021, i.e., in a journal with low ranking.

With the above reasons in mind, the final query to Scopus was stated as follows: (SUBJTERMS (1702) AND PUBYEAR > 2018 AND SUBJAREA(ENER) AND (LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (LANGUAGE, "English"))).

Methods

The main data structure used in text analysis is the term-document matrix (TDM), even if the terms are authors' names or affiliations. The terms can also be bibliographic data, authors' keywords, and the fields of research to which the papers belong. In turn, one can treat, to take one example, a journal issue as a single document, and use areas of research as terms and analyze trends in the research topics of a given journal.

TDM is the most common form of document vectorization [7], from which on can build a matrix of co-occurrence of terms and conduct further analysis using free software packages. Such software packages can handle the original bibliometric data available from the WoS, Scopus, and The Lens abstract databases directly.

The most common software tools for bibliometric studies are VOSviewer [8], Citespace [9], and Bibliometrix [10]. The Scopus database for 2019–2021 lists 1 927 documents that published with the term VOSviewer mentioned in their titles, abstracts, and keywords, 1 383 documents mention

Citespace, and Bibliometrix is mentioned 274 times.

When solving the problem of analyzing trends in research topics, the major usage of these programs is to analyze the co-occurrence of terms, even if the term is a cited document.

The approach of clustering documents by similarity of their texts using free software is much less common.

For example, the high-quality software Carrot2, which is used as a document clustering engine, appears only 9 times in Scopus-indexed articles for 2019–2021.

If we consider the use of the above software within our main query SUBJTERMS (1702) AND PUBYEAR > 2018 AND SUBJAREA(ENER) AND (LIMIT-TO (DOCTYPE, “cp”)) AND (LIMIT-TO (LANGUAGE, “English”)) then we get: **5** documents for VOSviewer, **3** documents for Citespace, **1** document for Bibliometrix, and **0** documents for Carrot2, respectively.

Comparing the occurrence of the terms “document clustering” and bibliometric* within our main query we get: **4** document results returned by SUBJTERMS (1702) AND PUBYEAR > 2018 AND SUBJAREA (ener) AND TITLE-ABS-KEY (“document clustering”) AND (LIMIT-TO (DOCTYPE, “cp”) AND (LIMIT-TO (LANGUAGE, “English”) and **18** document results returned by SUBJTERMS (1702) AND PUBYEAR > 2018 AND SUBJAREA (ener) AND TITLE-ABS-KEY (bibliometric*) AND (LIMIT-TO (DOCTYPE, “cp”) AND (LIMIT-TO (LANGUAGE, “English”).

One can come up with different examples but the result will be approximately the same: the “document clustering” term is used less often than “bibliometric”.

It is worth noting that for a subject-matter expert, the titles of research papers and their systematization prove more telling of the area of research than when identifying topics by keyword clustering.

Therefore, one of the goals of this paper is to explore and demonstrate the use of software that allows clustering of documents to identify dominant research topics that correspond to our main Scopus query.

Two tools were used in this work: Carrot2 and Clustering App (CSV Explorer). The algorithm Lingo3G used in Carrot2 is proprietary, while the latter package uses Topic Modeling by applying non-negative matrix factorization.

II. Analysis And Results

Discussion of the results of the analysis of bibliometric data and identification of dominant research topics covers the following: a brief discussion of the features of Russian conference proceedings, identification of countries whose publication activity is comparable with that of Russian authors, a comparative analysis of the main topics dealt with in these countries and Russian conference proceedings as based on document clustering and presented as lists of titles of papers in major clusters.

The main feature of the Russian conference proceedings that satisfied our main Scopus query is that the vast majority of them were presented at the three types of conferences held in Russia as listed below.

Of these, the vast majority of papers (1 005) are presented at the International Multi Conference on Industrial Engineering and Modern Technologies FarEastCon held in 2019 and 2020 in Russia. At international conference, held in Madrid in 2021, which is the second most important conference, only 14 Russian papers on the subject were published.

- International Multi Conference on Industrial Engineering and Modern Technologies FarEastCon 2020 (https://www.dvfu.ru/schools/engineering/far_east_con/) – 559.
- International Multi Conference on Industrial Engineering and Modern Technologies FarEastCon 2019 – 446.
- 3rd International Conference on Control Systems Mathematical Modeling Automation and Energy Efficiency Summa 2021 (https://summa.stu.lipetsk.ru/ Lipetsk, Russia) – 240.
- International Russian Automation Conference Rusautocon 2020 (https://rusautocon.org/index-eng.html) – 194.
- 2021 IEEE Madrid Powertech. Powertech 2021 Conference Proceedings – 14.

The data from this list show that Russian researchers need to develop and promote Russian scientific conferences to the international level; participation in conferences held abroad is fine but expensive.

Moreover, given that the majority of Russian articles are published in the International Journal of Engineering Research and Technology, which does not rank among the best journals, then what was said above about conferences holds to even greater extent for Russian journals where Russian researchers can publish their papers on AI as applied to the energy sector.

When considering the affiliations of the Russian authors of the conference proceedings, it can be seen that the list includes the major leading Russian technical universities and institutes: Russian Academy of Sciences (61 conference proceedings); Lipetsk State Technical University (57); National Research University “Moscow Power Engineering Institute” (53); Komsomolsk-na-Amure State University (52); V. A. Trapeznikov Institute of Control Sciences (51); South Ural State University (51); Far Eastern Federal University (43); Voronezh State Technical University (35); Platov South-Russian State Polytechnic University NPI (34); North-Eastern Federal University (33); Samara National Research University (32); Samara State Technical University (32); Kazan National Research Technical University named after A. N. Tupolev -KAI (32); Peter the Great St. Petersburg Polytechnic University (31); Novosibirsk State Technical University (30); Skolkovo Institute of Science and Technology (29); Kazan State Power Engineering University (28); Ufa

TABLE 1. Distribution of the number of conference proceedings on AI for Energy for 2019–2021 for Russia and the 4 countries by main areas of research.

Country:	Russia		India		China		US		Indonesia	
SUBJECT AREA	N	%	N	%	N	%	N	%	N	%
Computer Science	1577	22.868	6102	25.78	5678	25.032	1689	24.791	819	25.27
Energy	1577	22.868	6102	25.78	5678	25.032	1689	24.791	819	25.27
Engineering	1567	22.723	3805	16.07	4639	20.451	1422	20.872	807	24.9
Decision Sciences	1063	15.415	1695	7.16	1474	6.498	372	5.46	33	1.018
Mathematics	1037	15.038	2699	11.4	3353	14.782	962	14.12	367	11.324
Social Sciences	29	0.421	509	2.15	1121	4.942	323	4.741	117	3.61
Medicine	23	0.334	1332	5.63	286	1.261	72	1.057	83	2.561
Physics and Astronomy	12	0.174	1294	5.47	76	0.335	99	1.453	102	3.147
Environmental Science	6	0.087	43	0.18	33	0.145	62	0.91	11	0.339
Business, Management and Accounting	2	0.029	12	0.05	339	1.495	84	1.233	5	0.154
Materials Science	2	0.029	56	0.24	5	0.022	22	0.323	76	2.345
Chemical Engineering	1	0.015	25	0.11	1	0.004	17	0.25	2	0.062

TABLE 2. Frequency of keywords in conference proceedings for the 5 countries.

Keyword	N	%	N	%	N	%	N	%	N	%
Automation	119	12.332	117	2.075	54	0.869	30	1.174	11	2.326
Energy Efficiency	72	7.461	118	2.093	99	1.594	145	5.675	8	1.691
Neural Networks	63	6.528	176	3.121	155	2.495	56	2.192	33	6.977
Electric Power Transmission Networks	61	6.321	596	10.569	1736	27.946	614	24.031	22	4.651
MATLAB	57	5.907	430	7.625	171	2.753	44	1.722	21	4.44
Decision Making	50	5.181	73	1.295	106	1.706	46	1.8	10	2.114
Controllers	47	4.87	328	5.817	91	1.465	74	2.896	31	6.554
Optimization	45	4.663	135	2.394	110	1.771	43	1.683	15	3.171
Data Handling	43	4.456	71	1.259	105	1.69	26	1.018	15	3.171
Forecasting	40	4.145	239	4.238	223	3.59	92	3.601	34	7.188
Machine Learning	40	4.145	483	8.565	127	2.044	107	4.188	24	5.074
Efficiency	38	3.938	79	1.401	134	2.157	21	0.822	12	2.537
Energy Utilization	38	3.938	110	1.951	174	2.801	55	2.153	10	2.114
Digital Storage	34	3.523	114	2.022	169	2.721	85	3.327	10	2.114
Smart Power Grids	33	3.42	425	7.537	1452	23.374	552	21.605	17	3.594
Renewable Energy Resources	28	2.902	138	2.447	94	1.513	58	2.27	10	2.114
Costs	23	2.383	76	1.348	98	1.578	50	1.957	23	4.863
Learning Systems	21	2.176	273	4.841	176	2.833	93	3.64	33	6.977
Genetic Algorithms	18	1.865	88	1.561	149	2.399	22	0.861	16	3.383
Network Security	18	1.865	128	2.27	133	2.141	69	2.701	13	2.748
Classification (of Information)	17	1.762	204	3.618	103	1.658	20	0.783	26	5.497
Convolutional Neural Networks	16	1.658	255	4.522	117	1.883	31	1.213	21	4.44
Deep Learning	15	1.554	479	8.494	256	4.121	113	4.423	31	6.554
Learning Algorithms	15	1.554	251	4.451	87	1.401	47	1.84	15	3.171
Electric Inverters	14	1.451	253	4.487	93	1.497	62	2.427	12	2.537

Table 3. The 15 most frequent keywords that are typical of the conference papers by Russian researchers, but occur much less frequently in Chinese research contributions, and vice versa.

Keywords (Russia)	N	Keywords (China)	N
Engineering	71	Smart City	558
Industrial Engineering	67	Intelligent Computing	373
Control Systems	60	Data Communication Systems	345
Process Control	53	Internet of Things	328
Electric Drives	51	Power Electronics	295
Electric Power Systems	51	Big Data	290
Modeling	38	Social Networking (online)	265
Electric Network Parameters	35	Green Computing	228
Fuzzy Logic	35	Cloud Computing	224
Sustainable Development	35	Computer Aided Instruction	219
Technological Process	35	Trusted Computing	167
Mathematical Model	33	Ubiquitous Computing	162
Parameter Estimation	29	Data Mining	142
Differential Equations	28	Scheduling	142
Comparative Analysis	27	Electric Load Flow	134

State Petroleum Technological University (27); Bauman Moscow State Technical University (26); Tambov State Technical University (25); Moscow State University of Civil Engineering (25); Southern Federal University (25); Nosov Magnitogorsk State Technical University (25); Pacific National University (22); Kazan Federal University (22); Saint Petersburg National Research University of Information Technologies, Mechanics and Optics University ITMO (22).

As for funding sources, these are the well-known institutions: Russian Foundation for Basic Research (198); Ministry of Education and Science of the Russian Federation (52); Russian Science Foundation (41); Council on grants of the President of the Russian Federation (28). A certain discrepancy may be caused by the different spelling of the sources, for example, Ministry of Education and Science of the Russian Federation (52) and Ministry of Science and Higher Education of the Russian Federation (21). Here the data are given as they appear in the Scopus database. However, the key takeaway remains the same: public funding is the main source of funding for research.

In Russia, engineering disciplines historically have been more developed than social studies, as is reflected in the following list of research topics in Russia and all other countries represented in Scopus:

- Decision Sciences; in Russia – 15.4%, in all countries – 7.4%
- Social Sciences; in Russia – 0.42%, in all countries – 3.45%
- Environmental Science; in Russia – 0.09%, in all countries – 0.77%
- Business, Management and Accounting; in Russia – 0.03%, in all countries – 0.49%

According to Scopus, 2019-2021 conference proceedings on AI in Energy are mostly from the following countries: India (6,101 conference proceedings); China (5603); United States (1686); Russian Federation (1337); Indonesia (818); Bangladesh (798); Brazil (761); Pakistan (605); United Kingdom (595); Italy (579); United Arab Emirates (557); Romania (494); Germany (491); Canada (481); Turkey (468); Malaysia (457); South Africa (420); Taiwan (406); Japan (349); France (341).

In what follows, a comparative analysis of research topics will be carried out using data on the first five countries: India, China, United States, Russian Federation, and Indonesia.

Above, the data on Russia and the average for all countries were compared; Table 1 gives a comparison with the 4 countries with the highest publication activity for the query in question.

Table 1 shows that while Russian researchers are well-positioned in topics from Computer Science to Mathematics, they are significantly underrepresented in other fields.

Hence, a suggestion can be made to Russian researchers to use the experience from the areas at the top of the list to develop the areas of research presented at the bottom of the list.

Social Sciences, Medicine, Environmental Science, and Business play an increasingly important role in today's world.

Research topics can be described not only by the Subject Areas to which the Scopus platform attributes research papers but also by the keywords assigned to the papers. Such results are presented in Table 2. The table is derived using an inner join for country-specific keyword tables. I.e., keywords occurring in the research papers of all 5 countries are compared.

Table 4. The 15 most frequent keywords specific to Russian research papers, but much less common in U.S. papers, and vice versa.

Keywords (Russia)	N	Keywords (US)	N
Engineering	71	Smart City	200
Industrial Engineering	67	Internet of Things	164
Process Control	53	Embedded Systems	105
Electric Drives	51	Intelligent Buildings	97
Electric Power Systems	51	Distributed Energy Resources	94
Modeling	38	Machine Design	92
Monitoring	37	Automobile Drivers	89
Quality Control	36	Social Robots	88
Electric Network Parameters	35	Driver Training	87
Fuzzy Logic	35	Microgrids	87
Technological Process	35	Educational Robots	86
Mathematical Model	33	Multi Agent Systems	83
Parameter Estimation	29	Distribution Systems	79
Differential Equations	28	Motion Tracking	73
Comparative Analysis	27	Vibrations (mechanical)	69

As in Table 1, these data show that Russian research contributions can be attributed more to the engineering sciences.

Interestingly, all countries use MATLAB as the main software product. The query SUBJTERMS (1702) AND PUBYEAR > 2018 AND SUBJAREA (ene) AND TITLE-ABS-KEY (**matlab**) AND (LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (LANGUAGE, "English") returns **1 895** results, whereas the query SUBJTERMS (1702) AND PUBYEAR > 2018 AND SUBJAREA (ener) AND TITLE-ABS-KEY (**julia**) AND (LIMIT-TO (DOCTYPE, "cp") AND (LIMIT-TO (LANGUAGE, "English")) yields only **8** conference proceedings.

The Julia programming language is seen as an open-source alternative to MATLAB but its widespread application in engineering tasks will take a long time required to develop and implement a variety of specialized packages that have been created in MATLAB for decades.

To build the above tables, the inner join operator was used, i.e., what is found in the data of all countries was determined and compared.

Using the left join to the Russian data, it is possible to identify keywords that are widely used in the Russian conference proceedings but not found in the proceedings of other countries.

Below is such data for comparison with China and the U.S.

The data in the table highlights the dominance of well-established engineering topics in Russian research papers, while Chinese research papers are dominated by topics that can be described by the following words: Smart City – Intelligent Computing – Internet of Things – Big Data.

Table 4 provides a similar comparison for Russian and American research papers.

The Russian data are only slightly different from Table 3; the American topics, as well as the Chinese ones, reflect more the modern tasks of AI in the energy sector.

The above tables are based on the Scopus data presented in the files named Scopus_exported_refine_values, which contain generalized bibliometric data on the given query.

A. Clustering documents by subject

In this subsection, bibliometric data contained in exported files with detailed bibliometric information was used for analysis. Given the limited size of the article and its scope, in what follows we focus on studying the description and systematization of research topics using the titles of conference proceedings for description purposes.

By definition, the titles of research papers should briefly but fully reflect its content, and therefore reveal its topics.

Document clustering by its content can be performed by text mining using non-negative matrix factorizations. A lot of research papers are devoted to this issue, e.g., in the study [11] presents key methods for automatically determining semantic features and clusters of documents in a collection of texts based on the factorization of non-negative matrices. Manually grouping text files and assigning labels to the found groups is a time-consuming task and the authors [12] proposed the novel K-means Non-Negative Matrix Factorization (KNMF) system, which after preprocessing the texts uses NMF results for subsequent document clustering.

To show the effectiveness of the above approach a simple clustering was carried out, in which conference proceedings headings were used as texts for the 5 countries considered above. To spare the reader some unnecessary detail, below are examples in which the number of clusters is chosen equal to 5 and 5 most relevant headings are given to characterize each of them. The data were obtained using the Clustering APP listed in the Methods section.

For illustration purposes, only the first cluster of Russian and Indian research papers is examined in more detail. India has the largest number of research papers on the topic in question but its economy is weaker than that of China and the United States, so it was interesting to compare the data on Russia with those on a less-than-advance economy.

As already noted, the titles reflect well the topics of the articles, and it is easy to find articles themselves, as well as those similar to them in terms of their subject matter. The most of abstract databases provide the latter.

Russian Federation (1 577 titles)

CLUSTER: 1: SYSTEMS; BASED; INFORMATION; MODELING

- Digraph Modeling of Information Security Systems
- Ontology based method of data codification for information exchange
- Assessment of the Conflict Stability of Information Systems Using Mathematical Modeling
- Hierarchical Data Model Choosing in the Information Systems Design in Relational DBMS
- Decision Support for the Windfarms Siting Based on Multi-Attribute Analysis and Aerodynamic Modeling

CLUSTER: 2: POWER; SUPPLY; ELECTRIC; PLANTS

- Challenges in Power Supply of the Arctic
- The Linear Adjustable Power Supply
- Electric Power Quality in the Single-Phase Power Supply Networks of Electronic Means
- Power Supply System with Power Plant on Solid Oxide Fuel Cells
- Distributed Generation in Railroad Power Supply Systems

CLUSTER: 3: CONTROL; PROCESS; AUTOMATIC; AUTOMATED

- Using of Control Actions Shaper for Movement Control Process of Mobile Platform
- Automatic Control System of Electromagnetic Vault Down-Faller
- Dynamic Verification of Process-Oriented Control Software by the Case of Crossroad Control
- A Neural Network-Based Control System Using PID Controller to Control the Deaerator
- Development of the Predictive Control System for Ethylbenzene Dehydration

CLUSTER: 4: NEURAL; NETWORK; USING; NETWORKS

- Development Application for Traffic Classification Using the Neural Network Approach
- Neural Network Approach for Prediction of Pneumonia
- System of diagnosis of acute nazhopharingitis using artificial neural networks
- Neural Network Decoder of Automatic Process Control System
- Identification of Psoriasis by Images Using Convolutional Neural Networks

CLUSTER: 5: ENERGY; EFFICIENCY; STORAGE; TECHNOLOGIES

- The Energy System of an Autonomous Vehicle with Electric Energy Storages
- Modeling of the Processes of Regulating Energy Efficiency of Technologies and Combining Energy Resources
- Adsorption Equipment Energy Efficiency Increase
- Improving the Energy Efficiency of the Oil Well Electrical Complex
- Modeling of the Mechanism of Management of Efficiency of Energy Technologies

Based on the keywords of the cluster headings: “systems; information; modeling; power; supply; electric; plants; control; process; automatic; neural; network; energy; efficiency; storage; technologies” and the titles of the most representative research papers in each cluster, we can conclude that Russian research papers largely focus on engineering issues. This is consistent with the results presented in Table 1.

Next, here is a brief summary of the content of the articles representing the first cluster. A synopsis of an article, while being smaller than even its abstract, can give the subject matter expert sufficient insight into its topics and allow them to decide whether it is worth reading in its entirety.

Digraph Modeling of Information Security Systems [13]: The article considers a cognitive model of the state of information security system of an average organization. The model is a weighted oriented graph, the vertices of which are standard elements of the information security system of the organization. On the basis of the model the most significant factors affecting the state of information security of the organization are identified.

Ontology-based method of data codification for information exchange [14]: One of the problems of inter-system exchange of data coming from different sources is the ability to identify similar objects. A promising tool that can be used to uncover this complex form of identification is a codification system that allows comparing incoming data from different sources, aggregating different attributes of similar objects and providing qualitative data to end users. This paper describes an experiment in which this model was applied to different object categories - material, financial, and workforce information descriptions.

Assessment of the Conflict Stability of Information Systems Using Mathematical Modeling [15]: The article deals with conceptual, mathematical and computer models of asymmetric conflict interaction of systems, which are typical for the problems of conflict stability of information systems. Within the framework of the mathematical model the analytical relations for assessing the lower bound of the probability of victory of one of the parties to the conflict, which allow abstracting from a particular kind of densities of the distribution of the time of the parties in their possible states, are proposed.

Hierarchical Data Model Choosing in the Information Systems Design in Relational DBMS [16]: Hierarchical data handling is one of the typical tasks in the development of industrial information systems. The performance and operability of the developed application depends on the correct choice of storage structure and hierarchical data processing mechanisms.

Decision Support for the Windfarms Siting Based on Multi-Attribute Analysis and Aerodynamic Modeling [17]: The article gives an example of multiattribute assessment of wind farm sites based on aerodynamic modeling in the area of the village Ayan, Khabarovsk region. Many economic, technical, environmental and social factors should be taken into account when locating a wind farm. When assessing the economic efficiency of the option of wind farm location it is proposed to use aerodynamic modeling to consider how the topography of the area will affect the wind speed.

India (2 000 of 6 102 titles)

CLUSTER: 1: LEARNING; MACHINE; USING; DEEP

- Machine Learning Based Attrition Prediction
- Analysis of sentiments in political-based tweets using machine learning techniques
- FAB Classification based Leukemia Identification and prediction using Machine Learning
- Scrutinizing Students Performance using Machine learning
- Predicting Fitness and Performance of Diving using Machine Learning Algorithms

CLUSTER: 2: ANALYSIS; DESIGN; PERFORMANCE; ANTENNA

- Bibliometric Analysis of MOOC using Bibliometrix Package of R
- Design and analysis of X band pyramidal horn antenna using FEKO
- Design and Analysis of Proportional Integral Derivative Controller and it's hybrids
- Permutation Algorithm Analysis and Updation
- Derivation of thevenin's and norton's theorems using two-port network analysis

CLUSTER: 3: NETWORK; NEURAL; USING; CONVOLUTIONAL

- Real Time Handwritten Digits Recognition Using Convolutional Neural Network
- Voice recognition-based security system using convolutional neural network
- Leaf Based Trees Identification Using Convolutional Neural Network
- Handwritten Form Recognition Using Artificial Neural Network
- Neural Network Based Driver Warning System

CLUSTER: 4: BASED; SMART; IOT; MANAGEMENT

- IOT Based Smart Waste Management System
- An IoT based Smart Outdoor Parking System
- Smart intimation of mailbox using IoT
- IoT based smart intelligent vehicle systems
- A Study of Smart Farming Based on IOT

CLUSTER: 5: DETECTION; IMAGE; USING; TECHNIQUES

- Sarcasm Detection in Newspaper Headlines
- Cataract Detection using Digital Image Processing
- Motion Detection Using Image Processing
- Survey of skin cancer detection using various image processing techniques
- Detection of Skin Cancer Lesions from Digital Images with Image Processing Techniques

From the keywords of the cluster headings: "learning; machine; deep; analysis; design; performance; network; neural; convolutional; smart; IOT; management; detection; image; techniques" it follows that Indian research papers are more focused on analysis of design and performance of IOT and smart networks using deep machine learning and convolutional neural networks. According to Table 1, the topics of Indian research papers can be classified as Computer Science.

Summaries of the research papers of the first cluster of Indian conference proceedings.

Machine Learning Based Attrition Prediction [18]: The probabilistic estimation is used in this paper to predict personnel attrition based on a human resource database of a company with about 1 500 employees.

Analysis of sentiments in political-based tweets using machine learning techniques [19]: Tweets are useful for analyzing user preferences for different political parties. Users may not only be "for" or "against" a particular political party, but may also have ambiguous opinions about it. This study is an attempt to predict users' opinions about different political parties using machine learning algorithms. People's sentiments about political parties are analyzed using SVM and Naïve Bayes algorithms.

FAB Classification based Leukemia Identification and prediction using Machine Learning [20]: The method proposed by the authors is used to recognize, detect and distribute leukemia based on FAB classification. The shape, textural features, and color of the segmented image are selected by a neural network, classification is performed using a Support Vector Machine, and prediction is performed using a Naïve Bayes classifier. The proposed classifier improved the average classification accuracy to 99.06% and the mean square error is 0.0407.

Scrutinizing Students Performance using Machine learning [21]: To give a unique form to student learning and to apply what they learn to their work; the authors of this article propose using a regression algorithm to strictly assess student learning. They take the dominant attributes as performance data, normalize each element of the performance data by defining a set of models, and then build a model to measure the prophetic value of early student detection in assessing a student's learning ability. If the value is steep, instructors track the prophecy value of early detection to observe students' problems and their explanations in the course.

Predicting Fitness and Performance of Diving using

Machine Learning Algorithms [22]: Lack of data and knowledge exists about which fitness tests can be effective in predicting fitness, performance, and selection of potential divers in national and international competitions. The prediction accuracy using multivariate logistic regression with 6 variables was 52.1%, which was worse than the ordinal forest. The overall accuracy of the final ordinal forest was 70.4%. Balanced accuracy was 68.5% and 82.8% for national and international predictions, respectively.

According to Table 1, studies related to medicine are best represented in Indian studies compared to the other 4 countries, as is reflected in the brief summaries of articles belonging to the first cluster, which is despite the fact that energy was chosen as the subject area for filtering the research papers.

It should be noted that the importance of medical issues in research in various areas is also recognized by the Russian government. Among the target indicators for the fiscal year for research themes funded from the federal budget, there is the following item: Number of medical technologies planned for development within the framework of a scientific theme. This recognizes the importance of the development of medical technologies in research that is essentially not related to medical issues per se.

India’s approach to this issue may be useful for Russian researchers.

China (2 000 of 5 678 titles)

CLUSTER: 1: ALGORITHM BASED IMPROVED IMAGE

- Improved Design of des Algorithm Based on Symmetric Encryption Algorithm
- A Novel Feature Selection Algorithm Based on Artificial Bee Colony Algorithm and Genetic Algorithm
- Design of a Gearbox Based on Genetic Algorithm
- A Multi-population Whale Optimization Algorithm Based on Orthogonal Learning
- Multi-exposure image fusion based on improved pyramid algorithm

CLUSTER: 2: POWER CONTROL DC GRID

- Power Grid Model Data Governance System Based on Dcloud*
- Architecture Design and Evaluation of Hybrid AC/DC Power Grids Based on Power Electronic Transformer
- Analysis of DC line fault characteristics with the UHVDC hierarchical integration into AC power grid
- Optimal control of reactive power and voltage in active distribution network based on source-grid-load interaction
- Short-circuit Current Characteristics of Distributed Power and Fault Location Method after Distributed Power is Connected

CLUSTER: 3: NETWORK NEURAL DISTRIBUTION CONVOLUTIONAL

- BP Neural Network Based Fault Prediction of Distribution Network during Typhoon Disaster
- A Spiking Neural Network for Tooth Chromaticity Detection
- Research of Computer Network Security Evaluation Based on Backpropagation Neural Network
- Research on Distribution Network Topology Reconfiguration Based on LSTM Neural Network
- Fault classification model of distribution network based on rough neural network and decision tree

CLUSTER: 4: RESEARCH BASED TECHNOLOGY DATA

- Research on polygraph technology based on ballistocardiogram signal
- Research on Archives Information Management System Based on Computer Big Data
- Research on the Model of CVT Operation Performance Based on the PHM System
- Application and Research of Computer Mega Data Based on Structure in E-learning
- Research on the control of user privacy data disclosure based on blockchain Technology

CLUSTER: 5: METHOD DETECTION BASED FAULT

- Detection method of phishing email based on persuasion principle
- Edge Detection Method Based on Hysteresis Connection and Prediction
- Study on the Limited Space Detection Method Based on Ultrasonic Diffraction Time Difference Method
- Chip defect detection based on deep learning method
- A Pavement Disease Detection Method based on the Improved Mask R-CNN

Judging by the list of titles of research papers, China is focusing a lot of attention on algorithms and their application to optimize grid management and fault monitoring. This is in line with China’s strategy to take a key position in AI research, and the energy sector is no exception.

United States (1 689 titles)

CLUSTER: 1: POWER DISTRIBUTION SYSTEMS USING

- Power Displacement Analysis for Power Systems - A Commodity Model
- A review on impact analysis of electric vehicle charging on power distribution systems
- Adversarial examples on power systems state estimation
- Online Voltage Optimization of the Power Distribution System
- Transient Stability Analysis of Power Systems via Occupation Measures

CLUSTER: 2: LEARNING DEEP MACHINE USING

- Hemp disease detection and classification using machine learning and deep learning
- SwFLOW A dataflow deep learning framework on sunway taihulight supercomputer
- Microwave glucose concentration classification by machine learning
- Grape Leaf Disease Detection and Classification Using Machine Learning
- Survey of Machine Learning and Deep Learning Techniques for Travel Demand Forecasting

CLUSTER: 3: ENERGY DISTRIBUTED STORAGE MANAGEMENT

- Energy distribution in EV energy network under energy shortage
- Sharing Mobile and Stationary Energy Storage Resources in Transactive Energy Communities
- A Distributed Energy Management Approach for Residential Demand Response
- Technical_ financial_ and environmental effects of distributed energy resources on multi carrier energy networks
- Control and Dispatch of Distributed Energy Resources with Improved Frequency Regulation using Fully Active Hybrid Energy Storage System

CLUSTER: 4: SMART DATA GRID CITIES

- Big Data Analysis for Retrofit Projects in Smart Cities
- A LoRa-based Smart Streetlighting System for Smart Cities
- IMirror A Smart Mirror for Stress Detection in the IoMT Framework for Advancements in Smart Cities
- Data integration platform for smart and connected cities
- Making Smart Transportation Work in Smart Cities

CLUSTER: 5: BASED CONTROL TIME MODEL

- Modelica-based control of a delta robot
- Time-varying optimization-based consensus control for microgrid's secondary control
- Real Time Analysis of a Multi-Agent Based Distributed Control Strategy for Islanded AC Microgrids
- Phasor based control with the distributed_ extensible grid control platform
- Optimal control of a multirotor unmanned aerial vehicle based on a multiphysical model

The US also pays a lot of attention to machine learning for energy systems but much of this research focuses on renewable energy sources, such as distributed energy storage, intelligent transportation systems, and smart cities.

The Chinese and U.S. experience shows that Russian researchers pay insufficient attention to distributed systems other than energy systems. This may be due to the fact that the issues of energy transition in our country are only at the initial phase and less attention is paid to smart cities and smart alternative energy systems, due to less developed infrastructure compared to China and the United States.

Indonesia (819 titles)

CLUSTER: 1: USING DETECTION METHOD LEARNING

- Asphalt Pavement Pothole Detection using Deep learning method based on YOLO Neural Network
- Detection of Kinship through Microexpression Using Colour Features and Extreme Learning Machine
- Using Metadata in Detection Spam Email with Pornography Content
- Face Movement Detection Using Template Matching
- Feature selection algorithm for intrusion detection using cuckoo search algorithm

CLUSTER: 2: POWER STUDY PLANT ENERGY

- Economic analysis of renewable energy power plant in Sumatra_ Indonesia
- Improving loss of load probability through biomass power plant integration: A case study in Tanjung Balai Karimun
- Power Quality Enhancement on Hybrid Power Plants Using Shunt Passive Power Filter and Detuned Reactor
- Steady State Model of Wind Power Plant for Load Flow Study
- Achieving new and renewable energy target: A case study of java-bali power system_ Indonesia

CLUSTER: 3: BASED MONITORING DESIGN SMART

- Design and implementation of Intelligent Aquaponics Monitoring System based on IoT
- IoT-based smart gallery to promote museum in ambon
- Design of Algorithm Control for Monitoring System and Control Bridge Based Internet of Things (IoT)
- Designing of a Smart Collar for Dairy Cow Behavior Monitoring with Application Monitoring in Microservices and Internet of Things-Based Systems
- Surveillance Monitoring System based on Internet of Things

CLUSTER: 4: NETWORK NEURAL CONVOLUTIONAL ARTIFICIAL

- The Implementation of Neural Network Algorithm to Predict the Eligibility of Prospective Assistants
- Deep Convolutional Neural Network for Melanoma Image Classification
- Jaya-Neural Network for Server Room Temperature Forecasting Through Sensor Network
- Convolutional Neural Network for Automatic Pneumonia Detection in Chest Radiography
- Modeling vertical roller mill raw meal residue by implementing neural network

CLUSTER: 5: CONTROL ROBOT FUZZY LOGIC

- Fuzzy Logic-Based Wet Scrubber to Control Air Pollutant
- A New kicker system of wheeled soccer robot ersow using fuzzy logic method

Fig. 1. Circles diagram representing the clustering of Russian conference proceedings by the Lingo3 algorithm.

- Simulation Analysis of Formation Control Design of Leader-Follower Robot Using Fuzzy Logic Controller
- Water Distribution Control Using Arduino with Fuzzy Logic Algorithm Method: A Prototype Design
- Performance Comparison of Fuzzy Logic and Neural Network Design for Mobile Robot Navigation

Scientific research in Indonesia is actively developing. Obviously, it does not have the same resources as China and the United States or even India, but Indonesian scientists are working hard to embark on the new challenges of AI and energy, which is evident from the titles of research papers and the fact that they have more conference proceedings than the United Kingdom (595) and Italy (579).

The analysis presented above, as well as the software chosen to back it, are rather illustrative in nature, allowing to quickly showcase possibilities of document clustering for bibliometric studies.

For a more detailed analysis of document clustering features, it is advisable, at least briefly, to demonstrate the capabilities of the Carrot2 software.

This software has a long history of development, includes various algorithms for clustering and graphical representation of data, the ability to work with different data sources, including embedding in search engines and working with indexes of these systems. A detailed analysis of the capabilities of this program is beyond the scope of this study. We will give an example of only using its demo version, dealing with the Lingo3 algorithm, and one

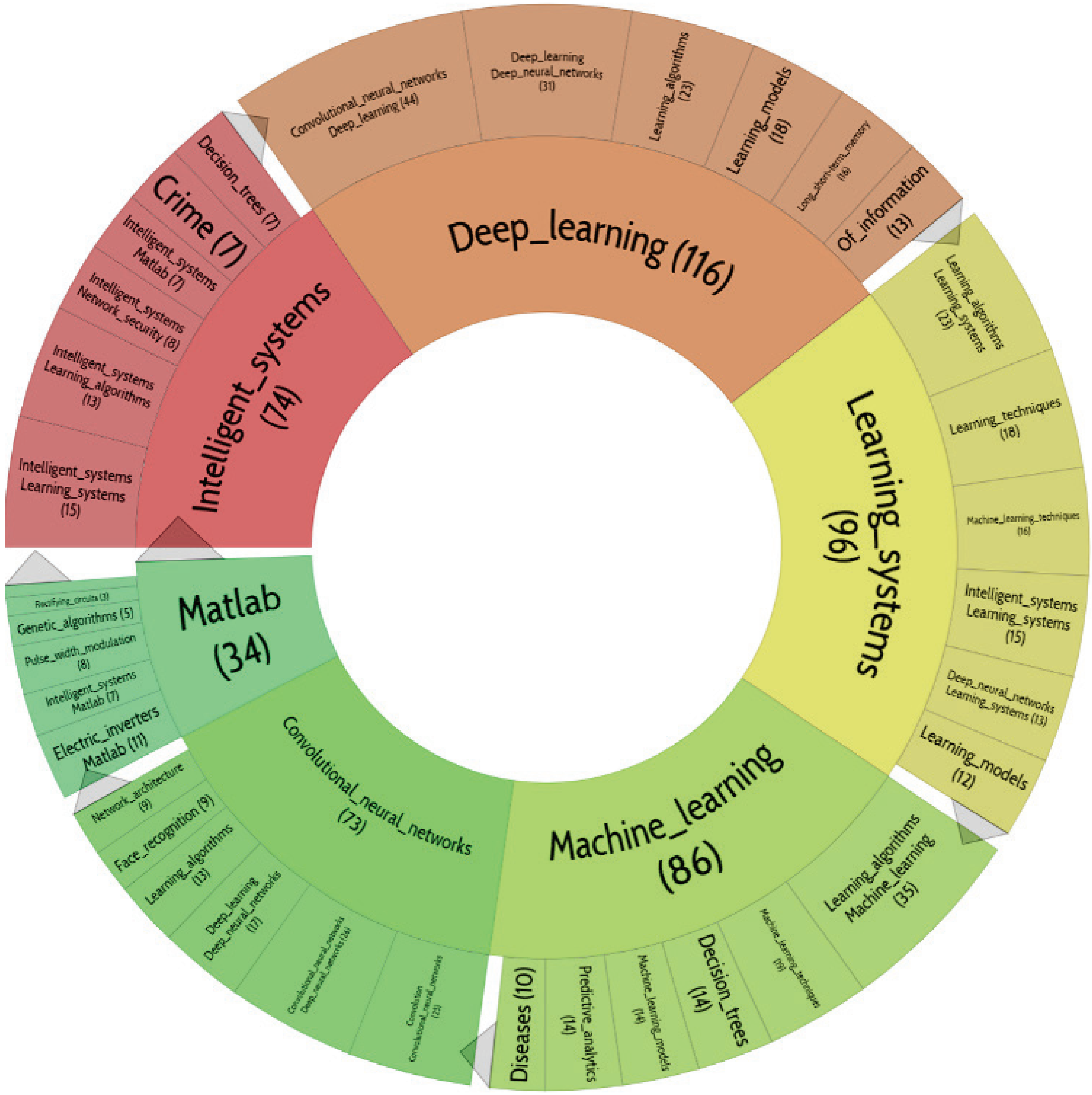

Fig. 2. Circles diagram displaying the clustering of conference proceedings by Indian researchers using the Lingo3 algorithm.

format for presenting the results as Circles, or multi-level pie charts in the carrot2 terminology. To avoid the issues of preprocessing textual data, the clustering proximity estimation was performed only by index keywords. For the rest of the parameters we used their default values. In order to avoid treating index keywords as separate words, we performed the simplest preprocessing using regular expressions to replace spaces in them with underscores, which can be seen in the graphs below.

The next section is a comparison of data for the five previously selected countries.

Figure 1 shows the results of clustering Russian conference proceedings by index keywords. The clustering is performed on the documents, so by knowing the DOI, we can get the title of the documents and other fields from the original tables.

Automation, Control systems, Energy efficiency, Engines, Electric power transmission networks and Neural networks – are the labels of the first-level clusters.

Examples of Russian research papers on the best represented topic being Automation Control_Systems as selected according to the number of their citations.

Development of Information Measuring Complex of Distributed Pulse Control System [23], 3 citations: The article synthesizes the law of temperature field distribution in an isotropic rod on the basis of impulse transition functions - the Green's function. The mathematical modeling of the obtained law was conducted on a hybrid supercomputer

Fig. 3. Circles diagram showing the clustering of conference proceedings by researchers from China using the Lingo3 algorithm.

using NVidia CUDA technology. The conclusion about the possibility of optimizing the temperature conditions in the considered control system was made on the basis of mathematical modeling.

Designing a Method for Constructing Distributed Open ACS Based on the ESP-NOW Wireless Protocol [24], 2 citations: The paper proposes a new approach to the implementation of open distributed automatic control systems, based on the use of cheap Espressif computational nodes exchanging data over the ESP-NOW wireless protocol. The proposed solution allows the use of distributed automatic control systems (ACS) to control complex mechatronic objects, such as industrial manipulators, and allows the placement of computing nodes at remote points of the workspace.

Determining the Hazard Quotient of Destructive Actions of Automated Process Control Systems Information Security Violator [25], cited once: The aim of the work was to formalize the assessment of potentially realizable violations of information security, which can lead to a breach in the functioning of multi-level distributed automated process control systems. The results of calculations using the proposed method of modeling threats and violators of information security in the design of information security systems of automated control systems of technological processes are presented.

Automatic Control of Hot Water Supply System on Solar Collectors [26], cited once: The article describes

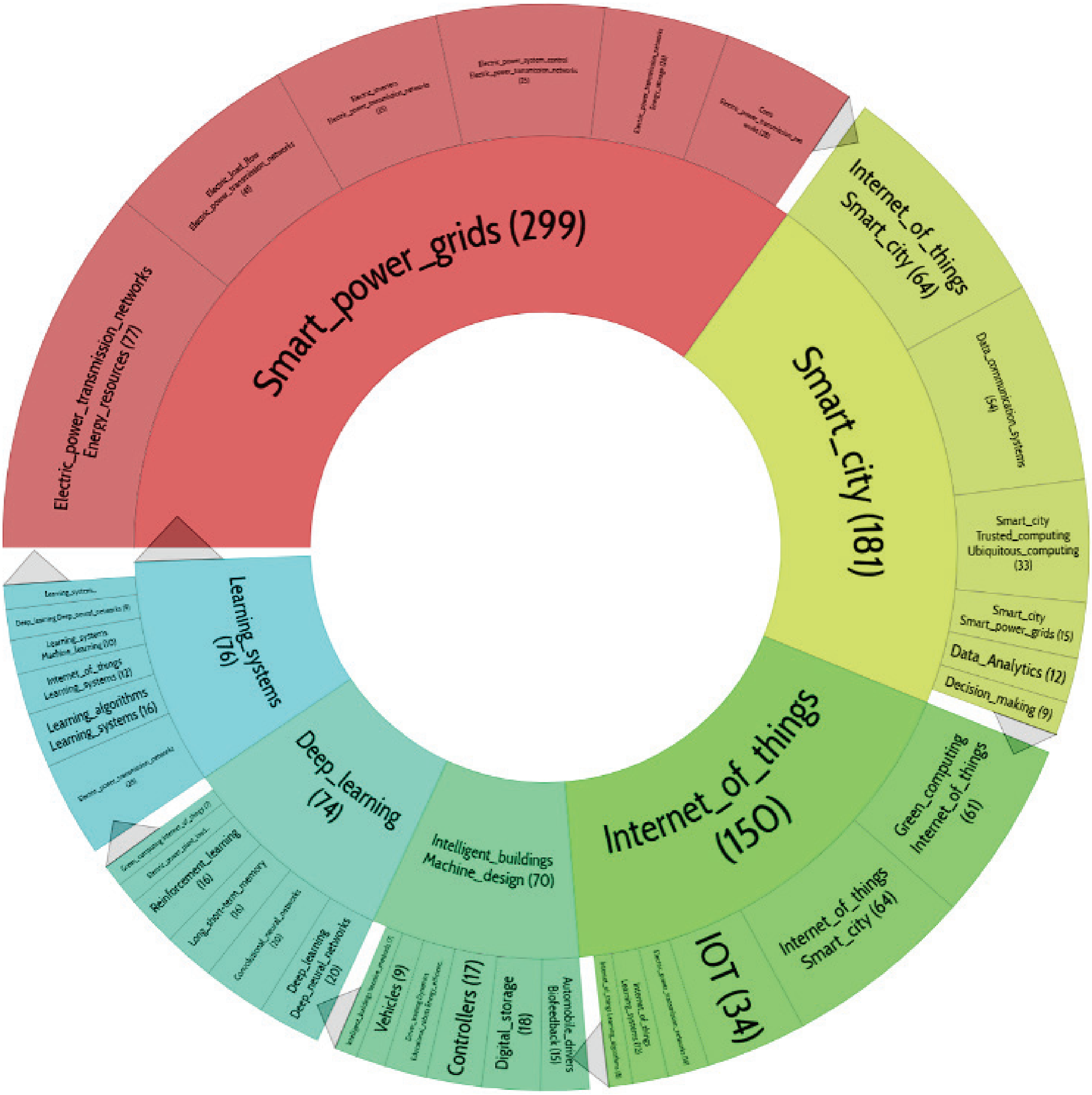

Fig. 4. Circles diagram showing the clustering of conference proceedings by US researchers using the Lingo3 algorithm.

experimental data on the operation of hot water system on solar collectors. The control problems associated with frequent switching of the circulation pump, also stray circulation of the coolant and imbalance of parallel connected collectors were revealed. Justified changes in the design of the control system to solve the identified problems.

Modernization of Setting for Symmetrical Optimum [27], cited once: The paper proposes a symmetric tuning for the calculation of a closed-loop automatic control system, which is obtained by analyzing the frequency characteristics of the tuning for the symmetric optimum.

Thus, the above examples of research papers align well with the major themes presented in Fig. 1, all of which are of an unmistakably engineering nature.

Relying on citations of research papers, it is possible to give examples of the most cited Russian research contributions related to all sections presented in the Fig. 1.

The below data are in the following format: research contribution title, citation, number of citations, key term describing the cluster to which the contribution belongs, a summary of the contribution.

Algoritm of Current Protection Based on Three Instantaneous-Value Samples [28], 19 citations, key term – Electric_network_parameters: In this work the authors have proposed a method of discretization of instantaneous values of currents and voltages, which allows extracting from instantaneous values of currents, containing periodic and aperiodic components, only sinusoidal information, necessary for the correct operation of digital relay protection and automation. The method made it possible to realize protections that fix faults by means of analog devices only for a few periods of current changes.

An Object-Oriented Design of Expert System Software for Evaluating the Maintenance of Lined Equipment [29], 16 citations, key term – Computer_software: The article describes the actuality of solving the problem of automating the process of assessing the state of critical embedded equipment. An object software model of the expert system for assessing the state of critical built-in equipment has been developed. This system allows to produce recommendations for managing the modes of operation of critical built-in equipment.

A Study on Cost-Effectiveness of Energy Supply Based on the Energy Hub Concept [30], 13 citations, key term – Electric_power_transmission_networks: The article discusses the principles of building a simulation model of an integrated multi-energy system based on the concept of an energy node. The proposed approach is applicable to the study of the problems of integrated power systems with multiple carriers, taking into account their properties and operation features.

A Guide to Solar Power Forecasting using ARMA Models [31], 11 citations, key term – Electric_power_transmission_networks: This paper describes a step-by-step methodology for predicting the power output of a photovoltaic solar generator using hourly autoregressive moving average (ARMA) models. The resulting model is suitable for incorporation into more complex operation and planning models, and shows relatively good accuracy. It is a good predictive tool for sample generation for stochastic energy optimization models.

Predicting cyber-attacks on industrial systems using the Kalman filter [32], 10 citations, key term – Sustainable_development: This paper proposes to use a Kalman filter to solve the problem of predicting the time series describing the gasoil heating loop process. The limitations of this approach are described, as well as the advantages over other prediction models.

The above examples show that the most cited Russian research papers are also related to solving engineering problems of control and automation of power systems using modern methods of analysis and modeling.

Environmental, social, and economic issues are not prevalent in these studies.

Figures 2–4 present diagrams illustrating the clustering of the conference proceedings of the other four countries. In order not to inflate the size of this article, each illustration will be followed by several titles of research articles reflecting the content of the first-level clusters.

The list below shows the titles of the Indian papers belonging to the Deep Learning cluster:

- Performance dependency of facial emotion recognition system on dropout and learning rate;
- An Improved Multifocus Image Fusion Algorithm Using Deep Learning and Adaptive Fuzzy Filter;
- Artificial intelligence based efficient phenotyping for agronomics;
- Weed Detection in Agricultural fields using Deep Learning Process;
- Artificial intelligence-based identification of total knee arthroplasty implants;
- Survey on Automatic Script Identification Techniques;
- Automated Food image Classification using Deep Learning approach;
- Analysis and forecasting of Time-Series data using S-ARIMA, CNN and LSTM.

It is clear that the research is general in nature and does not necessarily relate to energy. Moreover, in 1 793 records with 4 fields (title, abstract, author keywords, and index keywords), the term “Energy” appears only 377 times. However, Scopus attributes all of the records to the field of Energy research. Note: according to Scopus restrictions, data export is limited to 2 thousand data entries, not all records have the index keywords field filled in, so the analysis considered only 1 793 records (out of the total 2 000) that had the index keywords field filled in.

Thus, research on AI is most often general in nature. If one tries to find research papers on AI applications in the energy sector, one would need additional metadata filtering of research papers on specific energy systems, such as smart grids. But then it would be a completely different bibliometric study, such as “Applications of AI in Smart Grids.”

In the Chinese conference proceedings, the main cluster of documents is described by two terms and is more specific than in the case of the Indian research papers. It is described as Power Transmission Networks AND Smart Power System. This topic is directly related to the energy sector, so the Chinese papers on the topic under consideration will be of more interest.

Typical titles of Chinese conference proceedings for this cluster include the following:

- Transmission line electrification spanning construction technology;
- Component Importance Indices of Transmission Systems Based on The Impact-increment Based State Enumeration Method;
- Analysis of Half-Wavelength Transmission Lines System State in Operation;
- Time Difference Method to Calculate the Optimal Differential Point of Half-wavelength AC Transmission Line Differential Protection;
- Fault Diagnosis of Transmission Line – A Phasor Domain Approach;
- Study on charged detection method of porcelain insulator in single asymmetric transmission line;
- Dynamic Modeling and Simulation of the Large-scale Regional Integrated Electricity and Natural Gas System;

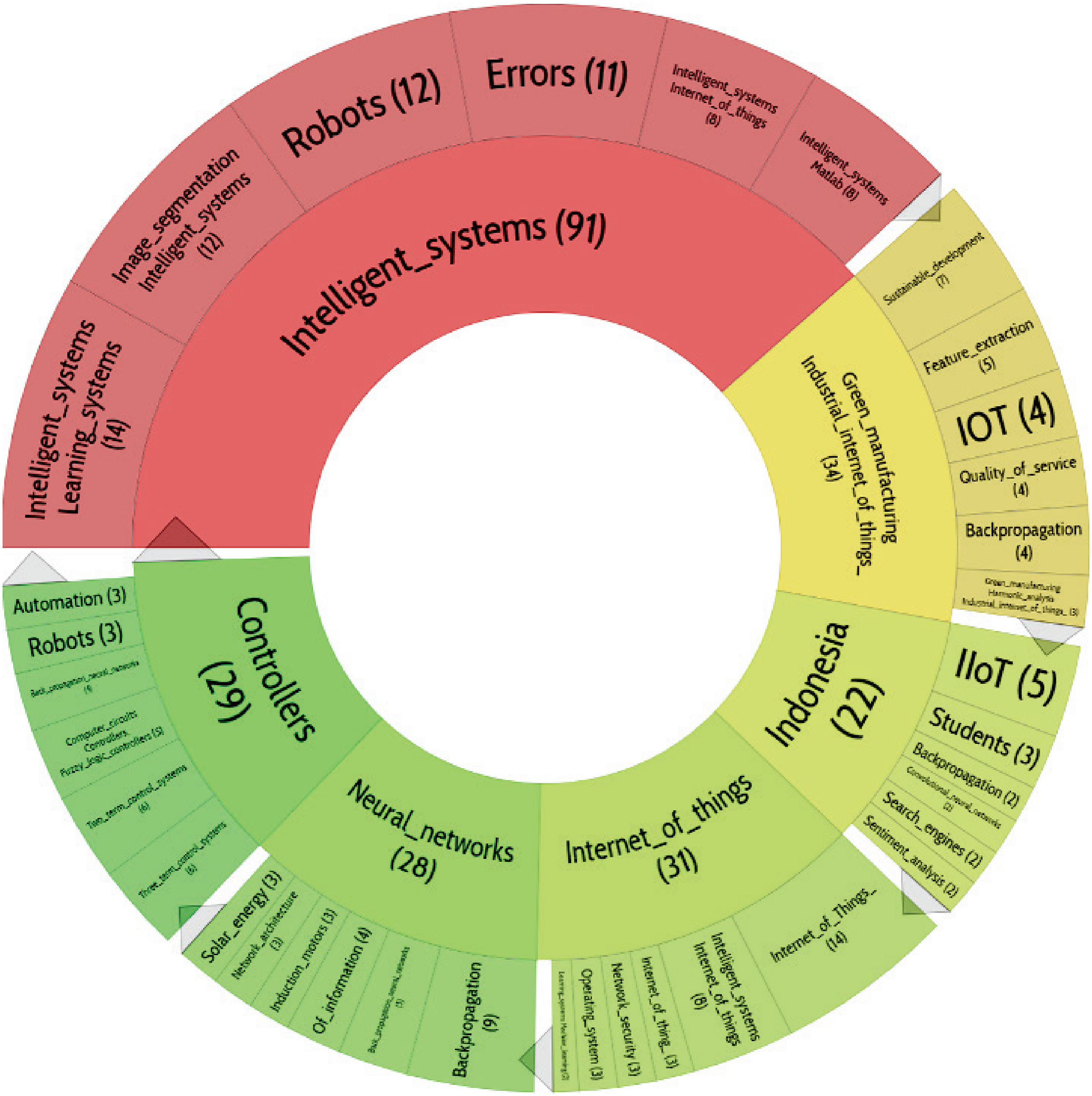

Fig. 5. Circles diagram showing the clustering of conference proceedings by researchers from Indonesia using the Lingo3 algorithm.

- Research on the Integral Metrological Performance of Evaluation Method of Smart Electricity Meters;
- Research on Non-Intrusive Load Monitoring Based on Random Forest Algorithm;
- The Problem Analysis and Solution Suggestion in the Process of City Information Model Construction.

The titles of the Chinese conference proceedings are also more specific and relevant to the energy sector.

In the U.S., Smart power grid, Smart city, Internet of things are clearly dominant.

Typical conference proceedings headlines for the Smart power grid cluster include the following:

- Anomaly detection of transactive energy systems with competitive markets;
- Evolving distribution utility rate structures to accommodate emerging technologies;
- Moving Towards Distribution System Operators: Current Work and Future Directions;
- Transactive Energy Versus Demand Response in Cutting Wholesale Electricity Prices;
- Quantitative evaluation of reliability improvement: Case study on a self-healing distribution system;
- Development of HELICS-based high-performance cyber-physical co-simulation framework for distributed energy resources applications;
- Quantifying technical diversity benefits of wind as a

distributed energy resource;

- A transactive grid with microgrids using blockchain for the energy internet;
- Defining a use case for the ADMS test bed: Fault location, isolation, and service restoration with distributed energy resources;
- An integrated transmission-distribution modeling for phasor-domain dynamic analysis in real-time;
- A Value-of-Service based Model for Resilient Distribution System Restoration with Microgrids;
- A universal multiple inverter control architecture with droop for unbalanced distribution grid;
- Analysis of Hybrid Smart Grid Communication Network Designs for Distributed Energy Resources Coordination;
- Control and Dispatch of Distributed Energy Resources with Improved Frequency Regulation using Fully Active Hybrid Energy Storage System;
- Toward a service-oriented broker architecture for the distribution grid;
- An intelligent energy router for managing behind-the-meter resources and assets;
- Transactive Energy Management with Blockchain Smart Contracts for P2P Multi-Settlement Markets;
- Network Configurations for IoT Services in Smart Grid.

In all of the above titles of research papers, the topic of AI smart grids and IoT is clearly visible. The U.S. research papers, like the Chinese ones, are more specific than the Indian ones and are of greater interest for further study.

As in the case of the Indian papers, the Indonesian conference proceedings are more general in nature, which is reflected in the title of the main cluster: Intelligent Systems.

Below are some examples of the titles of research papers related to this cluster:

- Exploring challenges of online learning activity in politeknik elektronika negeri surabaya at the beginning of covid-19 outbreak;
- Pedestrian crossing decision prediction based on behavioral feature using deep learning;
- CNN Based Autoencoder Application in Breast Cancer Image Retrieval;
- Determination of learning media in elementary school using multi-objective optimization on the basis of ratio analysis method;
- Student Behavior Analysis to Detect Learning Styles in Moodle Learning Management System;
- Deep Convolutional Neural Network for Melanoma Image Classification;
- Transfer Learning for Recognizing Face in Disguise;
- Violence Classification Using Support Vector Machine and Deep Transfer Learning Feature Extraction;
- A Deep Auto Encoder Semi Convolution Neural Network for Yearly Rainfall Prediction.

Indonesian contributions, like the Indian ones, are of less interest to Russian researchers. Rather, of interest is the experience of these countries in occupying their niche in current scientific research. For example, both India and Indonesia make great efforts to participate in international conferences, while for Russian researchers it is more typical to participate in international conferences organized and held in Russia. But this is the topic of a dedicated study, which is beyond the scope of this article.

III. Conclusion

1. The majority of Russian AI and energy-related conference proceedings indexed in Scopus are presented at conferences organized in Russia; in addition, one conference, the "International Multiconference on Industrial Engineering and Advanced Technologies" (FarEastCon2019 and FarEastCon2020), held in 2019-2020, predominates.

It should be noted that the absolute majority of articles on the topic in question have been published in only one journal, the International Journal of Engineering Research and Technology, which since 2021 is no longer indexed in Scopus.

Thus, it is necessary to further promote journals and conferences held in Russia, where our authors could present the results of their research on current topics such as AI and energy. Participation in prestigious international conferences is good, but expensive. Without developing domestic international-level publication resources, it will be difficult to foster the results of Russian research in the field of AI and energy.

2. Different methods of analysis of bibliometric data of conference proceedings: Subject Area, Index Keywords, Titles, give a similar result: engineering topics prevail in Russian research. The main areas of research can be described by the following words: systems; information; modeling; energy; power supply; power plants; control; process; automation; neural; networks; energy efficiency; technology. The social, environmental, economic and business aspects of AI in the energy sector are very poorly presented. These areas are untapped potential for Russian research.

3. China and the United States are of the greatest interest for AI and energy research.

The works of researchers from these countries are more specific than those of researchers from India and Indonesia.

China focuses on algorithms and their applications to optimize grid control and fault monitoring (most typical terms: Power Transmission Networks AND Smart Power System). This is in line with China's strategy to take a key position in AI research, and the energy sector is no exception.

Machine learning for energy systems has also received a lot of attention in the U.S., yet much of this research has focused on renewable energy sources such as distributed energy storage, intelligent transportation systems, and smart cities (dominated by such topics as Smart power grid, Smart city, and Internet of things).

The Chinese and U.S. experience shows that Russian researchers pay insufficient attention to distributed systems other than power systems. The reason may be that energy transition issues in this country are only at the initial stage, and less attention is paid to smart cities and smart alternative energy systems due to less developed infrastructure, if compared to China and the U.S.

4. India's and Indonesia's research papers are more general in nature and are not always related to the field of energy.

Of more interest is the approach of these countries to take their place in modern scientific research. These countries apply great efforts to participate in international conferences and try to establish their own journals and hold conferences on relevant topics, despite lacking the economic resources of China and the United States, and engineering capabilities of Russia.

The article demonstrates the effectiveness of using titles of research papers to describe topics by clustering documents but the Russian conferences proceedings are presented by a limited number of research papers indexed in Scopus. For a more complete study of the selected topics and for expanding the scope of sources of the analyzed research papers, it seems expedient to conduct a similar study using abstract databases other than Scopus, such as, for example, Dimensions, which indexes such notable sources as preprints.org, arXiv.org, EarthArXiv.org, engrXiv.org, OSF Preprints, Research Square, and other preprint services, and journals not indexed by Scopus and WoS, such as Energy Systems Research and Actual Problems of Oil and Gas.

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