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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.

Energy systems research methodology is based on a systems approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of systems analysis.

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

Priority Directions In The Development Of Corporate Governance In Russia's Power Industry

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***Abstract* — The study identifies the strengthening of the board of directors as a priority direction of the development of corporate governance in Russian power generating companies so as to best serve the interests of their investors. This is due to numerous non-compliances of the current corporate practice with respect to those principles of the Corporate Governance Code that they shall be in charge of. These non-compliances are identified by generalized and in-depth appraisals as per the criteria set out by the Bank of Russia for complying with these principles. We propose a range of measures to strengthen the boards of directors. They are concerned with the stages of nomination, election, current activities, and performance evaluation. To this end, we delineate professional competencies of the board of directors members that are relevant under the shortening of strategic planning time frames and the advent of new technologies.**

***Index Terms* — Corporate governance, Corporate Governance Code, Russian power generating companies, board of directors, investors.**

I. Introduction

One of the key objectives of the Russian power sector reform in 2003-2008 in the course of its transition to a market economy was to set the stage for attracting investment. However, the power generating companies established back then as part of the reform were indemnified for their investment in new capacity additions as per a non-market driven procedure of capacity contracting (CC). After the expiration of the CCs, the Government of the Russian Federation enacted another large-scale upgrading program for combined heat and power plants. The projects deemed eligible for the program will also be entitled to guaranteed break-even arrangements by imposing higher capacity tariffs on the consumer [1]. Under such circumstances, the issue of enhancing the investment appeal of the companies remains relevant. One of its key indicators adopted as part of international best practices is corporate governance. Its purpose is to facilitate the establishment of the environment of trust, transparency, and accountability required to provide incentives for long-term capital investment [2].

Apart from the guaranteed payback of investment through increased payments from consumers, which is practiced in Russia, the following main reasons impeding the development of domestic corporate governance are identified: relatively little experience in this area; insufficiently developed Russian corporate legislation and internal documents of the companies, which do not completely meet the internationally recognized corporate governance standards, their declarative and formal implementation; high concentration of ownership with the interests of major shareholders dominating those of minority shareholders, with characteristic violations of their rights (to membership in boards of directors and regulatory bodies; compulsory dividends; and access to complete, timely and reliable information about the company); permanent redistribution of ownership; mixing functions of the state as a major shareholder and regulator which contradicts the basic principle of corporate governance for state participation companies, which is established by the Organization for Economic Cooperation and Development and suggests separation of these functions; mixing powers and responsibilities between major shareholders and hired top managers; relatively weak external corporate control by the stock market and the banking system; lack of long-established traditions of corporate social responsibility, corporate ethics and business culture; lagging in the application of new management technologies.

The purpose of the study performed by the author is

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to identify a top priority direction of the development of corporate governance in Russian power generating companies that is aligned with the interests of investors and accommodates the changes that have taken place in the external environment.

The methodology behind this study is based on the Guidelines of the Bank of Russia on complying with the principles and recommendations of the Corporate Governance Code (Letter No. IN-06-52/8 of the Bank of Russia dated February 17, 2016) [3]. Identifying a priority direction of the development of corporate governance was carried out based on generalized data of comprehensive assessments of the current corporate practice adopted by 12 Russian power generating companies that made publicly available Addendum "On compliance with principles and guidelines of the Corporate Governance Code" to their 2017 annual reports. [4–15]. The proposals previously contributed by the author to this field have been updated to match the changes in the external environment [16]. The study makes use of the data provided by information agencies as well the research contributions made by the New Economic School and the Russian Institute of Directors to corporate governance studies [17, 18].

This study identifies the strengthening of the board of directors as a priority direction for the development of the corporate governance of Russian power generating companies. This proves to be in line with the findings obtained by the "Platforma" Center for Social Engineering, the Center for Strategic Studies at the Moscow State Institute of International Relations, the Association of Independent Directors, and the National Research University Higher School of Economics [19–21].

The findings of the study performed bear on further enhancing the investment appeal of Russian power generating companies and making more well-grounded and balanced decisions on the part of investors when investing their funds in these companies.

II. Current practice in corporate governance

The practice currently adopted in corporate governance of Russian power generating companies was assessed by the methods of generalized and in-depth evaluation. The generalized evaluation was performed against the 79 corporate governance principles of Level 2 that have three-digit codes assigned to them ('1.1.1.' or '1.2.3.' and so on). The status of compliance to these principles ("compliant", "partially compliant", "non-compliant") was treated without a further breakdown by the compliance criteria for each of them. This method of evaluation is common for the majority of the companies, which follows from their annual reports on the compliance with the corporate governance principles of the Code. For the rest of the companies, the "partially compliant" status was assigned in the case of their failure to meet at least one of the criteria. The findings of the evaluation of the compliance with the Level 2 corporate governance principles as stipulated in the Code are presented in Table 1.

The values presented in Table 1 show that there are substantial differences with respect to the extent Russian power generating companies comply with the corporate governance principles. The top ranking companies here are PJSC Inter RAO, PJSC Enel Russia, and PJSC RusHydro. Of the total of 79 principles covered by the study, they comply with 73, 62, and 59 principles respectively. PJSC Quadra and PJSC TGK-2 are the lowest ranked companies. They scored well below the rest with 33 and 32 principles to their credit respectively. The comparative analysis of the "partially compliant" status among the companies that rank both in the top and the bottom yields practically the same correlation. PJSC Inter RAO, PJSC Enel Russia, PJSC RusHydro partially comply with 4, 13, and 17 principles respectively. The corresponding values for PJSC Quadra and PJSC TGK-2 are 27 and 32 principles respectively, thus lagging behind PJSC Inter RAO scoring 7 to 8 times lower. The disparity between the companies that perform best and worst with respect to the number of principles they fail to comply with proves even more pronounced. In particular, the number of corporate governance principles PJSC Quadra does not comply with exceeds that of the PJSC Inter RAO by a factor of 9.5.

No less significant are the differences between all companies in their status of being compliant with corporate governance principles. It follows from the data presented in Table 1 that in the companies that scored best on corporate

Table 1. With compliance level 2 principles of the code.

Companies (PJSC)	Compliant	Partially compliant	Non-compliant
Inter RAO	73	4	2
Enel Russia	62	13	4
RusHydro	59	17	3
TGK-1	57	21	1
TGK-14	52	20	7
Unipro	45	27	7
OGK-2	41	25	13
T Plus	41	23	15
Mosenergo	39	30	10
Irkenergo	34	30	15
Quadra	33	27	19
TGK-2	32	32	15

Table 2. Meeting the criteria of complying with the principles of the code.

Companies (PJSC)	Compliant	Partially compliant	Non-compliant
Inter RAO	116	8	4
Enel Russia	104	16	8
RusHydro	100	25	3
TGK-1	102	23	3
TGK-14	81	38	9
Unipro	83	29	16
OGK-2	82	20	26
T Plus	56	50	22
Mosenergo	66	48	14
Irkenergo	50	59	19
Quadra	65	28	35
TGK-2	60	39	29

governance principles, the percentage of the components that make up their compliance status (i.e., "compliant", "partially compliant", and "non-compliant") of the total of 79 principles they were assessed against was as follows: PJSC Inter RAO – 92%, 5%, 3%; PJSC Enel Russia – 75%, 22%, 3%; PJSC RusHydro – 74.7%, 21.5%, 3.8%. In the case of the worst scoring companies we observed a relative shift towards an increase in the number of the principles a company "partially compliant" or "non-compliant" with: PJSC Quadra – 41.8%, 34.2%, 24.0%; PJSC TGK-2 – 40.5%, 40.5%, 19.0%.

In order to arrive at a more in-depth and unbiased view of the corporate governance practice in Russian power generating companies we have performed an additional study against the complete set of 128 evaluation criteria of compliance with the principles stipulated by the Code. The findings of such analysis are presented in Table 2.

Under the above evaluation method, we observed a well-anticipated increase in the number of the principles that the companies fail to comply with. To a larger extent this holds true for the worst scoring companies. As per the data of Table 2, the share the criteria they do not meet makeup of the total of 128 criteria of compliance to the principles stipulated by the Code saw an increase to 26% and 23% in the case of PJSC Quadra and PJSC TGK-2 respectively.

We have identified which of the evaluation criteria of the principles stipulated by the Code are not complied with. Those of them that are most frequently not complied with are highlighted by listing them in dedicated Table 3. They are arranged in ascending order of the share of the companies that failed to comply with the above criteria;

All of the criteria listed in Table 3 refer to the scope of responsibilities of the board of directors, to the extent of the authority was delegated to it:

- To back the observance of rights and equal terms for shareholders.
- To approve internal corporate documents.
- To establishe and to approve the policy of the companies with respect to remuneration, to ensure control over the implementation and enforcement of this policy, and, if required, to revise it and introduce amendments to it.
- To define the principles and approaches behind the system of risk management and internal control, monitor the compliance of the adopted system and the efficiency of its operation as judged against them.
- To ensure the development and implementation of the information policy, transparency, timeliness, and completeness of information disclosure, and unhindered access to it granted to shareholders.
- To exercise control over the corporate governance practice, to play a key role in material corporate actions.
- To approve third-party appraisal officers when performing material corporate actions to protect the rights and legitimated interests of shareholders.

The poor efficiency of the boards of directors in Russian

Table 3. Criteria the companies do not comply with.

Principles	Evaluation criteria for compliance with the Code principles
1.1.6.	3. When making decisions on arranging and holding general meetings of shareholders, the board of directors should consider the issue of making use of the means of telecommunication to provide remote access to shareholders so that they could take part in these meetings during the reporting period.
2.1.7.	1. During the reporting period, the board of directors considered the issues of the corporate governance practice.
2.2.1.	2. The annual report covers the information on key results of the board of directors performance evaluation.
2.7.4.	1. Decisions on most important issues relating to the company's business should be made at a meeting of the board of directors by a qualified majority of at least three-quarters of the votes or by a majority vote of all elected board of directors members.
6.1.1.	2. The board of directors (or a committee thereof) should consider the issues pertinent to compliance with the information policy at least once during the reporting period.
2.9.1.	1. An internal evaluation or a third-party performance evaluation of the board of directors should be carry out in the reporting period covered the performance evaluation of committees, individual members of the board of directors and the board of directors as a whole. 2. The findings of an internal performance evaluation or a third-party performance evaluation carried out in the reporting period should be reviewed during a meeting of the board of directors held in person.
4.1.2.	1. During the reporting period, the remuneration committee should consider the remuneration policy and its implementation practice and sumbitted the relevant recommendations to the board of directors as required.
4.2.2.	1. If an internal document provides for a transfer of shares to the board of directors members, there should also be provided and disclosed the clearly stated rights of their ownership aimed at long-term incentives to hold them.
7.1.2.	1. There should be a procedure set out for independent directors to state their opinions on material corporate actions prior to their approval.
2.9.2.	1. A third-party company should be involved at least once in providing an independent performance evaluation of the board of directors during the three most recent reporting periods.
4.3.2.	1. The company should put in place a long-term incentive programme for the members of the company's executive bodies and other key managers involving the company's share (or derivative financial instruments with its share serving as the underlying asset). 2. The long-term incentive programme for the members of the company's executive bodies and other key managers should provide for the right of disposing of shares or other financial instruments employed by such programme to arise no earlier than in three years from the date when they were provided. In addition, the right to dispose of the same should be made conditional on the achievement of certain targets by the company.
2.4.3.	1. Independent directors should account for at least one-third of all directors elected to the board of directors.
7.2.2.	3. Internal documents should expand a list of grounds on which members of the company's board of directors as well as other persons referred to in respective laws, are deemed to be interested in transactions of the company.

power generating companies served as the defining factor when deciding on the priority direction of the development of their corporate governance.

III. Development prospects

The priority direction for the development of corporate governance in Russian power generating companies should be the strengthening of the boards of directors. Their role as the key managerial body is getting truly strategic one. This is mainly due to the paradigm shift in corporate governance from a system of exercising control over the management team to a system of strategic governance and risk mitigation. The above is supplemented by the challenge thrown down by the advent of information technology that makes the flexibility and adaptability of companies stand out. The major driver behind the development of corporate governance in Russia nowadays is the set of tools enforced by formal requirements of the Central Bank of the Russian Federation acting as the regulating body. Notably, the strong board of directors is thought of as a key tool that ensures a leading position of companies with respect to corporate governance [19]. The board of directors is a key source of efficiency and sustainability of companies. The risks that investors face in the majority of Russian companies are those of poor governance, low rates of adoption of the state-of-the-art managerial techniques, an underdeveloped culture of the processes of working out and implementating the most important decisions [20]. Investors value more the companies that have the lack of the board of directors approaching the best practice, its crucial role in enhancing the quality of their corporate governance is one of the main takeaways from the research conducted by the Association of Independent Directors and the National Research University Higher School of Economics [21].

To establish a strong and qualified board of directors in Russian power generating companies one has to re-envision and bring up to date the approaches to the:

A. Nomination.
B. Election.
C. Current activities.
D. Performance evaluation.

A. The nomination of the candidates to the board of directors members

- To compile a checklist of select competencies for candidates to possess, so as to be in line with the objectives and tasks set out to further the development of companies. This is a required action to take due to higher requirements to be met by professional competencies given the shortening of the strategic planning time frames and the advent of innovations and information and digital technologies.
- To give due consideration to the commitment of candidates to moral and ethical values as based on the principles of reasonableness, integrity, justice, impartiality, incorruptibility, respect for the interests of their company, its partners, customers, the society in general, neither causing them any harm nor circumventing the law by pursuing illegal or otherwise deliberately unscrupulous ends.
- To have a preliminary review by shareholders of behavioral traits of candidates, on a par with their readiness for collaboration and trade-offs for the sake of effective decision making. One should not nominate to the board of directors the advocates of "support groups", bystanders, conventionalists, and "constant" critics. Unlike with the Code that recommends competencies, personal qualities, and behavioral traits as the criteria to judge the performance of the board of directors members against, we propose to apply these criteria in the course of their nomination and election. Preliminary discussions by shareholders of the candidates to the board of directors as well as the voting procedure may be held by means of online bulletin boards, teleconferencing, and video conferencing. In a sense, these are to be treated as the primaries hold at the corporate level. They are required to identify the most worthy candidates to be nominated and subsequently elected to the board of directors members during the actual election.
- To increase the number of independents among the candidates nominated for the board of directors. This is required, in particular, to strengthen the board of directors competencies, including the mastery of cutting edge managerial techniques. There should be a preliminary and thorough examination of such candidates with respect to their independence as per the guidelines provided in the Code, which is mainly due the nowadays common issue of "independent directors" who actually fail to act impartially.
- To select candidates to the board of directors who are supported by shareholders based on the actual evaluation of their contributions and the programme of development of the company during the next fiscal period.

B. The election of the board of directors members

- To timely disclose the information by the date of the general meeting of shareholders, including that on alterations of internal documents.
- To make available the comprehensive information on the results of the preliminary evaluation of the candidates to the board of directors in the documents on the preparation for and holding of general meetings of shareholders (nominators, biographical data, professional and personal qualities, education background, working experience, conflict of interest disclosure, data on independent candidates, etc.).
- To grant remote access to shareholders to participate in general meetings of the reporting period by relying on the means of telecommunication.

- To increase the involvement of professional investors with respect to voting during general meetings of shareholders.

C. Current activities of the board of directors

- To improve the work of the board of directors committees done with respect to the preparation for the decisions taken to enable higher operational responsiveness in having them reviewed by the board of directors members and their efficacy.
- To involve the board of directors members in the company's business and to strengthen the participatory principle in their activities by holding comprehensive discussions on the matters they deal with and on the decision-making that is informed by various opinions. Running meetings in person is preferable to written consents that have gained wide acceptance. Given the telecommunication means made available in the companies, they can be extended to enable the remote access for all Board members to participate in the discussion of the issues reviewed.
- To develop unified corporate standards of ethical conduct due to the lack of respective guidelines in the Code.
- To enable all interested parties to report on violations or suspicions thereof via dedicated channels established by the company. One of such tools is the confidential communication channel for informants to report on corruption. At the companies that run such hotline service, this channel generally boils down to an e-mail address or a phone number. This model of interaction is not very efficient and cannot guarantee feedback and complete confidentiality for the informant. The development of a dedicated electronic form for informants available at the official website of a company is a more up-to-date version of this model. It assigns each of them a unique pin code, whereas the claim is submitted for review to a third-party audit company with the feedback system put in place. Companies have to face penalties for any violations

D. The board of directors performance evaluation

- To develop a procedure for the board of directors performance evaluation due to the lack of respective guidelines in the Code. To develop a set of tools for the evaluation (the contents of the question lists that form the basis of the questionnaire) and an analysis of the data obtained thereby. To this end, one may involve third-party advisers. Their involvement will enable solving the issues related to overcoming the subjective bias inherent in such evaluation activities and make the analysis of the findings more balanced.
- To develop the Regulation "On the board of directors performance evaluation" which is subject to approval by the board of directors. Its content should cover the following: the development of the tools for the evaluation (the contents of justification of the need to perform the evaluation; evaluation types; procedures and employed evaluation tools; the format of the notification on performing the evaluation as intended for public disclosure (as it appears in the annual report on company's activities, at its corporate website, and so on).
- To modify the approach recommended by the Code with respect to the annual remuneration of the board of directors members by introducing its fixed and variable components in contrast to the fixed-only remuneration advocated by the Code. That said, the variable component of the remuneration shall not be the payments for attending the meetings of the board of directors or its committees as they are deemed to be s basic responsibilities of a director as per the Code. The variable component of the remuneration shall be linked to the financial performance achievements of the company (free cash flow, EBITDA, etc.) to align the financial incentives of the board of directors to those of the shareholders. When deciding on the amount of such remuneration, one shall account for objective grounds as based on the performance evaluation results of its members.

IV. Conclusion

The issue of enhancing the investment appeal of Russian power generating companies still remains relevant. Corporate governance is one of the key factors that contribute to its improvement. We have performed an evaluation of the current practice adopted by these companies. The evaluation was made against various criteria of the compliance of such practice with the Corporate Governance Code. As per the results of such evaluations, the majority of the companies have been found to have relatively poor corporate governance: the number of the criteria the companies that rank among the lowest fail to comply with, as yielded by the first appraisal method, is 7 to 8 times that of the leading companies. The second method yields the value of 9.5 times. We have identified the evaluation criteria that the companies fail to meet most frequently. All of them have proved to belong to the scope of responsibilities of the boards of directors. The strengthening of the boards of directors is identified as a priority direction of further development of corporate governance in Russian power generating companies. For the purpose of their strengthening under present-day circumstances; we have proposed certain changes applicable to nomination, election, current activities and performance evaluation of their members.

References

[1] The RF Government approves 1.9 trillion ruble spending on the programme of combined heat and power plants upgrading. Available: http://www.

bigpowernews.ru/print/86618.phtml (in Russian.)

[2] OECD (2016). Principles of corporate governance G20/OECD, OECD Publishing, Paris. Available: http://dx.doi.org/10.1787/9789264252035-ru (in Russian.)

[3] Corporate Governance Code. Normative acts and operational information of the Central Bank of the Russian Federation, Bulletin of the Bank of Russia, 40 (1518), 2014, (in Russian.)

[4] Report on the compliance of PJSC TGC-1 with the principles and recommendations of the Corporate Governance Code. Available: http://www.tgc1.ru/fileadmin/ir/reports/annual/2017/godovoi_otchet_tgk-1_2017.pdf, (in Russian.)

[5] Report on compliance of JSC TGK-2 with the principles and recommendations of the Corporate Governance Code. Available: http://www.tgc-2.ru/upload/iblock/f8d/areport_2016.pdf, (in Russian.)

[6] Report on compliance of PJSC Quadra with the principles and recommendations of the Code of Corporate Governance recommended by the Bank of Russia Letter No. 06-52 / 2463 of 10.04.2014. Available: https://www.quadra.ru/wp-content/uploads/2018/06/gosa2018_AnnualReport.pdf, (in Russian.)

[7] Information on compliance of PJSC Enel Russia with the principles and recommendations of the Corporate Governance Code. Available: https://www.enelrussia.ru/content/dam/enel-ru/documents/ru/investors/annual/Enel_Annual_report-2017-rus.pdf, (in Russian.)

[8] Report on compliance of PJSC Unipro with the principles and recommendations of the Corporate Governance Code. Available: http://www.unipro.energy/shareholders/disclosure/annual_reports/, (in Russian.)

[9] Report on compliance of PJSC OGK-2 with the principles and recommendations of the Corporate Governance Code. Available: https://www.ogk2.ru/rus/si/infodisclosure/year/, (in Russian.)

[10] Report on compliance of PJSC T Plus with the principles and recommendations of the Corporate Governance Code. Available: http://www.tplusgroup.ru/fileadmin/f/voltgc/ir/disclosure/documents/GO/T_Pljus_PAO_GO_2016.pdf, (in Russian.)

[11] Report on compliance of PJSC Mosenergo with the principles and recommendations of the Corporate Governance Code. Available: http://www.mosenergo.ru/d/textpage/ad/173/godovoj-otchet-17.pdf, (in Russian.)

[12] Report on compliance of PJSC TGC-14 with the principles and recommendations of the Corporate Governance Code. Available: https://www.tgk-1.com/upload/medialibrary/876/go_2017_dlya_sayta_itog.pdf, (in Russian.)

[13] Report on compliance with the principles and recommendations of the Corporate Governance Code. Annual Report of PJSC Inter RAO 2017. Available: http://www.interrao.ru/upload/doc/Inter_RAO_AR2017_ru_web.pdf, (in Russian.)

[14] Report on compliance with the principles and recommendations of the Corporate Governance Code. Annual Report of PJSC RusHydro 2017. Available: http://www.rushydro.ru/upload/iblock/90d/Kniga-Prilozhenij-2017-rus.pdf, (in Russian.)

[15] Report on compliance of PJSC Irkutskenergo with the principles and recommendations of the Corporate Governance Code. Available: http://www.irkutskenergo.ru/gi/31500, (in Russian.)

[16] Sheveleva G. I., Areas for the improvement in corporate governance in the Russian electric power industry, Proc. of 10th Int. Conf. "MLSD'2017", Moscow, pp. 1–5. DOI: 10.1109/MLSD.2017.8109686

[17] S. M. Guriyev, Myths of economis. Fallacies and stereotypes disseminated by mass media and politicians, 6th ed. Moscow, Mann, Ivanov, and Ferber, 2017. (in Russian.)

[18] I. V. Belikov, Performance evaluatio of the company's board of directors and senior, Aktsionernoye obshchestvo: voprosy korporativnogo upravleniia, no. 4, pp. 14–21, 2008. (in Russian.)

[19] Corporate governance in Russia: Genre identity crisis and hopes for the future, Moscow: "Platforma" Center for Social Engineering, 2018. Available: http://www.nand.ru/upload/medialibrary/news

[20] E. B. Zavyalova, V. B. Kondratiev, et al., Corporate governance as a contributing factor to enhancing the investment appeal, Moscow, MGIMO University, 2014. (in Russian.)

[21] Corporate governance Index of Russia, 2017. Available: http://nand.ru/upload/ux/corporate_governance_index_2017.pdf, (in Russian.)

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Effects Of The Adoption Of Renewable Energy Sources Within The "Baikal-Khövsgöl" Cross-Border Recreation Area

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***Abstract* — The study provides an analysis of the current state of the power supply system within the "Baikal-Khövsgöl" cross-border recreation area, which stands for the area spanning from the southern part of Lake Baikal to Lake Khövsgöl through the Republic of Buryatia (Tunkinsky and Okinsky districts). There are a fairly large number of consumers connected to the end sections of transmission lines, as well as decentralized consumers in the area in question. The operating parameters of the power grid were evaluated in terms of a prospective increase in electrical loads. To ensure reliable power supply to consumers and compliance with the requirements of GOST R 32144-2013 with regard to voltage deviations, the feasibility of using renewable energy sources was investigated. Given the geographical location and the presence of special areas of conservation, the use of renewable energy is a strategic area of Russian-Mongolian cooperation. The wind energy and solar energy potential in the "Baikal-Khövsgöl" cross-border recreation area was assessed using the NASA POWER project datasets. A comparative analysis of the financial viability of solar power plants, wind power plants, and small HPPs was made for the conditions of this geographical area. Calculations of the power grid operating parameters were carried out to determine the sites for installation and installed capacity of renewable energy sources, taking into account the prospects for the growth of electrical loads.**

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***Index Terms* — recreation area, renewable energy sources, solar and wind energy potential, remote consumers, electric power quality, voltage deviation, reactive power compensation units.**

I. Introduction

The Baikal-Khövsgöl basin is one of the geographical areas whose sustainable development is not only of national but also of great international importance. Mechanisms for the conservation of the natural and historical biosphere and the rational use of natural resources in the basin of the unique ecosystems of Lake Baikal (Russia) and Lake Khövsgöl (Mongolia) warrant priority attention. The basin of Lake Khövsgöl, which is one of the stable main sources that feed the Selenga River and, consequently, Lake Baikal, remain almost untouched by human activities. There are some threats to the security of the unique ecological system of lakes, and a network of special areas of conservation has been created to overcome them [1].

The Russian-Mongolian border section at the Mondy-Khankh border crossing is the interface zone between two large national parks: the Lake Khövsgöl National Park (Mongolia) and the Tunkinsky National Park (Russia). The Khardyl-Sardyk nature reserve, adjacent to the Lake Khövsgöl National Park borders in the south-west, forms a single large tract of land with the latter. On the Russian side of the border, there is the Pribaikalsky National Park and the Irkutny sanctuary [2, 3].

Currently, special conservation areas are actively involved in ecotourism: new economic mechanisms of their operation are being introduced; they are being integrated into the sphere of social and economic development; government funding is being increased; participation in environmental projects financed by international nonprofit organizations is being expanded; and they are being reorganized and consolidated [2, 4].

In general, the Baikal-Khövsgöl natural area is very promising for the development of international tourism. It is home to four national parks: Pribaikalsky, Zabaikalsky, Tunkinsky, and Khövsgöl; Baikalo-Lensky, Baikalsky, Barguzinsky, Ulan-Taiga, and Khardyl-Sardyk nature reserves [2, 3]; a lot of sanatoriums; recreation facilities; and sites of the tourist and recreational kind. Lakes Baikal and Khövsgöl are connected by a highway passing through the Tunka valley. The region is dominated by middle mountainous terrain, and close to it, on the Russian-Mongolian border, there is Mönkh Saridag, the highest mountain in the Sayan Mountains, which is a popular destination for sports tourism [5].

The development of ecotourism should be carried out with great care as it is required to ensure that all conditions are in place to minimize environmental impacts. This applies mostly to the electric power supply system, which should be developed at a faster pace to back the growth of tourism infrastructure in the region.

Renewable energy sources (RES) have a lower impact on the environment than conventional sources of energy. Their adoption may prove feasible in the districts remote from the centralized power supply or those districts where extended outages take place due to long power lines, as well as the districts that are home to special conservation areas and tourist and recreational zones [6-10].

In Mongolia, support for renewable energy development at the national level is enabled by the National Renewable Energy Program. The program claims to promote and extend renewable energy development in Mongolia, to create conditions for ecological balance, to reduce unemployment and poverty, and to promote social and economic sustainable development. In Russia, mechanisms to stimulate the development of the renewable generation were introduced by Resolution of the Government of Russia No. 449 “On the mechanism of incentives to use renewable energy sources in the wholesale electricity and capacity market” dated May 28, 2013, and Resolution of the Government of the Russian Federation No. 47 “On amending certain acts of the Government of the Russian Federation on the incentives to use renewable energy sources in retail electricity markets” dated January 23, 2015.

In connection with the above mentioned, the use of RES in the cross-border recreation area “Baikal-Khövsgöl” is one of the strategic directions of expansion of the Russian-Mongolian cooperation and the relevance of the assessment of economic and technical effects of the implementation of these activities needs no further justification.

II. Analysis of the current state of the electric power supply system in the “Baikal-Khövsgöl” cross-border recreation area

In Mongolia, the centralized power supply covers all 4 sums bordering Lake Khövsgöl. The Renchinlkhümbe sum located on the western shore of Lake Khövsgöl is connected to the Tsagaannuur sum by a power line. The Khatgal and Chandmani-Öndör sums, located in the south and south-east of the lake, respectively, are connected to Mongolia's central power grid. On the northern shore of the lake, there is the Khankh sum, which is supplied with electricity from the territory of the Republic of Buryatia via the 10 kV interstate power line “Mondy-Zavod” that is 35 km long.

In the Russian part of this recreation area, the key elements of the electric power supply system in the Baikal-Khövsgöl zone are the 110/35/10 kV “Kyren” and 110/35/10 “Zun-Murino” substations located in the Tunkinsky district. These substations are connected by a 110 kV line, as well as a 35 kV line passing through the following localities of the Tunkinsky district: Akhalik, Khuray-Khobok, Arshan, Zhemchug, Nilovka, and Badary.

Electric power supply to consumers of the Okinsky district is provided by a single-circuit 110 kV power line “Kyren — Mondy — Samarta", a single-circuit 35 kV power line “Mondy — Sorok — Samarta", and a single-circuit 35 kV power line “Sorok — Orlik” (Figure 1).

Transmission lines are characterized by significant wear and frequent prolonged shutdowns [11]. In case of a failure in one of the power lines, about 4,360 people, 1 hospital, 6 schools, 6 kindergartens, 7 boiler house, and 5 localities are affected by power outage [11]. There are no redundant power lines available. Work to restore the power is complicated by the mountainous terrain and the large distance covered by power lines. These districts are among the underdeveloped and hard-to-reach places in the Republic of Buryatia. In case of long-term outages, diesel power plants at the 35 kV Orlik substation and the 35 kV Sorok substation with the capacity of 0.5 MW and 0.25 MW, respectively, are used for power supply to consumers. The Orlik substation is capable of handling the 1.4 MW while the Sorok substation is limited to the load of 0.3 MW. Thus, when one of the 35 kV lines cuts off electricity, diesel power plants are unable to carry the full load, and

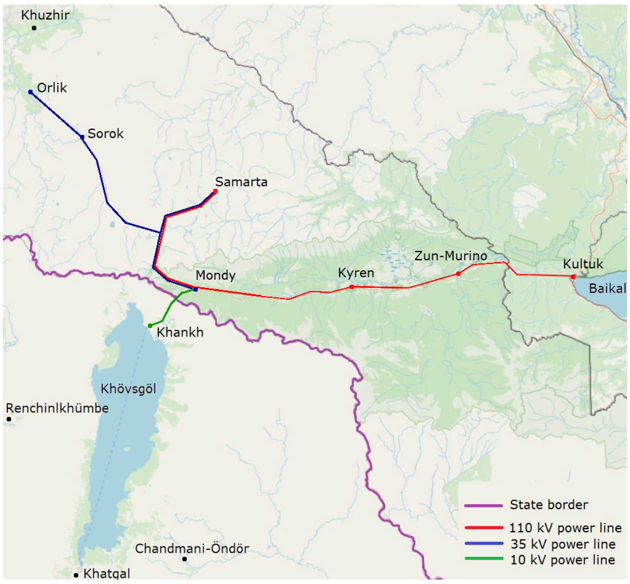

Fig. 1. General layout plan of the “Baikal-Khövsgöl” cross-border recreation area.

hence there is a cap for power consumption imposed on consumers [11].

Thus, the district under consideration is that of a large number of consumers connected to the end segments of transmission lines, as well as decentralized consumers supplied with electricity from low-efficiency diesel power plants.

When dealing with the system of electric power supply to consumers within the "Baikal-Khövsgöl" cross-border recreation area, one should highlight the low level of voltage at the consumer's end due to the extended length of single-circuit power lines. The dotted lines of the schematic diagram of the electric power supply in this geographic area (see Figure 2) indicate the planned construction of the Khuzhir power transmission line and the 35/10 substation for the power supply of the Konevinsky gold deposit. According to the Strategy of social and economic development of the Republic of Buryatia to 2035, the development of this field and the start of its operation is planned for the period from 2019 to 2021. [12]. The expected installed capacity of consumers at the Khuzhir substation is 4.1 MW [13].

Power grid operating parameters for the diagram in Figure 2 were calculated in two stages. At the first stage, all voltages at the nodes were assumed to be equal to nominal voltages, and the flows and power losses in the network sections in the direction from the loads to the power source were determined. The data on the level of electrical loads are assumed as per [13]. At the second stage, based on the specified voltage at the Kyren power substation and power flows at the sites, we calculated voltage losses at the sites and the substation busbar voltage.

Figure 3 presents the calculated electrical schematic diagram with the results of estimating the power grid operating parameters that has the Khuzhir 35/10 substation factored out. Busbar voltage levels of the 6, 10, 35 kV substations were obtained given the regulating capabilities of transformers. The voltage of the low voltage buses of Mondy, Sorok, Orlik, and Khankh substations ranges from 9.5 to 10 kV. The voltage deviation from 10.5 kV ranges from 5.1 to 9.9 % at the limit settings of voltage regulators. As per GOST R 32144-2013, the European standard EN 50160-2010 [14] such deviations are permissible. However, the expected increase in electrical loads due to the development of the geographic area under consideration will lead to a voltage deviation of more than 10% for the substation busbars.

Table 1 presents the results of estimating voltage levels for substation busbars under several power grid operating parameters: at rated transformation ratios and at available limit settings of regulators of devices of voltage regulation of transformers; with the

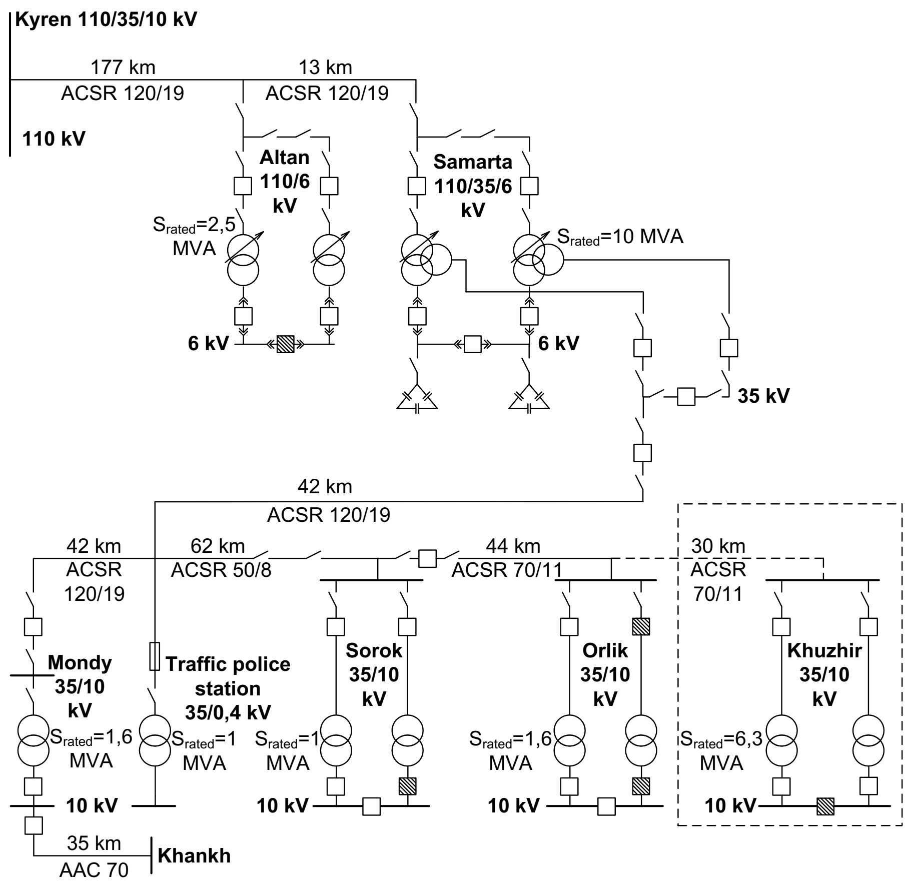

Fig. 2. Electrical schematic diagram of the power grid.

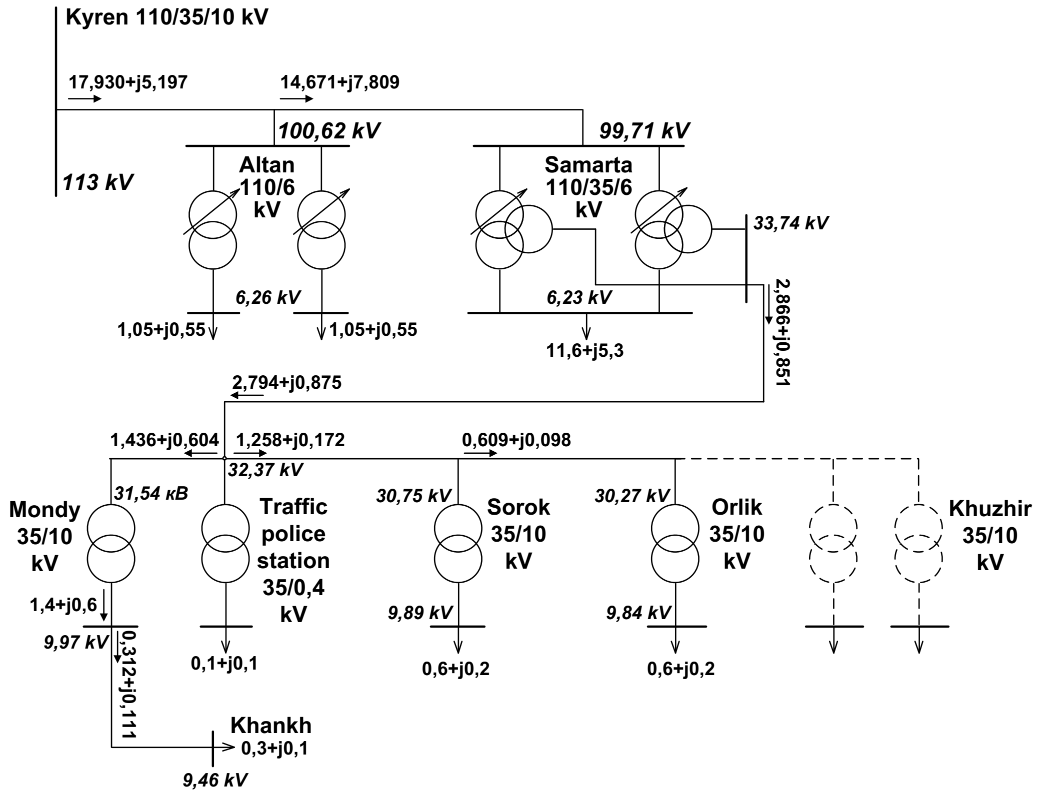

Fig. 3. Calculated power grid operating parameters.

Khuzhir substation factored in and out.

To assess the efficiency of measures aimed at increasing the voltage for the busbars of substations, Table 1 presents the relative voltage deviations from rated values δU, as well as estimates of the losses of active power ΔP in the power grid (Figure 2).

The estimation of the operating conditions considering the Khuzhir substation assumed its design load was assumed to be 50% of the installed capacity, and the power factor was assumed to be 0.8. The voltage for the low voltage buses of Mondy, Sorok, Orlik, Khankh, and Khuzhir substations ranges from 3.8 to 8.3 kV. The voltage deviation from 10.5 kV ranges from 21.1 to 64.3 % at available limit settings of voltage regulators. Thus, the growth of electrical loads will lead to significant deviations from the requirements stipulated by GOST R 32144-2013 and EN 50160-2010 with respect to the electric power quality when supplying power to consumers within the "Baikal-Khövsgöl" cross-border recreation area.

The following measures can be considered to increase the voltage level at the substation busbars: overhauling of the 35/10 kV Mondy substation with its conversion to 110/35/10 kV voltage, installation of compensating units and adoption of renewable energy sources located near consumers.

The estimation of the electric power operation performed in [12] has shown that overhauling the Mondy substation, including the adoption of compensating units at the Khuzhir substation, will not solve the problem of voltage deviation at the consumer's end.

In what follows we present an analysis of the RES potential within the "Baikal-Khövsgöl" cross-border recreation area carried out to assess the possibility and economic feasibility of construction of small power plants

Table 1. Results of estimating voltage levels for substation busbars and losses of active power in the power grid.

Localities / Parameters / Operating parameters	Mondy		Khankh		Sorok		Orlik		Khuzhir		ΔP,%
	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	
With the Khuzhir substation factored in											
1. At rated transformation ratios	8.9	15.5	8.3	20.9	8.8	16.3	8.8	16.7	-	-	8.5
2. At limit settings of the regulators of transformer voltage regulation devices	10.0	5.1	9.5	9.9	10.0	5.9	9.8	6.3	-	-	
With the Khuzhir substation factored out											
3. At rated transformation ratios	7.3	30.9	6.6	37.6	5.1	51.1	3.6	65.8	2.3	78.2	14.6
4. At limit settings of the regulators of transformer voltage regulation devices	8.3	21.1	7.7	26.9	6.2	40.7	4.8	54.2	3.8	64.3	

III. Assessment of the wind energy potential of the "Baikal-Khövsgöl" cross-border recreation area

To assess the wind energy potential of the "Baikal-Khövsgöl" cross-border recreation area we used the NASA POWER project resources [18] that allow obtaining the data on the average annual wind speed for the period 1983 to 2013 at a height of 10 and 50 m. Figure 4 presents a map of the average annual wind speed at the 10 m height, based on these data.

The analysis of the distribution of wind speeds during the year for all the localities under consideration shows the same two-peak pattern. Wind speeds are highest in the spring (April) and the fall (November, December) and lowest during the summer (July, August). The patterns of wind activity coincide with the average load schedule of the localities, which will allow for the efficient use of wind energy in the power supply of the population and tourism facilities.

Based on the NASA POWER dataset on the average daily wind speed at the 10 m height for the period from 1983 to 2013, with the help of the Wind-MCA software, we estimated possible electric power generation by the horizontal-axis wind turbine (WT) Aeolos-H 20 (Table 2) in selected localities of the "Baikal-Khövsgöl" cross-border recreation area (Table 3). Wind speed as based on the NASA POWER data is recalculated to match the height of the wind turbine rotor.

Table 2. Specifications of the wind turbine Aeolos-H 20kW

Parameter	Value
Rated power, kW	20
Cut-in wind speed, m/s	3
Rated speed, m/s	10
Maximum operating speed, m/s	25
Hub height, m	12

The capacity utilization factor (CUF) of WT in the areas under consideration is quite low, being below 10.4. To put this in perspective, as per the capacity supply contract, which is a mechanism of state support for renewable energy projects in Russia, the minimum value of the CUF is set at 27% for the operated WT. When 75-100% of this target value is achieved this will not attract a penalty, when the value is 50-75% of the target the penalty is imposed, while in the case of meeting less than 50% of the target the payment for capacity is declined.

Assessment of the solar energy potential of the "Baikal-Khövsgöl" cross-border recreation area

To assess the solar energy potential of the "Baikal-Khövsgöl" cross-border recreation area the NASA POWER project dataset [15] was used, which allows us to obtain data on the average annual total solar radiation inflow reaching the horizontal surface, given the cloudiness data for the period 1981-2018. Figure 5 shows the map with estimates of the solar radiation inflow based

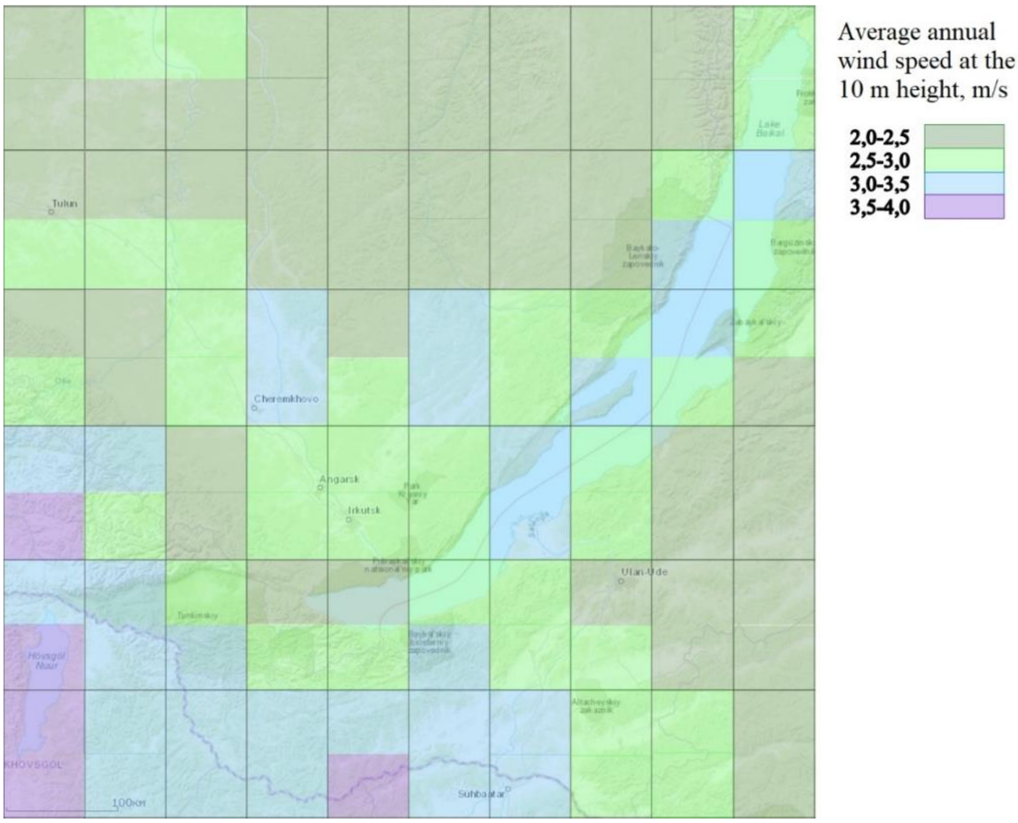

Fig. 4. Map of the average annual wind speed at the 10 m height within the "Baikal-Khövsgöl" cross-border recreation area.

Table 3. Estimates of electricity generation by wind turbines

Locality	Average annual wind speed, m/s	Average annual electricity generation by wind turbines, thousand kWh	Installed capacity utilization factor, %
Russia (the Republic of Buryatia)			
Mondy	3.3	13.1	7.5
Sorok	3.6	17.9	10.2
Orlik	3.6	18.2	10.4
Khuzhir	3.5	15.8	9.0
Mongolia (Khövsgöl aimag)			
Khankh	3.4	14.5	8.3
Renchinlkhümbe	3.5	15.9	9.1

on these data.

Relying on the NASA POWER dataset of the average monthly inflow of total radiation to a horizontal surface that takes into account the cloudiness levels for the period from 1981 to 2015, we used the approach outlined in [19, 20] to estimate possible generation of electricity by photovoltaic (PV) invertors tilted at an angle equal to the local geographic latitude. The AST-240 Multi PV inverter is used for the above assessment (see Table 4). The results of the assessment for individual localities of the "Baikal-Khövsgöl" cross-border recreation area are presented in Table 5.

Table 4. - Specification of AST-240 Multi PV inverter.

Parameter	Value
Maximum power, W	240
Efficiency, %	14.8
Dimensions (LxWxH), mm	1640x992x40

Table 5. Estimates of electricity generation by PV inverters.

Locality	Average annual total radiation incident on a horizontal surface, kWh/m^2	Average annual total radiation incident on a tilted surface, kWh/m2	Average annual electricity generation 1 PVI, kWh	Installed capacity utilization factor, %
Russia (the Republic of Buryatia)				
Mondy	1295	1720	414	19.7
Sorok	1224	1624	391	18.6
Orlik	1229	1625	391	18.6
Khuzhir	1229	1602	386	18.3
Mongolia (Khövsgöl aimag)				
Khankh	1295	1711	412	19.6
Renchinlkhümbe	1287	1698	409	19.4

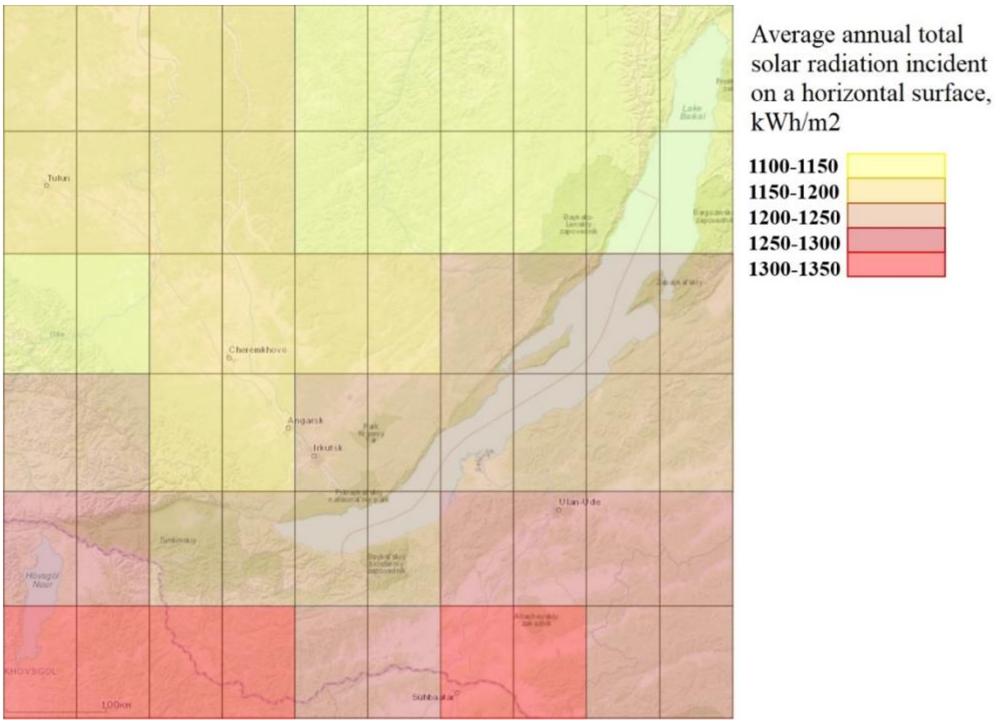

Figure 5. Map of the "Baikal-Khövsgöl" cross-border recreation area with estimates of the average annual total solar radiation incident to a horizontal surface within the area.

The capacity utilization factor in the districts under consideration is relatively high, ranging from 18.3 to 19.7%.

IV. Comparative analysis of the cost efficiency of individual types of RES under the conditions of their adoption in the "Baikal-Khövsgöl" recreation area

Wind power plants (WPPs), solar power plants (SPSs), and small hydropower plants (HPPs) were treated as alternatives for comparing RES-based electric power generation technologies. Table 6 presents interval estimates of specific capital expenditures for these types of power plants with energy accumulation factored out [15-17]. Interval estimates of the CUF for small HPPs are taken from the analysis of similar facilities, while for WPPs and SPPs it is the results of the calculations presented in Tables 3 and 5, respectively. Annual operating costs, including depreciation, are assumed to be 10% of the CapEx for WPPs and small HPPs, and 8% of the CapEx for SPPs. The electricity tariff that assumes a possible growth prospect is fixed in the range of 0.07-0.08 USD/kWh, based on the current (as of September 2019) maximum level of actual unregulated electricity prices in the Republic of Buryatia for the first price category of consumers with a voltage level of 0.4 kV. For Mongolia, the electricity tariff under the Renewable Energy Law is fixed at the level of 0.1-0.15 USD/kWh for wind power, 0.2-0.3 USD/kWh for solar power generation, and 0.08-0.1 USD/kWh for hydropower plants with a capacity of up to 500 kWh [21, 22].

Due to similar conditions with respect to possible changes in maintenance prices and electricity tariffs for the compared options, the cash flow assessment was performed with possible price dynamics and discounting factored out.

It follows from the results of the calculations presented in Table 6 that solar power plants have the greatest economic feasibility for use within the "Baikal-Khövsgöl" recreation area. Solar power generation in Mongolia is particularly promising due to the high legally-backed tariff for electricity produced by this type of plant.

To adopt small HPPs, one should carry out further detailed analysis at specific sites to clarify the CUF and capital expenditures due to a wide interval of estimates of their possible economic effect.

The use of wind energy can only have a limited scope of application, for example, at sites with higher than average wind energy potential due to local terrain features [23].

Thus, one of the most promising areas for improving the reliability of power supply and reducing voltage deviations on the consumer side to the permissible limits under increasing electrical loads is the construction of SPPs.

V. Deciding on the capacity and location of SPPs under conditions of their adoption in the "Baikal-Khövsgöl" recreation area

To determine the rational locations of the SPP sites and the amount of the minimum required installed capacity, calculations of the power grid operating conditions were carried out (Fig. 3). The cost-efficiency of reactive power compensation units (RPCU) was also assessed. The calculations took into account the regulatory capabilities of the transformer voltage regulators and the commissioning of the Khuzhir substation.

Considered were the options of installing RPCUs and SPPs at Mondy, Khankh, Sorok, Orlik, and Khuzhir substations. When working out the options for the installation location of SPPs, one should take into account the difference in solar energy potential of such installation locations However, the decisive influence on the process of solving the problem of voltage deviation at the consumer's end is due to the power supply distance of the installation location from the Samarta power substation. The greatest positive effect on the voltage deviation indicator is achieved by installing SPPs or RPCUs at the most remote substations. Thus, the total voltage deviation of the 5 substations is $\sum\delta U$=207.2% (Table 1, Operating parameters 4). Table 7 presents estimates of the total voltage deviation when installing 100 kW SPPs at various substations. Another factor of significant influence is the load at a substation as generated by its consumers.

Choosing the capacity and location of SPPs and RPCUs is an optimization problem. For the preliminary study, the calculation of the operating parameters was carried out for four options of RPCUs and SPPs installation (Table 8).

Option 1. Only the RPCUs installed at Mondy, Khankh, Sorok, Orlik, and Khuzhir substations are used. The capacity of the units was chosen to be 600, 100, 200, 200, 200, 100, 769 kVar, respectively, to fully compensate the reactive power of consumers.

Option 2. SPPs are installed in all localities, the capacity of SPPs is assumed to be equal to 50% of the load power of each of the substations.

Option 3. SPPs are installed only in the most remote

Table 6. Results of evaluating cost-efficiency of adopting RES in the Republic of Buryatia (Russia).

Renewables	CUF, %	Specific CapEx, USD/kW	Specific annual return, USD/kWh		Cost of electricity generation averaged over 25 years, USD/kWh
			Republic of Buryatia	Khövsgöl aimag	
WPP	7,5 to 10.4	1250 to 1560	-83.2 to -79.3	-59.7 to -19.6	0.24 to 0.27
SPP	18.4 to 19.7	1030 to 1200	30.1 to 42.0	238.9 to 421.5	0.08
Small HPPs	30 to 45	2185 to 4215	-34.5 to -106.1	-27.3 to -8.3	0.12 to 0.15

Table 7. Effect of the installation of 100 kW SPPs in individual localities on total voltage deviation at the consumer's end.

Locality	Distance to the Samarta power substation, km	$\sum\delta U$, %	Change, %
Mondy	84	203.85	3.35
Khankh	119	202.30	4.9
Sorok	104	201.31	5.89
Orlik	148	199.89	7.31
Khuzhir	178	181.90	25.3

locations, the capacity of SPPs is chosen as being proportional to the power load of the substation.

Option 4. SPPs are installed in all localities, the capacity of SPPs is distributed to take into account the remoteness and power load of the substations.

Table 9 presents the results of the evaluation of voltage levels of substation busbars under four calculation cases.

When RPCUs are installed the acceptable level of voltage is provided only at the Mondy and Khankh substations, while at the Orlik, Sorok, and Khuzhir substations deviations from the rated voltage range from 17,7% to 27%. It should also be noted that the installation of RPCUs offers little in the way of mitigating prolonged outages at the consumer's end as a result of accidents long power lines are prone to.

- Installation of SPP as per option 2 does not ensure permissible voltage deviations high installed capacity notwithstanding.
- Installation of the SPPs under option 3 proves the most cost-effective and ensures acceptable voltage levels at all substations. However, the problem of power supply redundancy on the consumer part is yet to be solved at the Mondy, Sorok, and Orlik substations.
- Installation of SPPs under option 4 ensures the necessary redundancy and acceptable level of deviation at the consumer's end but requires large capital expenditures.
- The considered options of SPP capacity additions in individual localities assume only minimal prospective growth of electric loads.

For the integrated development of the investigated geographical area, the adoption of RES is the main way of improving reliability, reducing voltage deviations at the consumer's end to acceptable limits, and reducing losses of active power in the power grid. These effects will be achieved with less environmental impact than when relying on conventional energy sources such as diesel power plants.

VI. Conclusion

Currently, special conservation areas are actively involved in ecotourism: The Baikal-Khövsgöl natural territory is very promising in this regard. There are a fairly large number of consumers connected to the end segments of transmission lines, as well as decentralized consumers supplied with electricity from low-efficiency diesel power plants in the investigated area. Further growth of electric loads will affect the quality of electricity: the deviation of voltage levels at the consumers' side will exceed 10%.

An assessment of wind and solar energy potential was made for the studied area. WPPs, SPPs, and small HPPs were considered as alternatives for comparing RES-based electric power generation technologies. The SPPs that have the lowest electricity production cost equal to about USD

Table 8. Installation site and capacity of PFCUs and SPPs for four calculation cases.

Substation	Option 1	Option 2	Option 3	Option 4
	Q_{PFCU}, kVar	P_{SPP}, kW		
Mondy	600	700	-	500
Khankh	100	150	100	100
Sorok	200	300	-	100
Orlik	200	300	-	100
Khuzhir	769	500	900	800
Total capacity	1869	1950	1000	1600

Table 9. Results of the evaluation of voltage levels on the substation busbars and active power losses in the power grid with the use of RES factored in.

Localities	Mondy		Khankh		Sorok		Orlik		Khuzhir		ΔP,%
Options \ Parameters	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	U, kV	δU, %	
1. Using reactive power compensation units	10.0	4.5	9.6	8.2	8.7	17.7	8.0	23.8	7.7	27.0	12.1
2. Installation of SPPs in all localities with the capacity equal to 50% of the load	10.0	5.1	9.7	8.0	9.3	11.9	8.8	16.1	8.6	18.4	9.3
3. Installation of SPPs in the most remote localities	9.9	6.0	9.5	9.6	9.6	8.6	9.5	10.0	9.5	9.2	8.9
4. Installation of the SPPs in all localities, the power is proportional to the remoteness of the substation and its load	10.1	3.8	9.7	7.3	9.7	7.9	9.5	9.9	9.5	9.8	8.6

0.08/kWh prove the most economically viable for use.

The procedure of choosing the capacity and installation location of SPPs under conditions of their adoption in the Baikal-Khövsgöl recreation area was performed. The estimation of the operating parameters performed under 4 cases of PFCUs and SPPs placement has shown the feasibility of SPP installation at the most remote substations with a higher power load.

Commissioning of small RES-based power plants in the localities of the Baikal-Baikal-Khövsgöl cross-border zone will ensure that the voltage level at the consumer's end meets GOST R 32144-2013 and EN 50160-2010, as well as reduce the loss of active power in the power grid. In the event of prolonged accidents on extended power lines, it will be possible then to supply power to individual consumers responsible for power supply to their respective localities.

Aknowledgements

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References:

[1] Martynova N.A. The soil cover of national parks of the Baikal-Khövsgöl natural area and its monitoring as a required element of sustainable development. Izvestija Irkutskoj gosudarstvennoj ekonomicheskoj akademii (Baikal State University of Economics and Law). 2010. No. 4. P. 360-367. (in Russian)

[2] Evstropieva O.V. Cross-border tourism in neighboring regions of Russia and Mongolia. - Irkutsk: Publishing House of the V.B.Sochava Institute of Geography, Siberian Branch of the Russian Academy of Sciences, 2009. — 143 p. (in Russian)

[3] Kalikhman T.P., Bogdanov V.N., Ogorodnikova L.Yu. Special areas of conservation of the Siberian Federal District. Atlas. - Irkutsk: "Ottisk" Publishing House, 2012. – 384 p. (in Russian)

[4] Evstropieva O.V., Korytny L.M. How to foster the development of cross-border ecological tourism in the Lake Baikal basin. EKO. 2014., No. 12, P. 76-85 (in Russian)

[5] Enkhtaivan D., Evstropieva O.V. Cross-border tourism in Mongolia. Sovremennye problemy servisa i turizma No. 4, 2015, Volume 9, P. 37-43. (in Russian)

[6] Calderón-Vargas, F., Asmat-Campos, D., Carretero-Gómez, A. “Sustainable Tourism and Renewable Energy: Binomial for Local Development in Cocachimba, Amazonas, Peru,” Sustainability, Vol. 11(18), p. 4891 (2019).

[7] Katircioglu, S.T. “International tourism, energy consumption, and environmental pollution: The case of Turkey,”. Renew. Sustain. Energy Rev. Vol. 36, pp. 180–187 (2014).

[8] Zhang, L., Gao, J. “Exploring the effects of international tourism on China’s economic growth, energy consumption and environmental pollution: Evidence from a regional panel analysis,” Renew. Sustain. Energy Rev. Vol. 53, pp. 225–234 (2016).

[9] Beer M., Rybár R., Kaľavský M. “Renewable energy sources as an attractive element of industrial tourism,” Current Issues in Tourism, Vol. 21 (18), pp. 2139-2151 (2018)

[10] Khaboot, N., Chatthaworn, R., Siritaratiwat, A., Surawanitkun, C., & Khunkitti, P. “Increasing PV penetration level in low voltage distribution system using optimal installation and operation of battery energy storage,” Cogent Engineering, 6(1), 1641911 (2019).

[11] The master plan and program of development of the electric power industry of the Republic of Buryatia for years 2019 to 2023, approved by the order of the Government of the Republic of Buryatia dated April 30, 2019, No. 229-r. (in Russian)

[12] The strategy of social and economic development of the Republic of Buryatia to 2035, adopted by the People's Khural of the Republic of Buryatia on February 28, 2019. (in Russian)

[13] The master plan and program of development of the electric power industry of the Republic of Buryatia for years 2016 to 2020, approved by the order of the Ministry of Transport, Energy and Road Facilities of the Republic of Buryatia dated April 30, 2015 No. 65. (in Russian)

[14] Vagin G.Ya. Comments on GOST R 54149-2010, the new standard for electric power quality, and its accompanying standards. Promyshlennaja energetika. 2013 - No. 01, pp.39-43. (in Russian)

[15] HEVEL Group of Companies. Available at: http://www.hevelsolar.com/https://www.hevelsolar.com/catalog/network/ (Accessed on November 14, 2019). (in Russian)

[16] Alternative energy. Available at: http://alen-e.ru/products/22489724 (Accessed on November 14, 2019). (in Russian)

[17] Blyashko, Ya.I. The current state and problems of the small hydropower industry in Russia. Trends in the development of mini HPPs / CJSC "MNTO INSET". International Congress REENCON-XXI, June 06, 2018, Moscow. Available at: https://www.hse.ru/data/2018/06/10/1149857960/%D0%91%D0%BB%D1%8F%D1%88%D0%BA%D0%BE%20%D0%AF.%D0%98.pdf (Accessed on November 14, 2019). (in Russian)

[18] NASA power. Available at: https://power.larc.nasa.gov/ (Accessed on November 31, 2019)

[19] Ivanova I.Yu., Tuguzova T.F., Khalgaeva N.A. Opportunities and issues involved in using solar

radiation for small-scale power generation. Proceedings of the All-Russian conference with international participation "Energy: Management, quality, and efficiency of energy resources use", Blagoveshchensk, May 2011. – P. 360-365 (in Russian)

[20] Ivanova I.Yu., Tuguzova T.F., Khalgaeva N.A. Determination of the optimal renewable energy source capacity for the consumer isolated from the power system. Izvestia RAN. Energetika. 2014. No.3. P.22-28.

[21] Mongolia: Upscaling Renewable Energy Sector Project. Available at: https://www.adb.org/sites/default/files/project-documents/50088/50088-002-pam-en.pdf (Accessed on November 14, 2019). (in Russian)

[22] Law of Mongolia on renewable energy. Available at: http://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/laws/1464%20English.pdf (Accessed on November 14, 2019)

[23] Shakirov V.A., Artemyev A.Yu. Selection of a wind farm site location using terrain and wind flow computer simulation. Proceedings of Irkutsk State Technical University. 2017. Vol. 21. No. 11 (130). P. 133-143. (in Russian)

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A Method And An Algorithm For Comparing The Performance Of Reciprocating Engine Power Plants In Electric Power Systems

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Abstract — **An increase in the performance of thermal power plants is the most important and pressing issue. Its importance is due to both a permanent rise in the fuel cost and an increase in the fleet of equipment whose service life has expired. In this context, traditional methods designed to maintain the efficient operation of the equipment call for improvement. A good example of that is the recommendations of operating rules and regulations, which suggest establishing the amount of planned maintenance based on the technical condition of the equipment rather than on a set periodicity. This increases the significance of measurements of the equipment diagnostic parameters and justifies the transition to the equipment longevity parameters. Intensive aging leads to an intensive change in energy characteristics of power units and a growing risk of their being improperly loaded. The improvement in the methods of quantitative estimation of plant performance tends to lower the risk of a wrong solution. Some operational problems, however, today are still solved at a qualitative level. These include the identification of significant kinds of attributes, i.e. significant factors influencing the performance; an estimation of the parameters of individual reliability, i.e. reliability of specific equipment; ranking the same equipment according to performance; an assessment of the repair quality, and some others. The improvement in the methods for solving these problems reduces the risk of erroneous solutions, and in the end, decreases the operational costs and enhances the overall performance.**

One of the most important facilities in electric power systems is a reciprocating engine power plant (REPP). The undoubted advantages of these plants are mobility, environmental compatibility, reliability, and cost-effectiveness of operation. There are however neither data on the experience of their operation, nor the methods of comparing their efficiency. The paper presents a method and an algorithm for periodic (monthly) comparison of the performance of large-power reciprocating engine power plants manufactured by Wartsila (Finland) by calculating an integrated index of the significance of realizations of monthly average values of technical and economic indices (TEIs). As a result, the Heads of these power plants (PPs) and the Management of the electric power system are provided with the data on technical and economic indices and receive recommendations for increasing the performance of the plant as methodological support.

Index Terms — **Method, algorithm, periodicity, comparison, efficiency, performance, reliability, profitability, reciprocating engine power plant, methodological support, recommendations.**

I. INTRODUCTION

In the current context, characterized by an increasing fleet of aging equipment in electric power systems and a rising fuel cost, the importance of enhancing the performance of thermal power plants (TPPs) increases greatly. [1].

The known methods for solving this problem requires considerable additional expenses, which are not always available [2]. Significant success here can be reached by switching from qualitative estimations of solutions to the

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problems of operation (organization of maintenance service and repair of worn pieces of equipment) to quantitative estimations, and by improving the methods for comparing the performance of thermal power plants (TPPs).

Traditionally, such a comparison is based on one of the basic technical and economic indices (TEIs). As a rule, this is the actual value or deviation between the design and actual values of the specific reference fuel consumption. Besides, according to [3], the correctness of the methods of calculating the specific reference fuel consumption has been disputed since the times of GOELRO (Russia's electrification plan). There have been about ten techniques, each of which purports to be the most exact. The paradox, however, lies in that we cannot check whether a technique is "correct" or "incorrect". An analysis of foreign experience shows that power engineers in other countries encounter similar problems.

In European countries, the comparison of economic efficiency in a broad sense is defined by the term benchmarking [4]. Benchmarking is a system of methods to achieve the highest results by comparing the considered objects. Benchmarking is not a single action. It is a continuous process.

This method, however, is not sufficient to consider the reliability of the TPPs operation. Therefore, the risk of erroneously solving operational problems can be significant. Consideration of the reliability of operation requires the comparison of corresponding thermal power plants. Here we encounter difficulties in simultaneously considering several thermal power plants. The calculation of an integrated index can help to overcome these difficulties.

Specific features of the integrated index calculation. The basic difficulties in estimating the integrated index include:

- The difference in measurement units of technical-economic indices (TEIs). It is impossible to sum specific reference fuel consumption, which is measured in g/kWh, and electricity output (in MWh);
- The difference in the dimensions of the main TEIs. There is no point in summing the duration of the forced outage (t_e), measured in hours, and service life (T_{sl}), measured in years. Conversion of measurement Tsl into hours does not solve the issue, since $T_{sl}>>t_e$. The difference in the TEIs is also observed for relative magnitudes. For example, the relative magnitude of auxiliary power consumption is estimated in units of percentage points while the capacity factor- in tens of percentage points;
- The difference in the TEI measurement directions. An increase in the capacity utilization factor is indicative of an increase in the power plant performance, while a rise in the auxiliary power consumption is evidence to its decrease;
- The interrelation of changes in some TEIs. For example, an increase in electricity output within a set time interval leads to a decrease in the specific reference fuel consumption, whereas an increase in the capacity utilization factor results in a rise in the conventional number of operation hours with rated power. The presence of interrelated TEIs leads to errors in the estimation of an integrated index;
- A short period (a month, quarter, week, shift) during which the comparable TEIs are measured. The smaller the time interval during which the thermal power plant performance is compared, the higher the effect due to a decrease in the risk of erroneous solution. The short control intervals, however, not only reduce the accuracy of TEI estimations but also exclude the possibility of using individual parameters. Even for a monthly interval, it is impossible to calculate such reliability parameters as availability factor,utilization coefficient, the failure probability of power unit when started, etc.;
- A potential difference in production processes leads to a difference in TEIs characterizing them, and consequently, to a decreasein the number of TEIssimultaneously characterizingthe power plants compared;
- The difference in the significance of the absolute magnitudes of TEIs. For example, the significance of specific reference fuel consumption and the significance of auxiliary power consumption differ greatly.
- A considerable divergence between the lower and (or) upper possible values of TEI. The use of the TEI "electricity output" to characterize the comparable power plants with different rated power leads to a high risk of an erroneous solution;
- The used TEIs should characterize the performance of all compared power plants. The employment of TEI "specific reference fuel consumptionfor electricity production" is inadmissible when comparing the performance of thermal power plants and hydropower plants;
- Insignificant variations in the values of individual TEIs of compared power plants. When the power plants are put into service almost simultaneously, it is not advisable to use the TEI "service life" to compare them.

Ranking the power plants in decreasing order of their performance makes it possible to identify the most reliable and economically viable power plants, to find out their "weak points", establish the sequence of using backup capacity, whereas ranking the kinds of the attributes allows determining the most significant factors.

II. Transformation of technical-economic indices of reciprocating engine power plants

This paper presents a method of a quantitative estimation and objective comparison of the performance of reciprocating engine power plants (REPPs) with a simple cycle, which work under semi-peak conditions. Similar to the comparison of REPP performance is the comparison of the performance of the same type 300 MW oil/gas power units of steam-turbine power plants (STPP) [5], and comparison of the performance of their boiler plants [6] and steam turbines [7]. The findings of the comparison show that the transition from intuitive load distribution between the power units to a recommended method alone provides an average annual reduction in the reference fuel consumption from 0.25% to 0.45% [8]. It is worth emphasizing that this concerns power units with the service life essentially exceeding the rated one. In this case, the pace of change in power characteristics is significant, and, therefore, the use of standard methods for calculating the optimal loading of power units is associated with great risk of erroneous solution.

As is known [9], the reciprocating engine power plants have higher efficiency, and a lower level of emissions of harmful substances, compared to other thermal power plants They are more reliable in operation, can work for a long time at partial loading without damage to their technical condition and decrease in performance. The specific gas consumption makes up 256 g/kWh of electric power, and the time between repairs is 12 years.

Some monthly average TEI values characterize these features. The main of these indices are the specific reference fuel consumption (Uf), auxiliary power consumption (Won), actual value of electricity output (W_Σ^{f}), capacity utilization factor ($K_u W_\Sigma^{\mathrm{f}}$ / W_Σ^{r} where W_Σ^{rp}=P_{rp}·$T_м$, P_{rp} is rated power of REPP, Tм is month duration, Tм=730 hr), the number of gas engine units (GEUs) removed from service for emergency repair (n_e) [10].

The TEI calculations also need some nameplate data of power plants. These are the rated power and the number of GEUs at the power plant (P_i and n_i), year of the power plant commissioning ($t_{y,i}$). By way of illustration, Table 1 presents the quantitative estimates of basic monthly average values of TEIs of REPP together with P_i, n_i, and t_i. As noted above, the basic conditions for estimating an integrated index include the interrelation between TEIs and REPP performance, the identity of TEI measurement units and dimensions.

Among monthly average values of TEIs shown and set in Table 1, the magnitudes $t_{y,i}$, W_Σ^{f}, W_{ac}, P_i, n_i and ne do not characterize the REPP performance. Thus, the REPP performance is determined not by the year of power plant commissioning but by the service life calculated as $\Delta t_{sl} = (t_c - t_{y,i})$ where t_c is the current year of REPP operation. Wac is determined, first of all, by the capacity of a power plant and cannot be used for comparison of the power plant performance. The possibility of the use changes when the absolute values Wac are converted to the relative ones under the formula $\delta W_{ac} = W_{ac}/W_\Sigma^{\mathrm{f}}$

Alongside with the capacity utilization factor, to characterize the REPP performance one can use the TEI "monthly average number of capacity utilization hours" (T_u), and for more complete characterization of power plant reliability - the GEU emergency repair time K_e=n_e/n_i, where ni is the number of GEUs, ne is the number of GEUs removed from service for emergency repair. Thus, the REPP performance is characterized by the following TEIs: Δt_{sl}, Uf, δW_{ac}, T_u, K_u, and K_e. The results of their quantitative estimation according to Table 1 are given in Table 2.

In [6], the authors propose two methods to overcome the differences in measurement units and dimensions,

Table 1. Some nameplate data and monthly average values of TEIs of REPP

Technical-economic indices (TEIs)	Symbol	Unit of measurement	Reciprocating engine power plant					
			PP1	PP2	PP3	PP4	PP5	PP6
Year of commissioning	t_{yi}	Year	2006	2006	2006	2007	2008	2009
Rated power and number of GEUs	P_i; n_i	MW	8,7x10	8,7x10	8,7x10	8,7x12	16,6x18	8,7x12
Electricity output	W_Σ^{f}	MWh	17.526	20.542	21.176	42.224	95.477	33.373
Auxiliary power consumption	W_{ac}	Thousand kWh	280.8	370.9	428.6	652.5	1.175.2	411.2
Specific reference fuel consumption	U_r	g/kWh	292,3	281,3	274,0	267,0	272,1	276,9
Number of GEUs removed from service for emergency repair	n_e	Piece	3	1	1	1	4	1

Table 2. The monthly average quantitative estimates of TEIs describing the REPP performance

Technical-economic index	Symbol	Unit of measurement	Reciprocating engine power plant					
			PP1	PP2	PP3	PP4	PP5	PS6
Service life	T_{sl}	year	12	12	12	11	10	9
Auxiliary power consumption	δW_{on}	%	1.60	1.81	2.02	1.55	1.23	1.23
Specific reference fuel consumption	U_f	g/kWh	292.2	281.3	274.5	267.0	272.1	276.9
The conventional number of operating hours at rated load	T_u	h.	201	236	243	404	320	319
Capacity utilization factor	K_u	%	27.5	32.3	3.3	55.3	43.8	43.7
Forced outage factor	K_e	%	30	10	10	8.3	22.2	8.3

Table 3. Data on the calculated technical-economic indices of reciprocating engine power plants

№	Index	Symbol	Unit of measurement	Direction of changes	Realization min	Realization max	Length of individual interval	Intervals of change	The importance of an interval	The formula of calculation of a relative deviation
1	Service life	T_{sl}	year	Opposite	0	35	7	≤ 7 8 - 14 15 - 21 22 - 28 > 29	5 4 3 2 1	$\sigma T_{sl} = \frac{T_{sl} - T_{sl}^{min}}{T_{sl}^{max} - T_{sl}^{min}}$
2	Auxiliary power consumption	δW_{ac}	%	Opposite	1.0	3.3	0.5	≤ 1.50 1,51 – 2.00 2.01 – 2.50 2.51 – 3.00 > 3.01	5 4 3 2 1	$\sigma\delta W_{ac} = \frac{\delta W_{ac} - \delta W_{ac}^{min}}{\delta W_{ac}^{max} - \delta W_{ac}^{min}}$
3	Specific reference fuel consumption	U_f	g/kWh	Opposite	260	300	8	≤ 268 269 – 276 277 – 284 285 - 294 > 295	5 4 3 2 1	$\sigma U_f = \frac{U_f - U_f^{min}}{U_f^{max} - U_f^{min}}$
4	Capacity utilization factor	K_u	p.u.	Coincides	0.23	0.70	0.1	≤ 0.33 0.34 – 0.43 0.44 – 0.53 0.54 – 0.63 > 0.64	1 2 3 4 5	$\sigma K_u = \frac{K_u^{max} - K_u}{K_u^{max} - K_u^{min}}$
5	Forced outage factor	K_e	p.u.	Opposite	0	0.5	0.1	≤ 0.10 0.11 – 0.20 0.21 – 0.30 0.31 – 0.40 > 0.41	5 4 3 2 1	$\sigma K_e = \frac{K_e - K_e^{min}}{K_e^{max} - K_e^{min}}$

which are simultaneously considered while comparing TEIs. These are the method based on converting the TEI deviation from the reference value to relative values, and the interval method.

Table 3 presents the data on the direction of changes in TEIs with respect to changes in REPP performance; the minimum and maximum TEI values; the length of a single interval; the calculated boundary values for five TEI variation intervals (the five-point system is assumed for assessing the significance of the TEI actual value); the TEI significances (points), which coincide with the ordinal numbers of the variation intervals in terms of the direction of their change; and the formulas for the calculation of a relative divergence of TEI.

The resulting range of TEI variation is selected by the minimum and maximum values of TEI during the previous year for all considered REPPs, allowing for the difference in the monthly average values of the range of changes in TEI of the considered REPPs by month of the year. For this very range, the length of an individual interval and

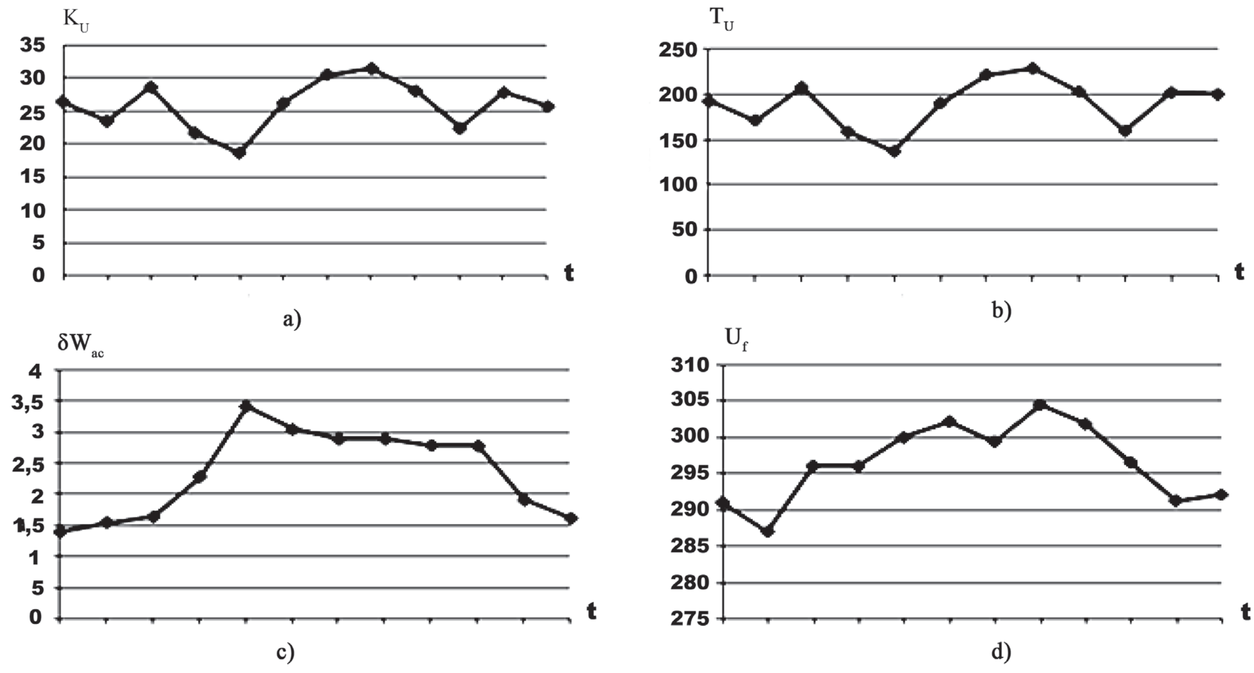

Fig.1. Dynamics of changes in TEIs by month of the year.

boundary values of the variation intervals are calculated.

For illustration, Figure 1(a-d) presents the principles of changes in K_u, T_u, δW_{ac}, and U_f by month of the year. Of interest is the identity of changes in Ku and Tu, some rise in estimates of U_f and δW_{ac} in summer months and reduction in winter months.

Let us consider the interrelation among these TEIs. A necessary condition for the objective estimation of the integrated index is the independence of TEIs [7].

Table 4 presents the calculated coefficients of Pearson correlation (according to Table 5) and Spearman correlation (according to Table 6). Given that for the number of TEI sample realizations equal to 6 the critical value of correlation coefficients for the Pearson and Spearman criteria is identical and equals 0.989, for a significance level of 0.05 [11], one can claim that for the analyzed TEIs, the correlation is significant only for K_u and T_u, which is proved by Figure 1 and formulas of their calculation. This method of the analysis is called a method of solving the inverse problems when the result of one of the comparisons is known in advance, and if it is confirmed, we can trust the other similar calculations made by the algorithm. From the foregoing, it is apparent that the joint use of K_u and T_u for the calculation of an integrated index is pointless.

Thus, the following independent TEIs will be subject to transformation: Δt_{sl}, U_f, δW_{ac}, K_u, and Ke.

III. Results of a performance analysis

Table 5 presents the relative values of TEIs calculated using the formulas given in Table 3. Since the possible deviation of TEIs is calculated with respect to a range of their change, these deviations characterize the extent to which the power plant is worn. The higher the value of the integrated significance of wear, the lower the performance of the power plant. The arithmetic mean for wear is a characteristic of the wear index (Iz(PP)) as a whole. It is obvious, that both In(Iz) and Iz(PP) allow ranking the compared REPPs and assessing the performance of the power plants.

Table 6 presents the results of calculation made by the interval method of estimating the integrated index of TEI significance, the ordinal number of the compared power plants in a ranked series and the estimates of the performance of the considered REPPs.

In [6], the authors show that the results of power plant ranking differ in both methods: since in the interval method the continuous TEI estimates are transformed into discrete ones, the results of ranking the integrated indices of the

Table 4. Estimates of factors of correlation of realizations TEI.

№	Criteria	Ordinal number of TEI					
	Pearson \ Spearman	1	2	3	4	5	6
1	T_{sl}	//////////	-	-	-	-	-
2	δW_{on}	0.877	///////////	0.571	0.557	0.571	0.657
3	U_f	0.401	0.165	///////////	0.214	0.600	-0.029
4	T_u	-0.530	-0.505	-0.849	///////////	0.843	0.557
5	K_u	-0.581	-0.505	-0.849	1	///////////	0.314
6	K_e	0.194	-0.212	0.634	-0.464	-0.465	///////////

Table 5. Results of calculation of monthly average relative deviations of REPP TEIs.

Index	Reciprocating engine power plants					
	PP1	PP2	PP3	PP4	PP5	PP6
Service life	0.343	0.343	0.343	0.314	0.288	0.257
Auxiliary power consumption	0.261	0.352	0.443	0.239	0.100	0.100
Specific reference fuel consumption	0.805	0.533	0.363	0.175	0.300	0.425
Capacity utilization factor	0.904	0.802	0.761	0.313	0.557	0.560
Forced outage factor	0.600	0.200	0.200	0.166	0.444	0.166
Integrated index of wear significance	2.913	2.210	2.210	1.207	1.589	1.508
Integrated index of power plant wear	0.583	0.442	0.424	0.242	0.318	0.302
Power plant ordinal number in a ranked series	6	5	4	1	3	2
Power plant performance	Satisfactory	Satisfactory	Satisfactory	Good	Good	Good

Table 6. Average monthly performance of reciprocating engine power plant.

Index	Reciprocating engine power plant						Total
	PP1	PP2	PP3	PP4	PP5	PP6	
Service life	4	4	4	4	4	4	24
Auxiliary power consumption	4	4	3	4	5	5	25
Specific reference fuel consumption	2	3	4	5	4	4	22
Capacity utilization factor	2	2	2	4	3	3	16
Forced outage factor	3	5	5	5	3	5	26
Integrated index of TEI significance	11	14	14	18	15	17	89
Ordinal number of a power plant in a ranked series	6	4-5	4-5	1	3	2	
Performance	Satisfactory	Satisfactory	Satisfactory	Good	Good	Good	Good

Table 7. A standard deviation and a variation coefficient of monthly average TEI estimates.

Index	Symbol	Unit of measurement	Reciprocating engine power plant					
			PP1	PP2	PP3	PP4	PP5	PP6
Auxiliary power consumption	$\sigma^*[\delta W_{ac}]$	%	0.67	0.67	0.42	0.39	0.25	0.37
	r_{ac}	p.u.	0.28	0.27	0.18	0.2	0.18	0.23
Specific reference fuel consumption	$\sigma^*[U_f]$	g/kWh	4.97	6.60	5.78	3.43	2.88	6.94
	r_f	p.u.	0.015	0.022	0.02	0.013	0.01	0.024
Capacity utilization factor	$\sigma^*[K_u]$	p.u.	3.61	2.80	4.88	3.62	4.41	5.34
	r_u	p.u.	0.13	0.099	0.15	0.066	0.097	0.127
Ordinal number of PP in a ranked series			5-6	3-4	3-4	1-2	1-2	5-6

discrete TEIs significance under a small number of TEIs appear to be somewhat larger. This difference can be seen when comparing Tables 5 and 6.

A great advantage of TEIs measured with a discrete scale is the possibility of their joint use with the TEIs measured by a qualitative scale.

The reciprocating engine power plants can also be classified according to the range of variation in the integrated indices of a series of monthly average values. Table 7 indicates the standard deviation $\sigma^*[\delta W_{ac}]$, $\sigma^*[U_f]$ and $\sigma^*[K_u]$ and variation coefficient of monthly average TEI values $r_{ac} = \sigma^*[\delta W_{ac}] / \delta W_{ac}$, $r_f = \sigma^*[U_f] / U_f$ and $r_u = \sigma^*[K_u] / K_u$ for a year of operation. These data are used to rank the considered power plants. Although earlier we considered the comparison of the performance of power plants during the previous month and based on this comparison recommended ways to enhance their performance, the results of a calculation using the data of TEI variation for a year almost completely coincide. This confirms the statement, according to which a decrease in the power plant performance leads to an increase in the TEI variation. According to Table 7, the greatest variation is observed at PP1 and PP6, average variation - at PP2 and PP3, and an insignificant variation is at PP4 and PP5.

Certainly, the operating personnel of the power plants, as well as the management staff of power plants and power systems do not need to know the details of integrated index calculations. There should be a methodology aimed at assessing the technical condition of power plants, the results of comparing the performance of other similar power plants, and providing the data on “weak points” and other similar data.

At the same time, these data, especially when the number of TEIs is small, cannot be absolutized. The decisions made reflect only the considered TEIs. For example, the TEI list does not include the data on financial capabilities and capacities available for repair work. Although the power plants and power systems are not always provided with necessary means to cope with the wear or they may have no equipment and materials to repair. In some cases, the managers completely agree with the recommendations. This consent in the majority of cases coincides with an intuitive solution, which provides grounds to trust these recommendations even without experts capable to recommend an objective solution to the operational problems.

Below is an example of the results of an automated analysis of monthly average TEI values. Along with TEIs, the presented recommendations include the proposals prepared by corresponding Departments of Management. They can be refined with time and depending on the energy system to be considered.

These results can serve as the basic document to carry out monthly discussion of TEI data recommended by Operating rules and regulations and as the methodological support for the decisions to be made. They (results) are monthly submitted to the Chief engineer of a power system and the Head of the Electricity Generation Department.

IV. Results of an analysis of reciprocating engine power plant performance

1. Initial data on TEIs for the calculated month.

Index	Unit of measurement	Reciprocating engine power plant					
		PP1	PP 2	PP 3	PP 4	PP 5	PP6
Year of commissioning	year	2006	2006	2006	2007	2008	2009
Rated power	MW	87	87	87	104,4	299,25	104,4
Electricity output	MWh	17.526.028	20.542.000	21.176.000	42.224.000	95.477.100	33.373.700
Auxiliary power consumption	MWh %	280.8 (1.60)	370.9 (1.81)	428.6 (2.02)	652.5 (1.55)	1.175.2 (1.23)	411.2 (1.23)
Specific reference fuel consumption	g/kWh	292.17	281.28	274.51	267.02	272.14	276.91
The number of GEUs removed from service for emergency repair	piece	3	1	1	1	4	1

2. Initial data on TEIs for the previous month

Index	Unit of measurement	Reciprocating engine power plant					
		PP1	PP 2	PP 3	PP 4	PP 5	PP6
Electricity output	MW	17.739.49	18.570.000	20.741.000	38.088.000	94.146.400	33.083.600
Auxiliary power consumption	MWh %	335.544 (1.89)	413.731 (2.31)	457.865 (2.21)	735.610 (1.93)	1.220.530 (1.30)	413.024 (1.25)
Specific reference fuel consumption	MWh	293.33	291.21	285.06	269.88	273.25	286.88
The number of GEUs removed from service for emergency repair	g/kWh	3	2	1	2	4	1

3. Results of ranking the power plants according to performance

Index	Month	Reciprocating engine power plant					
		PP1	PP 2	PP 3	PP 4	PP 5	PP6
Ordinal number when ranking the power plants by the data	C	6	5	4	1	3	2
	P	4	5	6	3	1	2
Performance according to the data	C	Satisfactory	Satisfactory	Satisfactory	Good	Good	Good
	P	Satisfactory	Satisfactory	Unsatisfactory	Satisfactory	Satisfactory	Satisfactory
Change in the performance	C→P	NC	NC	IN	IN	IN	IN

Note: C and P are calculated and previous months, respectively; (IN), (DE) and (NC) are an increase, a decrease, or no change in the performance, respectively; C→P - calculated relative to previous.

4. In calculated (C) month:
   - The REPPs with unsatisfactory performance – no
   - The REPPs with satisfactory performance – PP1, PP2, and PP3
   - The REPPs with good and excellent performance – PP4, PP5, and PP6
   - On average, the overall performance of diesel reciprocating engine power plants is estimated to be good.
5. The main TEI limiting REPP performance is the capacity utilization factor.
6. The results of ranking the REPPs according to their performance for the calculated and previous months demonstrate their differences
7. The performance of REPPs in the calculated period
   - increases for PP3, PP4, PP5 and PP6
   - does not change for - PP1 and PS2
8. On average, the performance of the considered REPPs in the calculated month has increased

Recommendations for the improvement of REPP performance. The general recommendations are:

- provide conditions for the use of exhaust gases heat;
- control changes in diagnostic parameters of REPP equipment every month and develop recommendations to increase the reliability of GEU;
- analyze TEIs of REPPs and provide recommendations to enhance the performance of REPPs;
- reduce the pace of equipment wear by improving the professional skills of the personnel;
- maintain an extramural system of professional skill improvement with the intramural one, to control if the qualification of personnel meets the requirements imposed, which makes it advisable to control the availability of an established set of technological normative materials;

Special recommendations are:

- analyze the pace of change in the GEU wear due to poor-quality operational control;
- improve the value of TEI “capacity utilization factor” by fulfilling the requirements of Operating rules and regulations;
- provide a qualitative repair of the worn 4-th GEU at PP1, 2-nd GEU at PP4, 7-th GEU at PP6;
- ensure that the engine oils used at REPPs meet the requirements.

V. Conclusion

1. A method and an algorithm for estimating an integrated index of the overall performance of the reciprocating engine power plants are developed;
2. The integrated index allows:
   - ranking the compared reciprocating engine power plants by performance values that reflect their reliability and economic viability;
   - estimating the performance of reciprocating power plants in the five-point system;
3. A mechanism for the practical use of this method is developed.
4. An increase in the REPP performance is achieved by providing the Management of a power system and power plants with the results of TEI analysis, which represents the necessary methodological support when solving the operational problems;
5. Along with monthly average values of technical and economic indices, of great importance are the ranges of variations in these values. The equality of monthly

average values of TEIs does not mean the equality of the performance of power plants. The larger the variation the worse the technical condition. A decrease in variation leads to an increase in the overall performance.

References

[1] Voropai N.I. SMART grid concept and reliability of electric power systems. Methodological problems in the reliability study of large energy systems. Issue 62, Ivanovo, *PresSto*, pp. 321-325, 2011.

[2] Dyakov A.F., Isamuhammedov Y.Sh. The current state of Russia's electric power industry and factors of decrease in electricity supply reliability. Methodological problems in the reliability study of large energy systems. Issue 63, Baku, ASRaDPPEI, pp.7-13, 2013.

[3] Telenkov Y.V. The unified method of calculating specific reference fuel consumption - a prerequisite for improving energy efficiency in the Russian Federation. Available at: http://www.peretok.ru/opinion/18817/ (In Russian.)

[4] Ivanova E.A., Razorvin I.V. Benchmarking as an effective marketing technique for comparative analysis of effectiveness. Management Issues, Available at http://vestnik.uapa.ru/ru/ issue/2009/02/12, (In Russian.)

[5] Farhadzadeh E.M., Farzaliyev Y.Z., Muradaliyev A.Z. Estimation of quality of repair of worn power units at thermal power plants. Minsk. *Energetika*, Issue 1, pp. 14-24, 2016, (In Russian.)

[6] Farhadzadeh E.M., Farzaliyev Y.Z., Muradaliyev A.Z. A method and an algorithm of ranking boiler plants of block power stations in terms of reliability and economic efficiency of operation, *Thermal Engineering*, No. 10, pp. 22-29, 2015.

[7] Farhadzadeh E.M., Muradaliyev A.Z., Farzaliyev Y.Z., Abdullayeva S.A. Comparing and ranking steam turbine plants at thermal power plant energy units in terms of their performance. M.: *Thermal Engineering*, No. 10, 41-49, 2018.

[8] Farhadzadeh E.M., Muradaliyev A.Z., Farzaliyev Y.Z. Ranking power units of power stations in terms of their reliability and economic feasibility. Baku, *Energy Problems*, No.2, pp.8-16, 2014, (In Russian.)

[9] Nikitin A., Vuorinek A. Peak and reserve REPPs. Experience of application in the USA. Foreign experience. *Turbines and diesel engines*. 22-26 p.

[10] RD 34.09.454. A typical algorithm for calculating f technical and economic indices of condensation power units with a capacity of 300, 500, 800 and 1200 MW., 1990

[11] Orlov A.I. Statistics. M.: Examination. 2006, pp. 672, (In Russian.)

[12] Farhadzadeh E.M., Muradaliyev A.Z., Farzaliyev Y.Z., Rafiyeva T.K., Abdullayeva S.A. Minimization of risk of an erroneous decision in assessing the importance of statistical communications of technical and economic indices of electric power system facilities. Minsk, Energetika, Vol.61, No. 3, pp. 193-206, , 2018, (In Russian.)

[13] Orlov A.I. Non-numerical statistics. A science and technology in Russia, No. 3(5), pp.7-8, . 1994, (In Russian.)

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A Study On Multi-Component Flows In Gas Transmission Systems (Flow And Measurement Processing Models)

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***Abstract* — The focus of the study is on multicomponent natural gas flows through gas transmission systems (GTSs). The key objective is to determine the natural gas composition in each GTS branch. The initial data for calculation include measured natural gas components for all GTS metering points. The obtained measurements are considered to be random values due to instrument errors. Heat (calorific) value can be considered instead of natural gas components. A mathematical model has been developed for the calculation of natural gas composition for each pipeline. The gas composition changes at the joint points of the system. The model takes into account the irreversibility and non-equilibrium properties of mixing processes. The model is based on the well-known method of mathematical statistics, which is also known as the maximum likelihood method. It allows converting the problem to the quadratic programming problem with equality and inequality constraints. The equality constraints are the mass conservation equations for each fluid component, and inequality constraints are the relations demonstrating the incompleteness of components mixing at the joint points. A calculation example is presented to illustrate both the recommended calculation method and the approximate algorithm based on heuristic considerations. The developed approaches and methods are used to support the decision-making of diverse technological problems related to variation in the natural gas composition by gas transportation direction.**

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***Index Terms* — Flow distribution, gas transmission systems, irreversibility condition, irreversible and non-equilibrium processes, mathematical models, maximum likelihood method, measurement processing, multi-component flows.**

I. Introduction. The significance of multi-component gas mixture flow studies

Natural gas from different fields varies in composition. Normally, methane is a basic component. Its share in the gas of Russian fields lies in a range of 90 – 98%. Natural gas also contains other hydrocarbons, such as methane homologs (ethane, propane, butane, etc.), carbon dioxide, nitrogen, water vapor, helium, hydrogen sulfide, etc.

In addition to gas and gas-condensate fields, the gas sources for the Unified Gas Supply System (UGSS) of the Russian Federation are the oil fields (associated gas), gas processing plants (GPP), and underground gas storages (UGS). The composition of gas supplied to the UGSS can vary significantly depending on its source. Rich gases, which are supplied to the UGSS from GPPs, oil fields and UGSs constructed in depleted oil fields, usually contain a higher share of heavy hydrocarbons, and therefore have a higher heat (calorific) value. Gas from some GPPs contains up to 12-18% of ethane and 16-18% of nitrogen and its composition differs greatly from gas coming directly from gas fields. Now, the ethane share in the gas from the main UGSS gas sources is about 3%, and the nitrogen share is about 1.3%.

Hydrocarbons of methane homologous series are a more valuable feedstock for gas chemical facilities than methane. The economic viability of producing them from natural gas and using in gas chemistry does not cause any doubt. A more serious problem is where to locate the gas chemical facilities. There are two possible options either to place them closer to the gas fields or the industrial centers. Each option has its pros and cons. Under the first option, the methane content in gas transported by the UGSS pipelines is about 100%. The second option suggests long-distance transmission of rich gas.

The gas fields of the Nadym-Pur-Taz region are the main source of the UGSS. A Russian port terminal on the Baltic Sea is considered to be a site for a gas-chemical facility. The transmission of gas along this route will require the collection of rich gas from the fields and modernization of the existing gas transportation corridors. The effective possible solution to the arising problems should be based on the scientifically proven models of multi-component gas mixture flows in large-scale main gas pipeline systems.

The range of applications of such models is not limited to the problems of UGSS prospective development. The calculation of the distribution of natural gas components concentration is also necessary for operating control of the gas transmission system. The mutual settlements, when both supplying gas to domestic consumers and exporting it, are performed not by volumetric indices but by energy ones, given heat (calorific) value of the supplied product. The procedure of gas pricing in Russia is regulated by federal legislation. The price is usually set according to the volumes of deliveries (in 1 000 cubic meters) adjusted for heat value. The differences in consumer requirements to gas calorific value make the supplier interested in delivering high-calorific gas to certain consumers but this makes it necessary to organize the UGSS flow control.

Another problem of GTS operational control is the need for the gas to be supplied to meet the requirements of dew point temperature. The dependence of dew point temperature value on water vapor mass concentration in natural gas is regulated by Russian [1, 3] and international [2, 4] standards. The dew point temperature values have to be controlled when exporting gas. The dew point temperature value is determined by calculating the mixing processes that occur in convergent and divergent gas flows, where the water vapor is considered to be one of the transported fluid components. This means that the calculation of the dew point temperature values is based on the models of multi-component gas flows in the pipelines.

It is worth noting that all the developed methods can be applied both to gases and to fluid flows. These methods can be used to solve the problems of oils blending which is rather important for maintenance services of the main oil pipelines. The oil-related issues are not considered in this paper, the gas transmission system terminology will be used.

II. Technological aspects

Gas samples are taken to track the calorific value and gas composition at gas measuring stations (GMS). Gas composition analysis is made periodically, using sample cylinders, or continuously, if the metering unit is specially equipped [3, 4].

The data on the distribution of calorific value and gas composition over the pipelines are of practical interest. To increase the information reliability one should take account of all the measurements carried out at the gas measuring stations. This approach will allow considering the measurements interdependency, however special methods and mathematical and computer models will be required for its implementation.

Depending on the specific character of technological problems, the models of both two-component and multi-component gas flows may be needed. The two-component model is required for example a) to determine the dew point, or b) in the case, if natural gas consists of two basic components (methane and ethane), and the share of other components is low and does not affect the result. Firstly, we will analyze the situation b) to simplify the understanding of the method and to facilitate its presentation.

The basic model will refer to the two-component fluid flow. Let us agree to call the components methane and ethane. The values of ethane concentration by gas transmission direction are the values to be determined. Gas calorific values can be considered instead of concentration values. The methods for determining calorific values for the flowing gas mixture are based on the same principles. The models of three- and more component- mixtures are based on the same principles as the models of two-component mixtures, only the calculation formulas become somewhat more cumbersome. The three-component model will be required for example to control the distribution of methane, ethane and helium concentration or to simultaneously calculate the distribution of calorific value and dew point temperature by transmission direction.

Further, in this paper, we will consider the pipeline system of an arbitrary configuration, which has several sources (i.e. fields, points of product inflow from adjacent systems, UGS under withdrawal conditions, etc.) and several sinks (points of product delivery to internal consumers and for export, UGS under injection conditions, etc.). The model is developed under the assumption that the total fluid rate for each pipeline of the system is known, i.e. the gas mixture flow distribution was calculated in advance and is the initial data to determine the flow rate of each component. At some points in the system — points, where the gas measuring stations are located — the fluid composition, is determined, i.e. the mass or molar the concentration of ethane in the transported product. Conversion of molar concentration to mass concentration does not cause difficulties. We use mass concentration for the sake of clarity.

The measurements may have errors, which means that the value of measured concentration is a random value. During gas transmission, the concentration values usually change due to the fluids mixing at the pipeline joint points. The concentration value does not change along each pipeline, consequently, it is usually related to the pipeline, and does not depend on the measuring point location. Conversion of molar concentration to mass concentration does not cause difficulties. We use mass concentration for the sake of clarity. The task is to estimate the concentration values for each pipeline over the entire set of measurements.

III. Non-equilibrium of mixing processes (technological aspect)

The success of solving this problem depends significantly on how correctly the calculation scheme is built. Calculation of large gas transportation systems often involves the replacement of several parallel gas pipelines with one equivalent arc of calculation scheme. This method is quite justified while searching for the flow distribution of gas mixtures in the system. However, if the fluids of different concentrations are mixed at any joint point of the calculation scheme, we cannot consider the concentration values for all pipelines diverging from that point to be equal. The concentrations would be equal if the mixing processes were equilibrium ones. In actuality, however, these processes are not equilibrium ones. The process could be an equilibrium one if the concentrations in the pipelines outgoing from the joint point were equal. However, the complete mixture of flows is not observed. Gas flows at rather high speeds. Concentrations in the outgoing pipelines depend on the local configuration of pipelines at the joint point. It is not possible to take into account such technological details in the aggregated models because the geometric dimensions of such an area are incommensurably smaller than the lengths of the pipelines. Therefore, to calculate the concentrations in all gas pipelines of the GTS, the calculation scheme should be disaggregated. It is necessary to ensure the possibility of reflecting the presence of different concentrations on the arcs outgoing from the joint point. Let us suppose that two pipelines or pipeline corridors meet at the joint point, and the multi-pipe corridor is the output. This corridor could be represented by one arc in the aggregated scheme. The aggregated model will not be suitable to calculate the concentration values in the case of different gas compositions in the incoming lines.

The processes of gas flow mixing are the main subject of this paper. The mixing occurs for two reasons – diffusion and turbulent mixing. The second reason is the main one for assessing changes in gas composition at the pipelines junction points. We study these particular changes and not a change in the distribution of components over the pipeline cross-section. In other words, one-dimensional problems on graphs are of practical interest. Observations of changes in operating parameters of the industrial gas pipelines do not give grounds to ascertain the generation of heat when the natural gas components mix. Even if the heat is produced, this does not affect the operation. Therefore, the mixing processes of multi-component gas flows are considered to be isothermal.

All gas mixing processes are irreversible, at least because it is necessary to spend some energy to separate the mixture into components. Mixing of the natural gas components during its transportation is a nonequilibrium process because complete mixing is usually not achieved, which should be considered as an experimentally established fact.

The irreversible nonequilibrium processes are studied by thermodynamics, physical chemistry, and kinetic gas theory. Irreversible and nonequilibrium processes are often used in mastered technologies for the production, transportation, and processing of natural gas [5, 6]. The application range of such processes is continuously expanding. Let us note some recent publications related to gas pipeline transportation. The problems of natural gas and hydrogen mixture transportation are considered in [7 – 8] and those of natural gas and nitrogen mixture transportation are discussed in [9].

The schemes of gas flow mixing are usually considered in theoretical and technical thermodynamics [10 – 16] with a focus on the study of pressure and temperature parameters of the mixing flows. Indeed, it is important to evaluate the additional efficiency loss due to irreversible heat transfer between mixing gases and due to their unused pressure difference.

The kinetic theory of gases and, in many aspects, physical chemistry use the models related not to volumes, but molecular or atomic structures. They use the apparatus of quantum chemistry, statistical mechanics, and analytical dynamics [17 – 19].

The industrial pipeline systems considered in this paper and the physical processes in them do not require the use of the methodological and mathematical apparatus traditionally used to study irreversible and non-equilibrium processes. It is highly likely that they have no immediate predecessors in the scientific and technical periodicals.

IV. Two-component gas. The mathematical statement of the problem

Structure of a pipeline system will be represented by oriented (by default, all arcs are assumed to be oriented in the direction of fluid flow) graph $G = (V,E)$, where value V is a set of nodes, and E is a set of arcs. The arc in the aggregated scheme corresponds to the flow direction. The number of nodes is denoted by m and the number of arcs - by n. The nodes are divided into three groups: V_{in} – sources, V_{out} – sinks and joint nodes V_{joint}. We assume that the sources and sinks are connected to the graph by a single arc – outgoing for sources and incoming for sinks. This paper uses the terminology from classical monographs on graph theory [20, 21]. The fluid flow $\boldsymbol{\xi} = \{\xi_{ij}\}, (i,j)\epsilon E$ is set on graph G. It consists of two mixing components $\xi_{ij} = \zeta_{ij} + \eta_{ij}$. Vector $\boldsymbol{\xi}$ is considered to be deterministic, although, the information used in its calculation is not reliable. The effect of this uncertainty on the calculation results is going to be a subject of future research. Here ξ_{ij} is fluid flow by arc(i,j). The values ξ_{ij} comply with material balance equations at all joint nodes x_k

$$\sum_{x_j\in\Gamma^{-1}(x_k)} \xi_{jk} - \sum_{x_i\in\Gamma(x_k)} \xi_{ki} = 0,\ x_k \in V_{joint}. \quad (1)$$

Hereinafter $\Gamma(x_k)$ is a set of nodes, which the arcs outgoing from x_k come into, $\Gamma^{-1}(x_k)$ is a set of nodes, which the arcs incoming to x_k go out (Fig. 1). Vector $\boldsymbol{\xi}$ is a set of all flow rates $\xi_{ij}, (i,j) \in E$. The sets of methane flow rate

$\zeta_{ij}, (i,j) \in E$ and ethane flow rate $\eta_{ij}, (i,j) \epsilon E$ are also the vector values $\boldsymbol{\zeta}, \boldsymbol{\eta}$. They must comply with the balance equations (1) changing $\boldsymbol{\xi} \longrightarrow \boldsymbol{\zeta}$ and $\boldsymbol{\xi} \longrightarrow \boldsymbol{\eta}$, respectively. The flow $\boldsymbol{\xi}$· is initially known, consequently, all arcs $(i,j) \epsilon E$ could be oriented by the flow direction, which is considered to be already done, thus, $\xi_{ij} \geq 0, (i,j) \in E$.

The task is to find the flow $\boldsymbol{\eta} = \{\eta_{ij}\}, (i,j) \epsilon E$. We can consider the mass concentrations r_{ij} instead of the values η_{ij} using the relation $\eta_{ij} = r_{ij}\, \xi_{ij}$. The source of the information for solving the problem is a set of the gas composition measurements, i.e., measurements of concentrations r_{ij}. The measuring points are attached to the graph arcs; the notation E^* is introduced for the set of such arcs. To indicate the measured ethane concentration, we also use the symbol "*". The resulting measured value r_{ij}^* consists of true (but unknown) value r_{ij} and the measurement error $\delta r_{ij}, (i,j) \epsilon E^*$. In the theory of errors, measurement errors are considered to be normally distributed quantities.

$$\delta r_{ij} \in N(0, \sigma_{ij}^2). \tag{2}$$

Symbol $X \epsilon N(a, \sigma^2)$ means that the random value X has the normal distribution with mean a and variance σ^2. The instrument errors (or the measurement method errors) are characterized by variance σ_{ij}^2.. The error in the determination of ethane flow rate $\delta\eta_{ij}$ also has a normal distribution $\delta\eta_{ij} \epsilon N(0, \xi_{ij}^2 \sigma_{ij}^2)$. According to the problem statement, one should find the distribution of ethane flow rate that to the greatest extent is consistent with the whole set of concentration measurements. The probabilistic statement of the problem normally suggests the assessment rather than the determination of the unknown quantities r_{ij}. Mathematical statistics recommend the maximum likelihood estimation (MLE) for the point estimation of unknown parameters. According to the MLE, the estimate is the maximum likelihood function, which in our case is the probability of the totality of all measured values. The MLE leads to the problem of conditional minimization of a quadratic function.

$$\sum_{(i,j) \in E^*} \left((\eta_{ij}^* - \eta_{ij}) / \xi_{ij} \sigma_{ij} \right)^2 \longrightarrow min \tag{3}$$

if two conditions are satisfied:
the condition of ethane material balance

$$\sum_{x_j \in \Gamma(x_k)} \eta_{kj} - \sum_{x_j \in \Gamma^{-1}(x_k)} \eta_{ik} = 0, x_k \in V_{joint} \tag{4}$$

and the condition of irreversibility of the components mixing process, which will be discussed later.

Problem (3), (4) is a linearly constrained quadratic programming problem.

V. Consideration of non-equilibrium mixing process

The optimization problem (3), (4) does not fully reflect the two-component gas flow process from the physical point of view. The condition of the process non-equilibrium should be added to condition (4). The mixing process of gases with different compositions is irreversible and non-equilibrium. We will consider again a mixture of methane and ethane. Let us formulate the non-equilibrium conditions of the mixing process for this gas.

The non-equilibrium nature of the process manifests itself in the fact that at different concentrations of the flows entering the node, the concentrations in the outgoing lines may also be not equal to each other, i.e., gases do not mix completely: the mixing process at the joint nodes does not lead to an equilibrium state. In a sense, the mixing process is similar to the heat transfer process. In the case of heat transfer, the temperature in the communicating vessels levels out over time, tending to a weighted average value. In the non-equilibrium process of mixing multicomponent gases, the concentrations approach the average value.

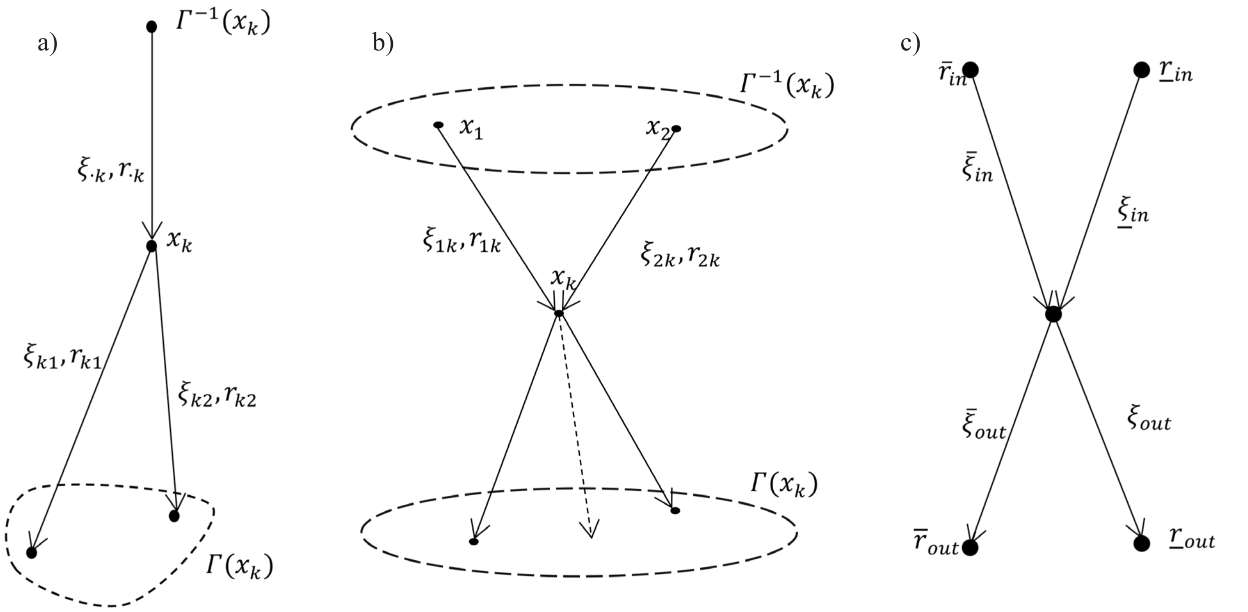

Fig.1. Schemes of diverging (a) and converging (b) flows at joint node x_k; notations for the non-equilibrium condition (c).

For simplicity, let us consider a scheme with two incoming and two outgoing lines. The parameters of the incoming lines will have the subscript *in*, and those of the outgoing lines – the subscript *out*, the parameters of the line where the concentration value of the 2nd component (ethane) is greater will be marked with an overscore and the parameters with lower concentration - with an underscore, i.e., $\max(r_{1k}, r_{2k}) = \bar{r}_{in}, \min(r_{1k}, r_{2k}) = \underline{r}_{in}$ (Fig. 1).

When the components mix completely, the concentrations in the outgoing lines (regardless of their quantity) are equal to $\overline{r}_{out} = \underline{r}_{out} = \rho$ independently of its quantity. The weighted average value ρ is expressed through the conditions at the inlet $\rho = \overline{\alpha} \cdot \overline{r}_{in} + (1 - \overline{\alpha})\underline{r}_{in}$, where $\overline{\alpha}$ is the share of the line where the ethane concentration is higher in the total (for two lines) gas flow rate. The following relations are necessary for the irreversible mixing process.

$$\underline{r}_{in} \leq \underline{r}_{out} \leq \overline{r}_{out} \leq \bar{r}_{in}. \quad (5)$$

These relations are necessary but not sufficient. They set the inequalities for extreme (maximum and minimum) concentration values at the outlet point but they do not take into account the relationship between the quantities of mixing components at the node inlet and outlet. Let the maximum concentration value in the outgoing lines be equal to the maximum concentration value in the incoming lines $\overline{r}_{out} = \bar{r}_{in}$. The flow rate in the outgoing line should not exceed the flow rate in the incoming line $\overline{\xi}_{out} < \overline{\xi}_{in}$ according to the physical non-equilibrium conditions. The similar physical relations should be satisfied for two, three and more outgoing lines.

We write these relations for the general case, denoting the number of incoming lines by N_{in}, and the number of outgoing lines by N_{out}. The consideration of lines with minimum and maximum concentration values will not be sufficient to make the analysis. We take any node and arrange the values of concentration in the incoming lines in decreasing order. A similar operation is performed for outgoing lines. Thus, two non-increasing sets of values are obtained

$$r_{in}^{(1)} \geq r_{in}^{(2)} \geq \cdots \geq r_{in}^{(N_{in})} \quad (6)$$

$$r_{out}^{(1)} \geq r_{out}^{(2)} \geq \cdots \geq r_{out}^{(N_{out})} \quad (7)$$

The superscript in brackets indicates the rank of the corresponding number in the sequence. It is obvious that $r_{in}^{(1)} = \bar{r}_{in}, r_{in}^{(N_{in})} = \underline{r}_{in}$ and $r_{out}^{(1)} = \bar{r}_{out}, r_{out}^{(N_{out})} = \underline{r}_{out}$. We use the ordered array of numbers (6) to construct the piecewise smooth curve of "limit concentrations" $r(x) = r_{in}(x)$ (Fig. 2). Thus, $r(x)$ is the maximum possible concentration of ethane in the gas mixture at the node inlet at the total fluid flow rate x.

$$r(x) = \begin{cases} r_{in}^{(1)}, if \quad 0 \leq x \leq \xi_{in}^{(1)} \\ \frac{r_{in}^{(1)}\xi_{in}^{(1)} + r_{in}^{(2)}(x - \xi_{in}^{(1)})}{x}, \\ if\ \xi_{in}^{(1)} < x \leq \xi_{in}^{(1)} + \xi_{in}^{(2)} \\ \ldots \\ \frac{r_{in}^{(N_{in}-1)}\sum_{j=1}^{N_{in}-1}\xi_{in}^{(j)} + r_{in}^{(N_{in})}(x - \sum_{j=1}^{N_{in}-1}\xi_{in}^{(j)})}{x}, \\ \sum_{j=1}^{N_{in}-1}\xi_{in}^{(j)} < x \leq \sum_{j=1}^{N_{in}}\xi_{in}^{(j)} \end{cases} \quad (8)$$

Let us consider a point with coordinates $[x; r(x)]$, marked in Fig.2. It means that we will obtain the maximum concentration value with the inlet flow rate equal to x, if we add the total amount of gas supplied by the incoming line where the concentrations equal $r_{in}^{(1)}$ and $r_{in}^{(2)}$ and part of the gas amount supplied by the line where the concentration is $r_{in}^{(3)}$ at the flow rate $x - \left(\xi_{in}^{(1)} + \xi_{in}^{(2)}\right)$.

In this case, the maximum mixture concentration value for flow rate x will be equal to

$$\frac{r_{in}^{(1)}\xi_{in}^{(1)} + r_{in}^{(2)}\xi_{in}^{(2)}x + r_{in}^{(3)}(x - \xi_{in}^{(1)} - \xi_{in}^{(2)})}{x}.$$

The distribution of flow rate and concentration values by outgoing lines will be acceptable if all points with coordinates

$$\left[\xi_{out}^{(1)}; r_{out}^{(1)}\right], \left[\xi_{out}^{(1)} + \xi_{out}^{(2)}; \frac{r_{out}^{(1)}\xi_{out}^{(1)} + r_{out}^{(2)}\xi_{out}^{(2)}}{\xi_{out}^{(1)} + \xi_{out}^{(2)}}\right], \ldots, \left[\sum_{j=1}^{N_{out}} \xi_{out}^{(j)}; \frac{\sum_{j=1}^{N_{out}} r_{out}^{(j)}\xi_{out}^{(j)}}{\sum_{j=1}^{N_{out}} \xi_{out}^{(j)}}\right] \quad (9)$$

lie below the curve (8). The first of the points corresponds to the outgoing line with the maximum concentration, the second corresponds to two lines with concentrations $r_{out}^{(1)}$ and $r_{out}^{(2)}$, etc. Columns in Fig.3 represent the points. The last point with x-coordinate $\xi_{\Sigma} = \sum_{j=1}^{N_{out}} \xi_{out}^{(j)}$ and y-coordinate ρ always lie on curve $r(x)$. The distribution of concentrations (7) is admissible if the other points do not lie above $r(x)$. If we specify the y-coordinates of aggregate points (9) as $y^{(1)} = r_{out}^{(1)}, y^{(2)} = \frac{r_{out}^{(1)}\xi_{out}^{(1)} + r_{out}^{(2)}\xi_{out}^{(2)}}{\xi_{out}^{(1)} + \xi_{out}^{(2)}}, \ldots,$

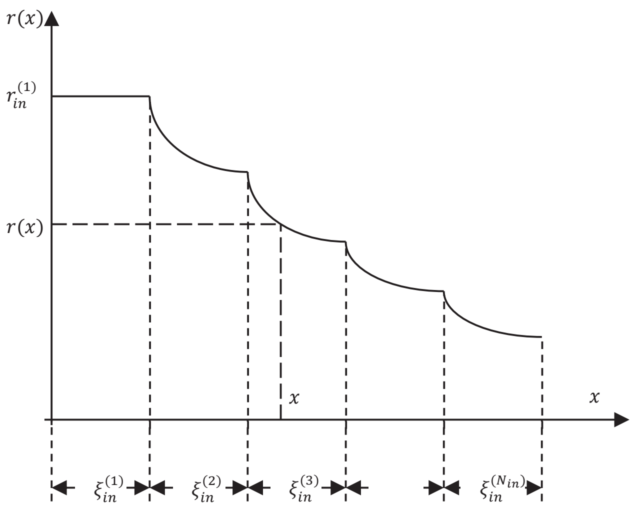

Fig. 2. Diagram of maximum possible concentrations (determined by the incoming lines of the joint node).

$$y^{(N_{out})} = \frac{\sum_{j=1}^{N_{out}} r_{out}^{(j)} \xi_{out}^{(j)}}{\sum_{j=1}^{N_{out}} \xi_{out}^{(j)}}$$

then the admissibility condition will be written as follows:

$$y^{(1)} \le r\left(\xi_{out}^{(1)}\right), y^{(2)} \le r\left(\xi_{out}^{(1)} + \xi_{out}^{(2)}\right), \dots, \quad y^{(N_{out})} \le r\left(\sum_{j=1}^{N_{out}} \xi_{out}^{(j)}\right) \tag{10}$$

VI. Problem-solving method

According to the problem statement, it is necessary to find the distribution of the component $\boldsymbol{\eta} = \{\eta_{ij}\}, (i,j) \epsilon E$, or, what is the same, the concentrations $\mathbf{r} = \{r_{ij}\}, (i,j) \in E$ that are most consistent with the whole set of concentration measurements. Using the maximum likelihood estimation (MLE), the only reasonable method of mathematical statistics for estimating unknown parameters, we obtained the problem of mathematical programming (3 – 5). Let us denote by $n^*, m_{in}, m_{out}, m_{joint}$ the number of measuring points, sources, sinks, and joint points, respectively. We will start with an analysis of the simplified problem (3 – 4), which is a quadratic programming problem with unknowns and m_{joint} linear constraints. There can be different cases depending on the values of $n^*, m_{in}, m_{out}, m_{joint}$. We will consider the simplest example – a system of three gas pipelines with one inlet and two outlets with 3 options of measured parameters. In option 1, concentrations are measured for each pipeline $n = n^* = 3, m_{joint} = 1$. Thus, we obtain the problem of quadratic function minimization of 3 variables at one linear constraint. From the constraint, one of the unknown values η_{ij} is expressed through the other two. The resulting problem on the absolute extremum of a quadratic function of two variables is reduced to the system of two linear equations with the same number of unknowns. While solving this problem, we obtain the estimates $\hat{\eta}_{ij}$ of unknown variables η_{ij}, which rely on all

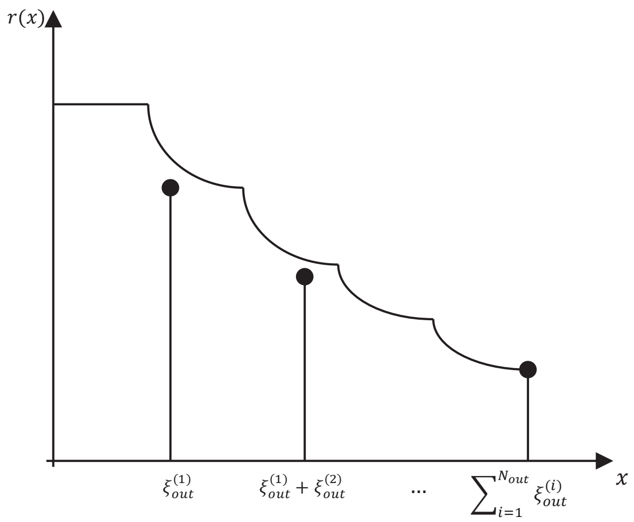

Fig. 3. Verification of the fulfillment of the non-equilibrium conditions at the joint node.

three measurements. They are more justified than direct measurements η_{ij}^* of each of the values.

In option 2, ethane concentration is measured only on 2 pipelines (for example, r_{k1}^*, r_{k2}^* in Fig.1a). Now $n = 3$, $n^* = 2$, $m_{joint} = 1$, we have the problem of minimizing the quadratic function of two variables η_{k1}, η_{k2} with one linear constraint. The minimum of the likelihood function is found directly, and the obtained estimates equal the measurements $\hat{\eta}_{k1} = \eta_{k1}^*, \hat{\eta}_{k2} = \eta_{k2}^*$.The constraint is used to find the estimate of the missing unknown of the ethane flow rate along the arc entering node x_k. In option 3, we measure only one value, for example, η_{k1}^* (Fig. 1a). The maximum likelihood method enables us to obtain only a trivial result, i.e. the estimate of ethane flow rate by one arc $\hat{\eta}_{k1} = \eta_{k1}^*$.

The same kind of reasoning is carried out in the general case for any relationship between n, n^*, m_{joint}. It helps to reveal what results can be obtained with the existing system for measuring gas composition. The estimates of concentrations cannot be always obtained for all arcs of the graph. Everything depends on the number and location of measuring points. For a graph of an arbitrary structure, the determining value is $d = m_{joint} - (n - n^*)$. When $d > 0$, the desired estimates are refined because the mutual influence of the entire set of measurements is taken into account. If $d = 0$, the results of measurements directly serve as estimates of the concentration values. If $d < 0$, the constraint equations are not enough to estimate all non-measured concentration values r_{ij}. Graph G can have the subgraphs that meet the condition $d > 0$. The subgraph G_l (X_l, E_l) of graph $G(X, E)$ is the graph for which $X_l \subset X$ and for every node $x_k \in X_l, \Gamma_l(x_k) = \Gamma(x_k) \cap X_l$ [20, 21]. Consequently, quite a lot of measurements are made on the arcs of these subgraphs to refine the concentration estimates based on them. An algorithmic procedure for finding such subgraphs is proposed. Estimates are obtained as a linear function of measurements

$$\hat{r}_{ij} = \sum_{(k,l)\in E^*} \left[a_0^{ij} + a_{kl}^{ij} r_{kl}^*\right], \ (i,j) \in E. \tag{11}$$

The quality of estimates is characterized by the variance. In the assumption (2) the variance of estimate $\hat{r}_{ij}$, following from the MLE, will be calculated by the formula

$$\mathbf{D}\hat{r}_{ij} = \sum_{(k,l)\in E^*} \left[\left(a_{kl}^{ij}\right)^2 \mathbf{D} r_{kl}^*\right], \ (i,j) \in E \tag{12}$$

Let us note that there can be inconsistent data in the initial information due to its stochastic nature. Consider the following situation: at the junction of 3 pipelines (Fig. 1a), measurements are made on the incoming and one of the outgoing lines $r_{\cdot k}^*, r_{k1}^*$, with $r_{k1}^* > r_{\cdot k}^*$. Relationship (5), which in our case looks like $r_{k1} \le r_{\cdot k}$, should be satisfied to obtain the true concentration value. If the probability of inequality $r_{k1}^* > r_{\cdot k}^*$ is low, the result should be considered to be senseless. A possible reason could be the presence of systematical measurement errors at one or both measuring points, which requires an audit of the devices or the qualifications of the personnel making the measurements.

Let us discuss the general case – the problem (3 – 5). We paid so much attention to the simplified version (problem (3, 4)), because the procedure for numerically solving it is rather simple. Potentially, this solution can satisfy condition (5). Then the required result is achieved by small efforts, and further analysis is not required. Otherwise, a more complex mathematical programming problem is obtained, which, however, can be solved using standard optimization packages. While preparing the information to solve the problem, it is worthwhile to take into account the relations

$min(x, y) = (x + y - |x - y|)/2$,

$max(x, y) = (x + y + |x - y|)/2$,

and formalize search of $min(x_1, \dots, x_n)$ and $max(x_1, \dots, x_n)$ as algorithmic procedures.

VII. Heuristic algorithms of local optimization

The procedures proposed above make it possible to obtain a solution (distribution of concentration values r over the arcs of graph G). Moreover, the set of arcs E of the graph splits into 3 noncrossing subsets $E = E' \cup E'' \cup E'''$. E' is a set of arcs with the estimates of concentration values for which $\hat{r}_{ij}, (i, j) \in E'$ takes into account the entire set of measurements affecting these estimates. The estimate of concentration values $\hat{r}_{ij}, (i, j) \in E''$ on the arcs E'' is equal to the concentration value measured on the corresponding arc $\hat{r}_{ij} = r^*_{ij}$, because due to limited information contained in the set of measurements, there are no other measurements that affect this estimate. E''' is a set of arcs for which the estimate of concentration $\hat{r}_{ij}, (i, j) \in E'''$ cannot be obtained under the existing system of measuring points in the considered GTS.

In practice, with insufficient measurements, it is worthwhile to have a picture of the concentration distribution, which is not necessarily rigorously substantiated but at least plausible. To this end, a heuristic algorithm is developed to sequentially look through the joint nodes, one at a time. Moreover, at each step, the calculation procedure is simple, and the amount of calculations is small, which is an attractive feature of the method.

Let us give some comments before the algorithm description. All nodes of the graph can be numbered so that the source node number for every arc is less than the sink node number. We order all arcs $(i, j) \in E$ and all nodes $x_k \in V$ of the graph by the numbers of the natural series. Assigning a number to an element – a node or an arc – we will say that this element is colored. We start numbering the nodes from the sources, assigning numbers $1, 2, \dots, m_{in}$ to them in random order. The joint nodes $x_k \in V_{joint}$ will be numbered as $m_{in}+1, \dots, m_{in}+m_{joint}$, by following the rule – the next number is assigned to node $x_k \in V_{joint}$ after all nodes from set $\Gamma^{-1}(x_k)$ have been colored. After numbering and coloring the node, we number and color all arcs outgoing from this node. The sinks are numbered as $m_{in} + m_{joint} + 1, m_{in} + m_{joint} + 2, \dots, m_{in}$ in any order. As a result, the numbers of nodes can increase only in the direction of flow. The source node number for each arc will be lower than the sink node number. The presented numbering scheme takes into account that graph G is an oriented graph, which does not have loops, i.e. oriented closed circuits. An example of numbering the graph nodes and arcs is presented in Fig. 4.

According to the numbering, the components of vector r are sequentially determined. With this in view, two heuristic algorithms of local optimization were developed.

Algorithm 1.

Step 0. Start of calculation. Color the nodes of set V_{in} because the information about gas composition in sources is included in the input data. Color the dangling arcs outgoing from the sources, assigning the appropriate concentrations to them.

Iteration: steps 1, 2, 3.

Step 1. Color the nodes, for which the incoming arcs are colored.

Step 2. Randomly select one of the colored nodes. Let this node be x_k. Determine concentrations r_{kj} at the arcs of the set $(k, j) \in \Gamma(x_k)$ outgoing from node x_k. If none of these arcs is included in the set E^*, then assign the same concentrations r_{kj} calculated from mass conservation condition (4) to arcs $(k, j) \in \Gamma(x_k)$, and color these arcs and node x_k. If one or several arcs $(k, j) \in \Gamma(x_k)$ (but not all arcs) belong to set E^* (i.e. the concentration values $r_{kj} = r^*_{kj}$ are measured), assign concentration values r^*_{kj} to these arcs and assign equal concentration values, calculated from condition (4)

$$r = \left(\xi_k r_k - \sum_{j \in E^*} r_{kj} \xi_{kj}\right) / \sum_{j \quad E^*} \xi_{kj}$$

to the other arcs $(k, j), j \notin E^*$.

If all arcs from $\Gamma(x_k)$ are included in set E^*, i.e., $\Gamma(x_k) \in E^*$,, all measured concentration values should be corrected by mass conservation condition (4) for ethane $r^*_{kj}, j \in \Gamma(x_k)$. Introduce the corrective multiplier $\lambda = \xi_k r_k / \sum_{j \in \Gamma^{-1}(x_k)} r^*_{kj} \xi_{kj}$, and assign the concentration values λr^*_{kj} to the arcs. Here ξ_k, r_k are the total fluid flow rate and ethane concentration at the inlet of node k.

All arcs $(k, j), j \in \Gamma(x_k)$ are colored. All nodes, for which all incoming arcs have already been colored, are also colored.

Step 3. Check if there are any uncolored arcs. If *yes*, go to step 1, if *no* –stop. The proposed algorithm takes into account that the values r_{ij} are small $r_{ij} \ll 1$, so it will be possible to limit the calculations by first-order terms in the calculations and assume, in particular, that fluid flow rates through the arcs cannot be changed when adjusting the concentration values.

Note. The order of algorithm realization can be reverse

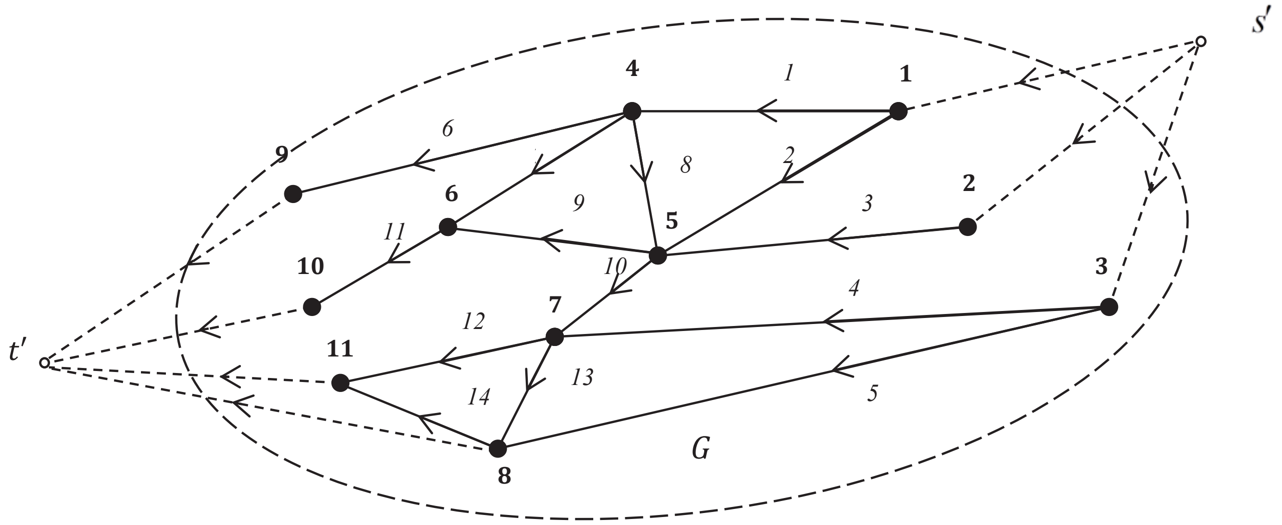

Fig. 4. Graph of the system with fictitious source and sink.

if the elements are colored against the orientation of arcs. It is advisable if the data on concentration in sinks $r_{kj}, j \in V_{out}$ are included in the initial information.

The proposed algorithm gives an approximate solution that does not take into account the information on the entire set of measurements, both in sources and at other points of the system. The exact statement and solving the problem under standard assumptions about measurement errors were given above.

VIII. Decomposition methods

All ideas of algorithm 1 are generalized in algorithm 2 to be discussed later. We will give some definitions before describing the algorithm. We introduce the fictitious source s' by drawing arcs from it to each actual source and the fictitious sink t' by drawing arcs to it from each actual sink.

With the view to obtaining plausible and more precise numeric results than the results obtained with algorithm 1, we can also apply the decomposition methods. These methods allow reducing the search for solution *r* on graph *G* to a sequence of similar problems on its subgraphs. These problems are of smaller dimension and, consequently, are easily calculated. The decomposition methods are approximate and it is hardly possible to determine the extent to which they are accurate. Without going into detail, we will describe the idea of the methods.

The *minimal cut S* (hereinafter we use the term cut for simplicity) is a set of the graph arcs $S \coloneqq (i,j) \in E$, without which the graph loses its connectivity. The property of connectivity loss will disappear after removing any arc from the set.

We can introduce partial ordering $\succ$ on the set of cuts assuming that $S_j \succ S_i$ if the numbers (the numbering is considered to be made as mentioned above.) of all arcs S_j or some of the numbers of arcs S_j are greater than numbers of all arcs S_i, and the other arcs from S_j belong to S_i (Fig.5).

We introduce the notation: the cut *S* divides *G* into two connectivity components which will be denoted by $G_{source}(S)$, $G_{sink}(S)$, (the first includes the source and the second – the sink.), i.e. $G = G_{source}(S) \cup S \cup G_{sink}(S)$.

Adjustment of a solution by minimum cuts (Algorithm 2).

We sequentially proceed from cut S_{l-1} to cut $S_l \succ S_{l-1}$. . When doing so, we adjust the concentration values of arcs in set $(G_{source}(S_l) \cup S_l)/(G_{source}(S_{l-1}) \cup S_{l-1})$ using the ethane balance conditions as in algorithm 1, the transition from one node to another of a larger number was made. Then, the components of the solution on the subgraph (G_source $(G_{source}(S_l) \cup S_l)/(G_{source}(S_{l-1}) \cup S_{l-1})$ will not have the inverse effect on the solution on the subgraph $G_{source}(S_{l-1}) \cup S_{l-1}$.

IX. Calorific value distribution

It is easy to switch from the distribution of concentration values by an arc of the calculation graph to the distribution of heat (calorific) value. According to the State Standard 31369-2008 [22], the molar calorific value of gas mixture is calculated as a weighted average value by the gas

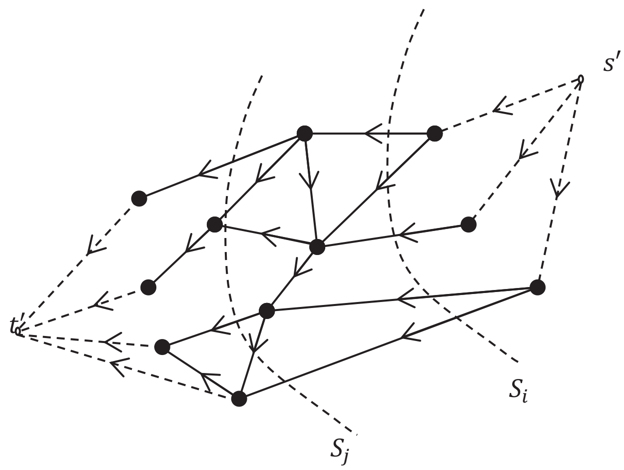

Fig. 5. The concept $S_j \succ S_i$.

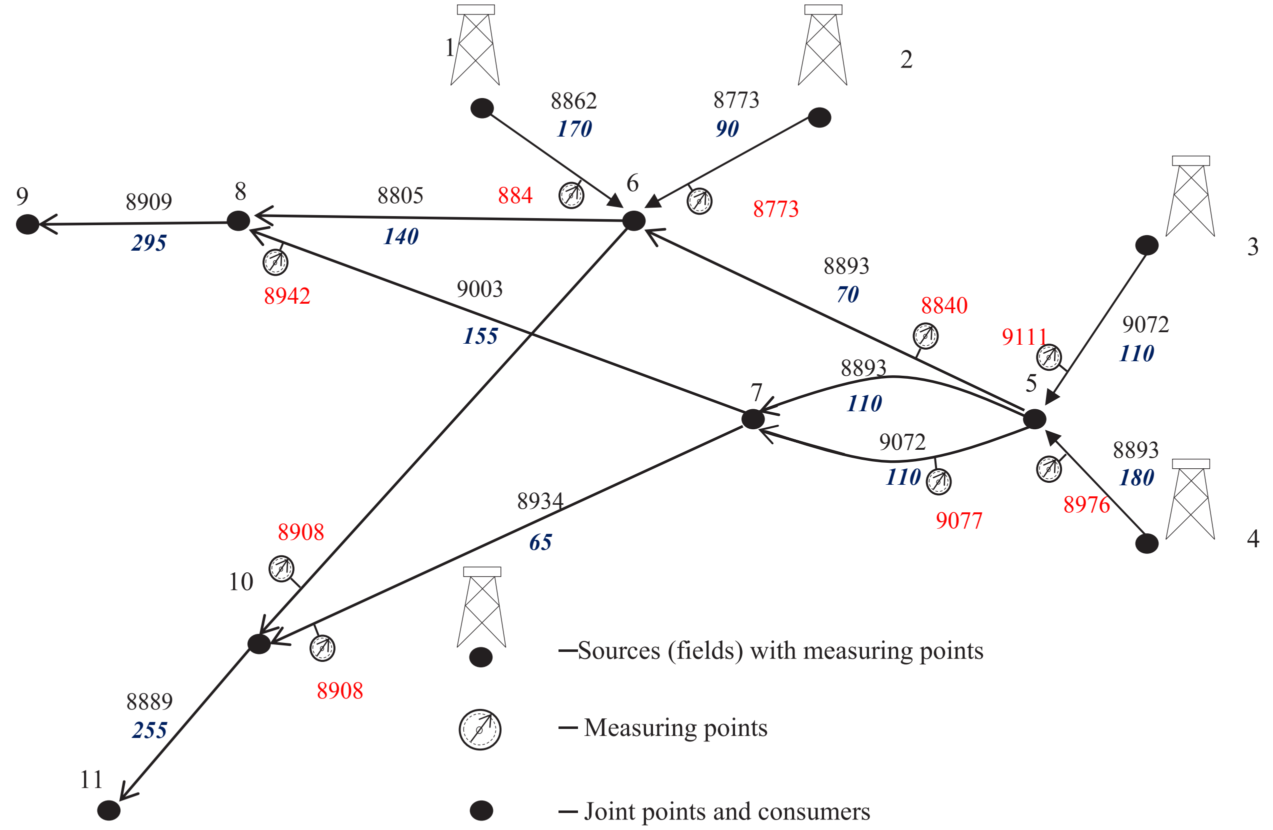

Fig. 6. Example. Distribution of gas volumetric calorific value (in kcal/cub m). 11 – number of node, 8936 – calorific value H_{ij} by arc, 65 – flow rates ξ_{ij} by arc (in MMcmd), 8910 – measured calorific values.

composition $\overline{H} = \sum_j x_j \overline{H}_j$, where x_j is the molar fraction of component j, and $\overline{H}_j$ is its calorific value. The values $\overline{H}_j$ for ethane and methane are 891,56 and 1562,14 $\frac{\text{kJ}}{\text{mol}}$, respectively. The mass calorific value $\widehat{H}$ is calculated by the molar one, using the formula $\widehat{H} = \overline{H}/M$, where M is the mixture molar mass. Volumetric heat value $\widetilde{\widetilde{H}}$ is also proportional to value $\overline{H}_j$. Therefore, the calorific value can be calculated either by the concentration values or by the formulas mentioned above with changed notations. The calorific value plays a significant part in mutual settlements between gas suppliers and consumers, which is why this concept is used rather widely. A calculation example below clarifies the results in terms of calorific value.

X. Calculation example

By way of illustration, we will demonstrate the calculation of the calorific value distribution by transmission direction. Figure 6 presents the GTS structure, input data, and results of calculations.

Graph of the system includes n=13 arcs (transmission directions), m = 11 nodes (of which m_{in} = 4 sources, m_{out} = 2 sinks (consumers), m_{joint} = 5 joint nodes), *and* n^* = 9 measuring points. Therefore, $d = m_{joint} - (n - n^*) = 1$, and the number of measurements is sufficient to take into account their cross-impact and to make a system-wide estimation of unknown values.

The input data (flow rates, measured calorific values) and calculation results are demonstrated in the Table and some of them are given in Figure 6. $\widehat{H}_{ij}^{(1)}$ are the estimates of calorific value provided that condition (5) is met, $\widehat{H}_{ij}^{(2)}$ are the estimates obtained without meeting condition (5), $\widehat{H}_{ij}^{(3)}$ are the estimates obtained using the heuristic algorithm 1, $\hat{r}_{ij}$ are the estimates of concentration values in the main calculation with condition (5) satisfied. An analysis of the obtained results indicates that estimates $\widehat{H}_{ij}^{(2)}$ do not satisfy conditions (5) at node 5, while at the other nodes, conditions (5) are satisfied. Checking makes it possible to establish that in the case of solution $\widehat{H}_{ij}^{(1)}$ the sufficient condition (10) is also satisfied. In other words, simple models were used for the calculation, which did not include condition (10), but this condition appeared to be satisfied and further studies were not required. Therefore, one can hope that in many practical problems the solution to the optimization problem (3) subject to (4) and (5) will satisfy more stringent conditions (4) and (10).

The values of MLE criterion (3) are demonstrated in the last line of the Table. Value $\widehat{H}_{ij}^{(2)}$ is 14% less than the value $\widehat{H}_{ij}^{(1)}$. Such a large difference in the criterion values shows its sensitivity. The difference between vectors $\|\widehat{H}_{ij}^{(1)}\|$ and $\|\widehat{H}_{ij}^{(2)}\|$ is not large, whereas the difference between the values of the criterion for these vector arguments is considerable, i.e. if we do not allow for the irreversibility

Table 1. The initial data and calculation results

Arcs(i,j)	Flow rates ξ_{ij}MMcmd	Measurings $\widehat{H}_{ij}^{(*)} kcal/m^3$	Estimates $\widehat{H}_{ij}^{(1)} kcal/m^3$	Estimates $\widehat{H}_{ij}^{(2)} kcal/m^3$	Estimates $\widehat{H}_{ij}^{(3)} kcal/m^3$	Estimates $\hat{r}_{ij}$
1	2	3	4	5	6	7
(1,6)	170	8840	8862	8840	8840	0,043
(2,6)	90	8773	8773	8773	8773	0,030
(3,5)	110	9111	9072	9063	9111	0,074
(4,5)	180	8976	8893	8897	8976	0,047
(5,6)	70	8840	8893	8871	8840	0,047
(6,8)	140	No measuring	8805	8720	8705	0,035
(6,10)	190	8908	8873	8908	8908	0,045
(5,7)	110	No measuring	8893	8900	9097	0,047
(5,7)	110	9077	9072	9077	9077	0,074
(7,8)	155	8942	9003	9010	9097	0,064
(8,9)	295	No measuring	8909	8872	8911	0,050
(7,10)	65	8908	8934	8937	9062	0,053
(10,11)	255	No measuring	8889	8915	8947	0,047
Objective function value			17350	14971	47863	

condition (5), the criterion value drops significantly (14%).

The use of the heuristic algorithm of local optimization (solution $\widehat{H}_{ij}^{(3)}$) demonstrates its ineffectiveness. Indeed, the criterion of MLE, which characterizes the extent to which the interdependence of the measured parameters is taken into account, is significantly greater (2.75 times) than for the (solution $\widehat{H}_{ij}^{(1)}$). This proves that the heuristic algorithm can hardly be considered a satisfactory approximation to a reasonable (solution $\widehat{H}_{ij}^{(1)}$), despite its seeming natural algorithmic constructions.

XI. Conclusions

The proposed technique allows calculating the distribution of the composition of natural gas when transported via gas transmission systems of an arbitrary configuration. The developed mathematical model takes into account the irreversible and non-equilibrium nature of gas mixing processes due to various gas composition, as well as the random nature (instrument errors) of the initial data on measurements of the concentration of the components.

Instead of components concentration, formalization can be carried out in terms of gas calorific value. Using the maximum likelihood estimation, the search for the concentration distribution is reduced to the problem of mathematical programming with equality and inequality constraints, which follow from the law of mass conservation and the conditions of the process non-equilibrium. The problem is solved by well-known numerical methods using standard software packages.

The calculation example demonstrates the efficiency of the method and the potential difficulties in solving practical problems due to insufficient information and systematic instrument errors. The proposed technique can be applied to control calorific value when supplying gas to domestic consumers. It is also suitable for calculating the dew point temperature during flows through transmission systems of arbitrary configuration, which is necessary for the operational control of export supplies.

The analysis of the multicomponent gas mixture flows can serve as a methodological basis for accomplishing the prospective flow management tasks in the UGSS of the Russian Federation, which are related to the construction of gas chemical facilities using natural gas as a feedstock.

References

[1] State Standard (GOST) R 53763-2009. Combustible natural gases. Determination of dew point temperature by water, (in Russian).

[2] ISO 18453. Natural gas — Correlation between water content and water dew point. International standard First edition 2004-07-01.

[3] State Standard (GOST) R 57851.1-17 Gas condensate mixture. Part 1. Separation gas. Determination of component composition by gas chromatography. - M.: , 2017 .p. 53. (in Russian)

[4] ISO 39254.2016. Petroleum products – Determination of boiling range distribution – Gas chromatography method. p. 25.

[5] Mokhatab S., Poe W.A., Mak J. Y. *Handbook of Natural Gas Transmission and Processing Principles and Practices.* 2019.

[6] Kidnay A. J., Parrish W. R. Fundamentals of Natural Gas Processing. *Taylor & Frensis Group*. p. 433, 2006.

[7] Hébrard J. Safety of hydrogen/natural gas mixtures by pipelines: *ANR french project HYDROMEL*, Hébrard J., Studer E., Jallais S., Blanchetière V., Gentilhomme O.

[8] Kuczy´nski S. Thermodynamic and Technical Issues of Hydrogen and Methane-Hydrogen Mixtures Pipeline Transmission, Kuczy´nski S., Łaciak M., Olijnyk A., Szurlej A.,Włodek T. Energies 12(3):569 February 2019.

[9] Jieying L. Research on mixing law of natural gas

pipeline replaced by nitrogen, Jieying L., Meijuan Dang, Rui L., Xianbo G., Juntao Y. Advances in *Mechanical Engineering*, Vol. 9(6), pp. 1–8., 2017.

[10] J.W.Gibbs. Thermodynamics. Statistical mechanics. M.: *Nauka*, p.584, 1982, (in Russian.)

[11] S.R. de Groot. Thermodynamics of irreversible processes, p.280, 1956, (in Russian.)

[12] S.R. de Groot and P. Mazur, Non-equilibrium Thermodynamics, North-Holland, Amsterdam, 1962. Translation S.R. de Groot and P. Mazur, *Non-equilibrium Thermodynamics*. M.: Mir, p.456, 1964. (in Russian)

[13] Gurov K.P. Phenomenological thermodynamics of irreversible processes, M.: *Nauka*, p.127, 1978, (in Russian)

[14] Balesku R. Equilibrium and non-equilibrium statistical mechanics, p.756, 1975.

[15] Porshakov B.P., Romanov B.A. Fundamentals of thermodynamics and heat engineering. - M.: *Nedra*, 1988.

[16] Nikolaev G.P., Loyko A.E. Technical Thermodynamics. - Yekaterinburg: UrFU, p.227 2013.

[17] Purtov P. A. Introduction to non-equilibrium chemical thermodynamics. Novosibirsk: NSU, 2000.

[18] Baykov V.I. Thermophysics. Non-equilibrium heat and mass transfer processes Baykov V.I., Pavlyukevich N.V., Fedotov A.K. Shnip A.I. *Higher School*. p.476, 2018. (in Russian)

[19] Nagnibeda E., · Kustova E. Non-Equilibrium Reacting Gas Flows. Kinetic Theory of Transport and Relaxation Processes. *Springer-Verlag*, p.252, 2009. (in Russian)

[20] Berzh K. Graph theory and its applications, p.320, 1962, (in Russian)

[21] Christofides N. Graph theory: an Algorithmic Approach, p.400, 1975.

[22] State Standard (GOST) 31369-2008. *Natural gas*. Calculation of calorific value, density, relative density and Wobbe number based on component composition. (in Russian)

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A Study Of Factors Influencing The Development Prospects Of The Coal Industry In The Eastern Regions Of Russia

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Abstract — **The study provides an overview of the coal-producing regions in Russia. A set of factors influencing the development of coal mining in the regions is determined. An analysis of the interdependence of factors is carried out. The extent to which various factors affect the development of the coal industry in the eastern regions of Russia is assessed. Most of the factors are capable of influencing the development of the coal industry only in the long run due to the inertia inherent in the industry development. The findings indicate that the development prospects for the coal industry in the regions are largely determined by the development of coal energy facilities and the demand for coal in the international market. Russia's regions differ significantly in terms of their coal industry development, coal resources, coal category with respect to its carbon content rank, mining and geological conditions, the geographical location, and other characteristics. There are also significant differences between the sets of main factors that influence the opportunities for coal production development in a region. The study shows that forecasting the development of the coal industry in the regions calls for a case-by-case approach, including the development of an individual model for each coal-producing region.**

Index Terms **— coal industry, region, factor, coal, characteristics, consumption, production, exports, energy industry**

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I. Introduction

Unlike oil and gas, coal is a widely available resource. Coal reserves in the world and individual countries are significantly larger than other fossil energy reserves. The availability of coal reserves ensures energy security in many countries. Coal is mainly used to produce electricity and coke for the steel industry. The former use is constantly increasing, while the latter is constantly decreasing. Coal serves as the backbone of the world's electricity supply.

Coal resources are available in many countries. Coal mining plays an important role in both national economies and the economies of coal-producing regions. The effect of various factors on the volume and dynamics of coal mining was studied by many scholars [1-9]. Many factors influencing the development of coal mining have been revealed. The above studies outlined, on the one hand, the factors that lend themselves to being evaluated and can be taken into account quantitatively in the studies of the dynamics that make use of economic and mathematical models [10-24] and, on the other hand, the factors that are difficult or impossible to take account of.

For different countries and different regions of coal mining, the sets of main factors affecting the development of coal production differ greatly. This is due to significant differences between these regions in some of the aspects of their industrial development. This is, first of all, the role of the coal industry in the region's economy, coal mining and transportation conditions, coal quality indicators, to name just a few.

The countries (as well as regions of the countries) possessing coal resources can be provisionally divided into three classes based on their use: for domestic consumption, mainly for export, and both for domestic consumption and export. For Russia, and especially for the eastern regions of Russia, coal has become an important resource for the development of export in recent years. Whereas in 2000 the share of coal supply to the international market in the overall supply of the Russian coal was 11.4%, in 2018 it amounted to a mere 55% [25].

Various organizations studied the prospects for coal industry development at the national level and the regional level, i.e. for the federal districts (FD) and federal subjects (FS), as well as individual companies and their groups [1-22, 26-34].

Models, software, and information support developed with the participation of the authors were used in the studies carried out at the Melentiev Energy Systems Institute, SB RAS [23,24,35, 36]. An analysis of the long-term experience of research conducted by the scholars both in Russia and abroad, including that with participation of the authors [30-34], and an analysis of the statistical data and other resources, revealed the trends of the coal industry development in the coal-producing regions of Russia as shaped under the conditions of previous years and expected to unfold further in the future. This made it possible to identify the factors influencing the development trends of the coal industry in Russia and its regions. The objective of this study was to systematize and identify the most significant factors affecting the development of coal mining for various regions.

II. Overview of the Russian coal industry

The coal industry, being one of the largest energy systems, has certain properties [37]: those of its entities (structural units of the industry and coal products) and those that are information-based. Entities are defined as companies or groups of companies. Of the entity properties, the most important are structural complexity, large scale, heterogeneity, and scarcity. Properties of coal products are heterogeneity, poor interchangeability, and high demand. Information-based properties include incompleteness of information on entities and uncertainty of future conditions of economic and energy development in the regions, and international coal markets, including coal demand and coal prices [38]. Factors influencing the development of the coal industry are directly related to

Table 1. Profile of coal mining federal subjects (as of 2017)

Index	Production mln. t	Processing, as % of production	Export mln. t	Share of locally produced coal in total consumption, %	Structure of supplies, %		
					exports	regions of Russia	
						total	Coal – producing region*
Export coals							
Siberia and the Far East							
Novosibirsk region	10.8	51	9.8	2	96	4	4
Kemerovo region	241.3	57	135.8	95	64	36	24
Republic of Khakassia	20.6	57	7.3	26	39	61	4
Zabaykalsky Territory	22.1	54	9.0	96	57	43	40
Republic of Sakha (Yakutia)	17.5	62	7.4	97	57	43	21
Khabarovsk Territory	6.6	90	2.6	30	59	41	20
Sakhalin region	7.6	1	7.5	100	64	36	18
Regions of European Russia							
Rostov region	5.8	71	2.3	99	34	66	66
Murmansk region	0.12		0.04	0	100	0	0
Nationally significant coals							
Regions of European Russia							
Komi Republic	8.8	88	0.03	92	6	93	19
Siberia							
Krasnoyarsk Territory	39.3		2.2	89	5	95	58
Locally significant coals							
Regions of European Russia							
Tula region	0.2			0	0	100	100
Orenburg region	0.2						
Chelyabinsk region	0.7			7	0	100	100
Siberia and the Far East							
Republic of Tuva	0.7		0.08	1	0	100	100
Irkutsk region	11.5	26	1.0	71	9	91	90
Republic of Buryatia	2.4			24	0	100	100
Primorsky Territory	8.5	0.2	1.2	81	2	98	98
Amur region	3.4			90	0	100	100
Magadan region	0.3			65	0	100	100
Chukotka Autonomous Okrug	0.2			70	0	100	100
Kamchatka Territory	0.03			10	0	0	0

Note: * a share of the supplies to the regions of Russia

Sources: Statistical data by Federal State Unitary Enterprise “Central Dispatching Department of the Energy Sector”, calculations performed by the authors the above properties. Factoring them in is important when researching the development prospects of the coal industry and performing a computational experiment based on economic and mathematical models.

The large scale and structural complexity of the Russian coal industry are evident not only in the presence of numerous companies but also in their being scattered across a vast territory of the country in different climatic zones and time zones. The Russian coal industry is made up of more than two hundred coal mining (180) and coal processing (65) companies located in 21 Federal entities. It supplies consumers in the regions of Russia and supplies coal for exports. Coal reserves are available in 34 federal subjects. The heterogeneity is due to the uniqueness of coal deposits in terms of coal quality characteristics, coal mining conditions, and other indicators. Scarcity manifests itself in available reserves, demand, interchangeability of products, labor, and financial resources, etc. To this end, it would be more correct to consider specific deposits rather than coal-producing regions. Statistical data used for analysis and projections, as well as other resources, are usually linked to regional structures. This study does not deal with the coal of individual deposits, but rather with the coal of federal subjects, which is in line with the official statistical data.

The coal industry is one of the most important sectors of the Russian economy. Russia has great potential for the development of coal mining. The majority of coal mining entities of the Russian Federation are located in the Siberian Federal District and the Far East. Together, they produce more than 95% of all coal produced in Russia. In this study, the coals are distinguished by their significance in terms of markets, i.e. local, regional (significant for adjacent Federal entities), national, and international. The coal significance is determined by the quality rank of the coal deposit, which is being developed or is to be developed in the future, and is assessed based on the 2017 statistical data (Table 1). The coal is considered to be of export and nationwide significance if its larger share (above 30%) is supplied to these markets; whereas locally significant coals are those which are consumed mainly within the region of their production with insignificant volumes consumed in the adjacent regions. Some federal subjects may produce coal of various significance when several deposits are developed there. In the event that the regions producing locally significant coals implement coal mining development projects and create an appropriate transport infrastructure, they may also start to export about 90% of the production volumes, as is the case, for example, the Republic of Tyva and Kamchatka Territory.

Coal-producing regions of Russia differ significantly in terms of their structure of supplies, availability of coal preparation plants, and coal mining development projects. Only three regions (Kemerovo region, Republic of Sakha (Yakutia) and the Republic of Komi) supply coal for the by-product coke industry, and only 14 regions produce coal for export. According to the coal industry development program (long-term program for the development of the Russian coal industry to 2030; approved by Resolution of the Government of the Russian Federation No. 14-r dated January 24, 2012), only four regions have the projects for constructing coal-fired power plants: the Republic of Sakha (Yakutia), the Sakhalin, Irkutsk and Amur Regions; whereas in the case of the coal chemical industry, respective

Table 2. Factors influencing the development of the coal industry

Internal factors		External factors	
Factors that are common for all regions			
1.	resource base	3.	natural factors: water availability in rivers (in the case of HPPs), winter temperatures
2.	the geographical location (remoteness from coal markets or coal suppliers)		
Coal-producing region			
4.	coal quality characteristics and coal significance	8.	projects for the reconstruction of existing companies and establishing new coal mining and processing companies, inclusive of availability of resources for project implementation: investments, labor resources, etc.
5.	mining, geological, and hydrological conditions of coal deposit development		
6.	technical and economic indices of the company: production capacity of the company, etc.	9.	projects for construction of coal-fired power facilities
7.	processing capacities available		
Factors common to coal-producing and coal-consuming regions but classified as belonging to different categories			
Coal-consuming region		**Coal-producing region**	
10.	internal demand for coal and coal products - a fuel that power plants are designed to run on - miscellaneous demand.	10.	demand for coal and coal products - internal (in the case of a coal-producing region) - in other regions of Russia - for export - competition with other energy carriers
11.	economic indices of coal use as a fuel	11.	economic indices of coal production and processing
12.	availability of transport and social infrastructure	12.	availability of transport and social infrastructure
Production and consumption relations			
13.	economic indices: coal prices at mine, coal transportation rates, domestic and global market coal prices		
14.	existing coal supply pattern		
15.	development of port and transport infrastructure, including that for coal export		
16.	scientific and technological advances affect all components of the coal market		

Source: estimates by the authors

projects are in place in the republics of Khakassia and Sakha (Yakutia), Krasnoyarsk Territory, the Amur, and Magadan Regions.

III. Factors influencing the development of the coal industry

We will distinguish between three key aggregated components of the coal market: A "Coal-producing region (a set of coal-mining and coal-processing companies that operate in a region or a Federal entity), a "Coal-consuming region", and "Production and consumption relations". “Production and consumption relations" implicitly include intermediaries between the seller and the buyer, as well as coal and energy companies that are both coal producers and coal consumers.

Factors influencing the development of the coal industry in Russia and its regions for each of the coal market components can be divided into internal and external. Internal factors are determined by the profile of the region: the status of energy sector companies (coal mining and coal processing companies; power plants and boiler houses that use coal as their fuel; other consumers); transport infrastructure condition; resource base, etc. External factors depend on the forecast scenarios of coal industry development in the region and scenarios of the overall economic development. The scenarios cover the measures aimed at changing the volume and structure of production, consumption, and supply of coals in terms of their uses. External factors also include poorly predictable factors, for example, natural, geopolitical factors, and others.

The identified factors were ranked and structured for coal-producing regions and coal-consuming regions (Table 2). The presented factors differ in their impact on the development of coal production.

IV. Effect of factors on coal mining development

The effect of individual factors (coal transportation rates, coal demand, coal resources, etc.) has been studied when forecasting the development of the coal industry in the country and its regions [30-34]. Some factors were assessed based on expert estimates relying on the findings of the studies and the analysis of the historical dynamics of the indices showing the performance of the coal industry of the country and its regions: production, inter-regional and export supplies, consumption, etc.

The greatest impact on the development of coal mining is that of the demand for coal. Coal is consumed in most federal subjects of Russia. An analysis of the historical data of coal consumption indicates that domestic consumption (power plants and boiler houses, by-product coke plants, households, and other consumers) is decreasing, while export is growing. Domestic coal consumption also decreased in absolute terms from 207.5 million tons in 2000 to 169 million tons in 2018, while coal export supplies increased from 35.4 million tons to 205 million tons over the same period. At the same time, the proportions in the structure of coal consumption remained relatively stable: energy industry facilities (thermal power plants and boiler houses) account for 50%, by-product coke plants - 20%, and other consumers - 30%.

The main components of the demand are the demand for coal in the production region itself, the demand in other regions of Russia, and the export demand. An analysis of the dynamics of coal consumption in the regions in terms of its use in retrospect as well as the studies show the relative stability of coal supplies to by-product coke plants, households, and other consumers. The most significant impact on coal production levels is that of the demand for coal to be exported, for coal to be used by power plants and the future demand for coal in the coal chemical industry. Forecasting the demand for coal is rather challenging, and requires both dedicated models and expert estimations [27]. In the short run, coal consumption by power plants varies depending on natural factors, and, in the long run, it is affected by the implementation of projects for construction of coal-fired power plants, and the planned replacement of an energy carrier. The need for coal at existing energy facilities will decrease due to the modernization and replacement of obsolete equipment and, accordingly, an increase in the efficiency of these facilities.

The export demand for coal is also affected by the competitiveness of coal, the remoteness of markets, and the throughput capacity of transportation facilities. Growing export demand for coal stimulates the development of production and processing of the coal that is in demand in the global coal market. The lack of demand for low-grade coal processing products for the energy industry may restrain the growth of coal production and processing, and, consequently, limit the resources for exports. This is especially relevant for companies that produce large amounts of export coal.

As the domestic demand for coal in a coal-producing region grows, the following measures are used to increase production:

- full utilization of production capacities;
- reduction in coal supplies to other regions of Russia.
- If there are no constraints on the resource base and if local production is economically justified compared to coal delivery from other regions, coal production may increase due to:
- reconstruction and expansion of production capacities;
- preparation and commissioning of new capacities.

The resource base and mining, geological and hydrological conditions for coal deposit development determine the feasibility of constructing new production facilities and expanding the existing ones, shutting down companies, and using the methods and technologies for the development of deposits.

Economic indices are of paramount importance,

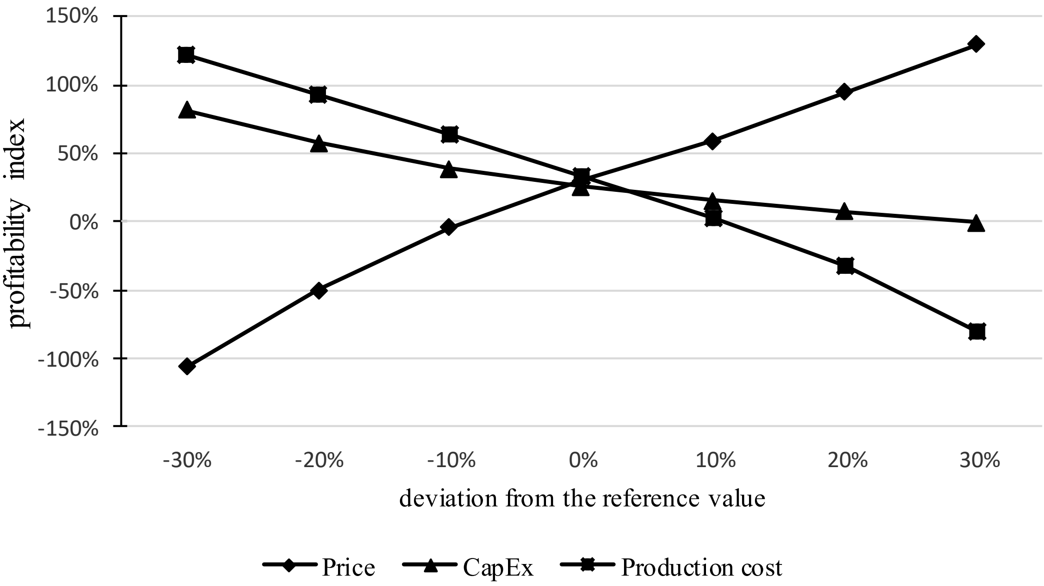

Figure 1. Profitability index versus deviations of input parameters from reference values

especially when making decisions on the implementation of new deposit development projects. At the stage of investment project valuation, there is an uncertainty of future conditions for economic and energy development in the regions along with incompleteness of information about the facilities. Sensitivity analysis enables one to determine the limits of changes in economic indices that still make the project implementation feasible. Figure 1 shows the change in the profitability index of a project depending on the deviations from the assumed reference values of coal prices, production costs, and required investments.

The availability of processing capacity in the regions producing the coal of export quality influences possible export volumes. With the increase in coal processing volume, it is possible to increase the volume of coal production and export given the demand for this coal and favorable prices in the global coal market. While the volume of coal processing in the country as a whole grew from 117.6 million tons in 2010 to 199.0 million tons in 2018, the volume of exports increased from 116.4 million tons in 2010 to 193.2 million tons in 2018. The growth of export supplies, given the growing processing volume, is typical of the majority of the Federal subjects that supply coal for export.

The geographical location (remoteness from the target coal markets) of the mining region, the quality characteristics, and the significance of coal may restrain or encourage the development of coal mining. This includes (un)availability of transport infrastructure between coal mining companies and railway stations, coal shipping ports, land border crossings; constraints on the capacity of railways, seaports, and coal terminals. The transportation rate to a significant extent depends on the remoteness from the target markets, which affects the volume of coal supplies.

The availability of projects for reconstructing the existing facilities and building new coal mining and processing facilities determines the development of the coal industry in the region. Factors affecting the feasibility of the project depend on the conditions of project implementation (Figure 2) and its focus (Table 3).

Competition with other energy carriers may have a catastrophic impact not only on the decrease in demand for coal and, consequently, on the production volume but also on the social stability in coal-producing regions, especially in company towns, of which there are more than 30 in Russia, including 8 ones with the most problematic social and economic status. Moreover, the reduction in coal mining will have an impact on related industries, primarily on the transport system [39].

Natural factors, not easily lending themselves to forecasting (winter temperatures; water availability of rivers, given the availability of hydropower plants, and others), have the most significant impact in the short term. This impact is most noticeable for local coal supplies when hydropower plants are involved.

Production and consumption relations affect the

Table 3. Factors affecting the implementation of coal production projects as a function of the project objective

Project objective	Factors
Coal export	prices in the international market, competitiveness, processing volumes, coal transportation rates, the throughput capacity of transport facilities, availability of transport and social infrastructure
Coal-fired electric power generation	demand for electricity in domestic and international markets, electricity sales prices
Coal chemical industry	the demand for coal chemical industry products, availability of coal processing technologies acceptable in terms of economic and other indices of coal processing technologies

Source: estimates by the authors

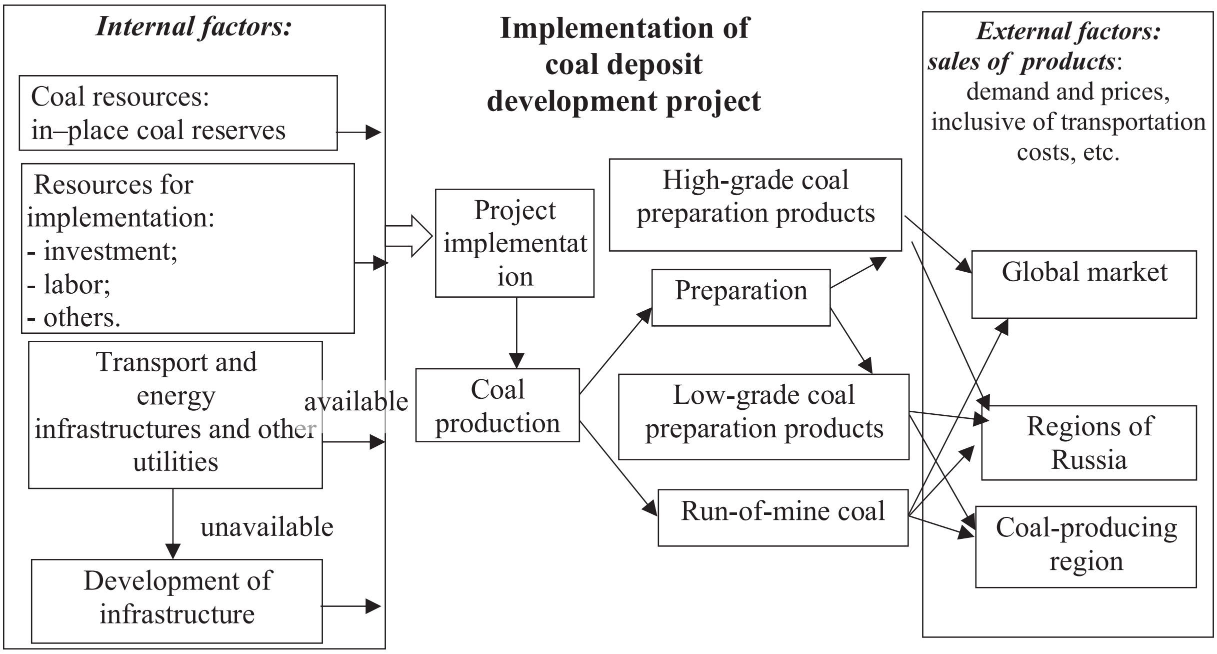

Figure 2 – Implementation conditions for the project of establishing a coal mining enterprise

pattern and volume of coal supply through prices at mine, and coal transportation rates. The impact of railway rates on the development of production and supply of steam coal was assessed for various energy development scenarios and consumption levels, respectively. The studies examined the change in transportation rate by a factor of 1.5 and 2. The findings of the study indicate that the increase in the railway rate encourages the development of local coal mining of not very high quality, whereas the decrease in the railway rate leads to the expansion of the market for quality coals and fosters the development of their mining [29]. Changes in the railway rate may alter the pattern and volume of coal supply, depending not only on the transportation rate but also on the qualitative characteristics of coal. If railroad rates are increased, nationwide coal supplies (e.g. Kuznetsk and Kansk-Achinsk coal) compete with each other:

- high-quality Kuznetsk coal acquires more local significance and the overall demand for it increases as the target market shrinks;
- the demand for Kansk-Achinsk coal decreases.
- Supplies of coal that serves as the fuel for power plants are not affected by changes in coal prices and transportation rates.

(Un)availability of transport infrastructure facilities, the capacity of ports and other facilities, including those intended for coal export, may limit coal supply, and, consequently, the production volumes that depend on demand.

Scientific and technological advances due to the inertia of the coal industry development may have a major impact on all components of the coal market only in the long term. This manifests itself through long lead times for the adoption of new coal mining, processing, consumption, and transportation methods. In the short term, the development of coal mining is influenced only by the projects commenced in previous years. Modification of technologies for production, processing, transportation, and use of coal (key production processes) based on innovations that improve them are linked to medium- and long-term cycles of development of scientific and technological advances [40]. The energy sector industries, if judged by the number of patents held, without decomposing the sector into individual industries including the coal industry and coal-fired power industry, lag behind all other sectors of the economy, accounting for less than 5% of the total number of patents. The ranking is topped by the pharmaceutical industry and food chemistry industry (over 15%). Furthermore, the time it takes to adopt advanced scientific technologies exceeds six years for 50% of patents in the energy sector [41].

V. Functional dependencies

Possible functional dependencies that take the form of equations and constraints are formulated in optimization and simulation economic and mathematical models [21, 22, 24, 27, 29] that were developed for the study of prospects for the development of the coal industry. The models take into account the impact of constraints on the resource base, the established supply chain, demand for the fuel that power plants are designed to run on, coal prices at mine and transportation rates, implementation of projects for construction of new facilities and reconstruction of existing ones.

Production volume in the coal-mining region is limited by the total production capacity of the existing and, in the long run, new companies, in-place coal reserves, and the demand for coal of individual deposits.

Some factors, such as mining and geological conditions and hydrological conditions of coal deposit development, etc. can be taken into account through economic indices. Energy carrier switching and projected amounts of electricity export can be allowed for through coal demand. Consideration of natural factors, such as water availability in rivers, winter temperatures, etc. is beyond the scope of the industry-specific problem but this can be done by the scenario approach to projecting fuel consumption at energy facilities and by other consumers. The effect of most factors on the development of the coal industry in the regions is difficult or even impossible to formalize, which contributes to the leading role of the expert in performing such studies.

VI. Region-specific features of coal-mining federal subjects

Russia's regions differ significantly in terms of resources and quality characteristics of coal, the production structure (underground mining, surface mining, grades), mining and geological, hydrological and economic conditions of coal deposits development, potential opportunities for coal production development, the existing structure of coal consumption and supply, transport and social infrastructure, natural and other factors.

Most coal-producing regions of Russia have significant coal reserves for meeting their demand, for supplies to other regions, and for exports. Only a few regions have a limited resource base. These are the Republic of Buryatia, Primorsky Territory, and the Novosibirsk region. Constraints on transport infrastructure are characteristic of northern regions and regions with low population density, such as the Republic of Tuva, the north of Krasnoyarsk Territory, the Republic of Sakha (Yakutia), and the Amur region, Magadan region, and Chukotka Autonomous Okrug.

The sets of factors influencing the development of production in the regions depend on the significance of coal supplies dominating the region and the period of development prospects under consideration, i.e. short-term and long-term prospects. For any coal-mining region, regardless of the period under consideration, significant factors include the availability of a resource base and absence of constraints on its development; economic indices of coal deposit development, demand for coal, resources required for project implementation (investments, labor resources, etc.); transport and social infrastructure. In the short term, natural factors have a greater or lesser impact on the internal consumption of all types of coal.

For the regions where export and nationwide coal supplies prevail, apart from the above-mentioned factors, the most important ones are the availability of processing capacity and demand for low-grade coal processing volume; coal transportation rates; development of transport infrastructure, including port infrastructure. In the long term, almost all internal and external factors, including production and consumption relations, affect production volume.

For the regions producing coal for local supplies and the supplies to the adjacent regions, the sets of factors remain virtually the same. The most important of them, in addition to the ones mentioned above, are energy carrier switching; commissioning of HPPs and other measures to reduce/increase coal consumption at coal-fired power plants.

In what follows we provide an overview of several coal-producing regions that have significant differences in various parameters.

The Kemerovo region is Russia's largest region in terms of coal production. Over the years, the region's coal production volume ranged from 50% to 60% of the country's total coal production volume. Coal from the Kemerovo region is in demand in both domestic and international coal markets. Export supplies from the Kemerovo region over the years ranged from 75% to 84% of the total export from Russia. The share of Kuznetsk Basin coal in domestic coal supplies amounted to about 40%, and the share of coking coal alone was from 80% to 89% of the total supply of coking coal in the country. There are about 100 coal mining companies operating in the region that produce coal by surface mining and underground mining, along with more than 20 coal preparation plants. Kuzbass mines are among the most challenging ones in the world in terms of the gas hazard, methane content in mine workings, and the coal dust explosion hazard, which results in high on-the-job injury rates and human casualties. Almost all the presented factors (Table 2) influence the development of coal mining in the region. For individual companies, there are constraints on the available resource base. Since the coal reserves of the Kemerovo region account for 45% of Russia's coal, this constraint can be considered negligible. Taking into account the challenging conditions for the development of coal deposits in the Kemerovo region, apart from the other factors, of the utmost importance is the scientific and technological advances. The prospects for the development of the coal industry in the Kemerovo region are related to the creation of coal clusters, the development of the coal chemical industry, and the introduction of innovative coal mining technologies as well as the growing demand for coal exports [21, 42].

In previous years, The Republic of Sakha (Yakutia) had 10 to 13 coal mining companies, including one mine and two coal preparation plants. The Republic produces coals of various significance. According to the criteria of transport accessibility and key target markets, coal mining companies of the Republic of Sakha (Yakutia) can be provisionally divided into two groups: northern and southern. Most of the coal is produced in the southern coal-mining regions that have access to the Russian and international markets. The group of northern companies operates in the domestic market of the republic and their development is limited by infrastructure capabilities. These companies have only seasonal sales of their products: in summer, coal is supplied by inland transport, in winter this is done by motor vehicles via winter roads [32].

The Republic has coal reserves for export, nationwide, and local coal supplies, with few to no constraints on the resource base. The JSC Yakutugol provides the bulk of the total production volume (over 50%) and export supplies. Export supplies coming from the republic tended to grow and, in 2016, amounted to 7.9 million tons out of 13.8 million tons. In 2018, the export of Yakut coal decreased to 6.6 million tons. The change in the international coal market in 2017-2018 and the emergence of new exporters (Khabarovsk Territory) or the increase in export from regions with a more favorable geographical location, in terms of the importing countries (Sakhalin region, Zabaikalsky Territory), had an impact on the overall situation. Yakut coal supplies to the power plants account for 35-45% of domestic supplies.

Production volume in the republic depends on the demand for local coal supplies, coal for supplies to regions of Russia, including by-product coal plants, and export coal supplies, as well as the availability of processing facilities, demand for low-grade processed products, transport tariffs and transport infrastructure development.

In Krasnoyarsk Territory, 11 coal mines were involved in coal production in 2018. Three of them (71% of total production) are owned by OJSC "SUEK". Only about 60 percent of the production capacity is utilized due to the low demand for Kansk-Achinsk basin coal. There are no constraints on the resource base. The region provides about 75% of all domestic Russian supplies that are used for energy needs. Coal is supplied mainly by railway. The prospects for coal production development may depend on the increase in domestic demand by energy facilities, including those for electricity export, development of the coal chemical industry, and the demand for Kansk-Achinsk basin coal in regions of Russia. The environmental aspects of Kansk-Achinsk basin coal production and consumption are a limiting factor.

In the Irkutsk region, three coal mining companies and one coal preparation plant operated in 2018. OJSC "SUEK" provides the great bulk of production (99%). Coal is produced by surface mining techniques. There are no significant constraints on the resource base in the region. Irkutsk region coal is mostly consumed locally. Coal supplies from the Irkutsk region to neighboring regions and for export do not significantly affect the demand for coal. Coal is supplied by rail. More than 98% of coal is consumed by power plants and boiler houses. Production volume depends mainly on coal consumption by local energy facilities, fuel switching prospects, hydropower plants capacity, and, in the short term, climatic factors. Thus, coal production in the Irkutsk region in 2013 was 13.3 m tons, while totaling 13.3 m tons in 2014. These data indicate that coal production decreased by more than 20%, mainly due to a warm winter. Low quality of coal (high sulfur content, etc.) can be a limiting factor in the development of individual deposits. The main opportunities for the development of coal mining in the Irkutsk region are likely to be related to the construction of power plants for electricity exports.

The Republic of Tuva has coal reserves for export and local supplies with no constraints on the resource base. All coal mined at the two surface coal mines, with an annual production capacity of 750 thousand tons, had been consumed within the republic until 2016. Since 2017, coal produced in Tuva has been exported in small amounts (80-160 thousand tons). The main constraint on coal production is the lack of transport infrastructure, whereas the demand for export serves as the main driver.

In 2018, five coal mines and one coal preparation plant operated in Zabaikalsky Territory. The great bulk of the production volume (84%) is provided by OJSC "SUEK". The region has coal reserves for export and local supplies with no constraints on the resource base. More than 50% of the production volume is processed at the coal preparation plant, with most of the produced coal concentrate being exported. Run-of-mine coal is also exported. Export quality coal is produced at two deposits: Tugnuyskoye deposit and Apsatskoye deposit. The coal of export quality is mainly the coal from the Tugnuyskoe deposit. Challenges facing the development of the Apsatskoye deposit are related to the geological features of the rock structure and the hard-to-reach location of the deposit. In 2018, production at the deposit totaled only 7% of the planned production capacity. The key opportunities for the development of coal mining in the Zabaikalsky Territory may be related to the construction of power plants, mainly for electricity export and further development of coal export.

In the Amur region, two surface coal mines produce 99% of the production volume. For internal consumption, coal produced in the region (90% of the consumption) and imported coal are used. The region's significant coal reserves are more suitable for the coal chemical industry and the construction of energy facilities at the edge of surface coal mines. This is due to the mining, geological, and hydrological conditions of deposit development and quality characteristics of coal.

In the Chukotka Autonomous Okrug, until 2014, two companies had mined coal to satisfy the demand within the Okrug, while in 2015-2016, there was only one company active, the Ugolnaya mine. Coal mined in the Chukotka Autonomous Okrug was used for local consumption. The pattern of fuel delivery to the districts of the Okrug is quite complicated, which leads to a significant variation in price indices. In 2017, one more company, Beringpromugol LLC, started operating there to produce coal for export. The owner of this company is the Australian company

Tigers Realm Coal Limited. Chukotka coal export began in 2018. The main target markets are the countries of the Asia-Pacific Region.

In the Sakhalin region, there is one major surface mine, the Solntsevsky (Sakhalinugol 2) surface coal mine, along with small companies. Over the years, the number of such companies varied (from 12 to 18) with the production capacity ranging from 50 thousand tons per year to 1 million tons per year. Coal production at the Solntsevsky surface mine in 2018 amounted to 7.5 million tons, while other companies produced from 10 thousand tons to 1.3 million tons. Coal reserves available to small companies are low. The Sakhalin region stands out from other coal-producing regions by dynamic changes in the list of small companies and their frequent rebranding. The existing coal mining companies fully meet the internal demand for fuel of the Sakhalin region, with the excess coal exported to Japan, South Korea, and China. In 2018, 9.9 million tons of coal out of 10.8 million tons mined in the region were exported. The geographical location of the Sakhalin region, its proximity to major coal importers (Japan, South Korea, and China) are instrumental in developing coal exports. As for the domestic coal market, the presence of a large number of suppliers, coal grades, and modes of transportation (rail, sea, road, water-rail, road-rail) creates great difficulties in addressing the issues of fuel volume to be supplied.

The coal deposits in the Sakhalin region are of high quality and diverse properties, which means that they can be used in a variety of ways - for export, as both an energy-producing fuel and as feedstock for the coal chemical industry. The most important factors for the development of coal production in the Sakhalin region are the development of transport infrastructure, scientific and technological advances, economic indices, and mining and geological conditions for coal deposit development.

VII. Conclusion

The studies carried out for the coal mining eastern Federal Subjects show that the regional features are smoothed over when considering Russia as a whole or its federal districts. Thus, in Russia as a whole, it can be assumed that all coal is supplied by rail and the cost of inter-regional supplies can be calculated using railway rates for coal transportation. When projecting the development of the coal industry in some regions, this assumption does not hold, since coal is supplied there by various modes of transport. Coal-producing regions are located in various climatic zones. The development of promising coal deposits in the northern regions is complicated by the presence of permafrost, lack of transport and social infrastructure, and depends on the availability of resources for the development of deposits (investments, labor resources, etc.).

The main factors determining the development of coal mining are the demand for coal and the possibility and economic feasibility of implementing coal mining development projects. These, in turn, depend on a combination of other factors that differ from region to region.

Structural complexity, the large scale, heterogeneity, and inertia of the coal industry development, availability of different areas of coal use determine the lack of unambiguous dependence of the opportunities of coal industry development in the regions of Russia on individual factors. Quantitative assessment is not possible for all of the factors due to the lack of explicit functional dependencies, the incompleteness of available information, and uncertainty of conditions for the development of the regions of Russia and the global coal market. Most of the factors may affect the development of the Russian coal industry as a whole, and coal-producing regions as well only in the long run, due to the inertia inherent in the industry development.

Each of Russia's coal-producing regions is unique in its way, and the conditions that determine the opportunities for the development of coal mining in the region are also unique. Forecasting the development of the coal industry in the regions calls for a case-by-case approach, and, when it involves modeling, the development of models for each coal-producing region is required.

References

[1] Mohr S., Höök M., Mudd G, Evans G. Projection of long-term paths for Australian coal production – comparisons of four models, International Journal of Coal Geology. 2011. Vol. 86. Part 4. P. 329–341. DOI: 10.1016/j.coal.2011.03.006 [Online]. Available: https://www.researchgate.net/publication/286295507_Projection_of_Australian_coal_production_-_Comparisons_of_four_models

[2] Trends and Issues for Future Coal Use [Online]. Available: https://www.nap.edu/read/4918/chapter/7#55

[3] Coal – Energy for Sustainable Development/ World Coal Association// [Online]. Available: https://www.worldcoal.org/file_validate.php?file=coal_-_energy_for_sustainable_development_final(16_04_2012).pdf

[4] Izabela Jonek-Kowalska Method for Assessing the Development of Underground Hard Coal Mines on a Regional Basis: The Concept of Measurement and Research Results//Energies 2018, 11, 1370 http://dx.doi.org/10.3390/en11061370

[5] Bija ´ nska, J.; Wodarski, K. Risk management in the planning of development projects in the industrial enterprises. Metalurgija 2014, 53, 276–278.

[6] Betz, Mike and Farren, Michael and Lobao, Linda and Partridge, Mark D. Coal Mining, Economic Development, and the Natural Resource Curse [Online]. Available: https://mpra.ub.uni-muenchen.de/58016/ MPRA Paper No. 58016, posted 22 Aug

2014 18:35 UTC

[7] Yoshimitsu MIMUROTO, Koichi KOIZUMI Coal Supply and Demand Trends and Challenges Facing a Stable Coal Supply in Japan - Coal Use Considering Global Warming Prevention and the Prospects of Coal Use //- The 388th Forum on Research Works June 30, 2004

[8] Adriana Popa, Ajith Das Menon, Bartłomiej Walentyński John Rudoph Young, Hing Yee Ching, Lia Cairone, Miguel Brito, Wilson Ying Kit Yung, The Challenges of the U.S. Coal Industry and Lessons for Europe //Columbia SIPA /United Nations Economic Commission for Europe, May 2016. - 72p. [Online]. Available: https://www.unece.org/fileadmin/DAM/energy/se/pdfs/cmm/pub/Challengs_US.Coal.Ind_LessonsEurope.pdf

[9] D. Creedy, W. Lijie, Z. Xinquan, L. Haibin, G. Campbell China's coal industry transformation: performance, challenges, and prospects [Online]. Available: https://www.researchgate.net/publication/300904555_China's_coal_industry_transformation_performance_challenges_and_prospects

[10] Coal Market Module of the National Energy Modeling System: Model Documentation 2018/ U.S. Energy Information Administration June 2018. 41 p. [Online]. Available: https://https://www.eia.gov/outlooks/aeo/nems/documentation/coal/pdf/m060(2018).pdf

[11] S. Mohr, M. Höök, G. Mudd, G. Evans. Projection of Australian coal production - Comparisons of four models/ Paper presented at International Pittsburgh Coal Conference 2011/ [Online]. Available: https://www.researchgate.net/publication/286295507_Projection_of_Australian_coal_production_-_Comparisons_of_four_models

[12] Suwala W. Modelling Adaptation of the Coal Industry to Sustainability Conditions, Energy. 2008. Vol. 33. Issue 7.P. 1015–1026.

[13] MD Budeba, JW Joubert, RCW Webber-Youngman A proposed approach for modeling competitiveness of new surface coal mines, November 2015 Journal of the Southern African Institute of Mining and Metallurgy 115(11):1057-1064, DOI: 10.17159/2411-9717/2015/v115n11a10

[14] Bogucki, R., Lasek, J., Milczek, J.K., Tadeusiak, M.: Early warning system for seismic events in coal mines using machine learning. In: IEEE Federated Conference on Computer Science and Information Systems (FedCSIS), pp. 213–220 (2016) [Online]. Available: https://arxiv.org/pdf/1609.06957.pdf

[15] Syed Aziz Ur Rehman, Yanpeng Cai, Rizwan Fazal, Gordhan Das Walasai and Nayyar Hussain Mirjat. An Integrated Modeling Approach for Forecasting Long-Term Energy Demand in Pakistan. November 2017. 23 p. [Online]. Available: https://www.researchgate.net/publication/321089708_An_Integrated_Modeling_Approach_for_Forecasting_Long-Term_Energy_Demand_in_Pakistan

[16] Energy forecasting and modeling [Online]. Available: https://www.enerdata.net/brochure/energy-forecast-models-consulting-brochure-enerdata.pdf

[17] Strager MP, Strager JM, Evans JS, Dunscomb JK, Kreps BJ, Maxwell AE (2015) Combining a Spatial Model and Demand Forecasts to Map Future Surface Coal Mining in Appalachia. PLoSONE 10(6): e0128813. DOI:10.1371/journal. 26 p. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4474888/pdf/pone.0128813.pdf

[18] Yanbin Li and Zhen Li. Forecasting of Coal Demand in China Based on Support Vector Machine Optimized by the Improved Gravitational Search Algorithm. Energies 2019, 12(12), 2249; https://doi.org/10.3390/en12122249 [Online]. Available: https://www.mdpi.com/1996-1073/12/12/2249/htm

[19] Assumptions to the Annual Energy Outlook 2015, U.S. Energy Information Administration. September 2015. 224 p. URL: https://www.eia.gov/outlooks/aeo/assumptions/pdf/0554(2015).pdf (19.06.2018).

[20] Tsvetkov N.I. Using the mathematical modeling method at the complex design of a coalfield. - Ugol' (Coal), 1967, No. 2, pp. 10-15, (in Russian.)

[21] Plakitkina L.S. Simulation models to predict the coal industry., Izvestiya RAN (Proceedings of the Russian Academy of Sciences). Power engineering, No. 3, 2010. - pp. 162-175, (in Russian.)

[22] Nikita Pavlov and Nikolai Petrov Coal industry of the Republic of Sakha (Yakutia): tools and forecast 03002 Published online: 25 January 2019 DOI: https://doi.org/10.1051/e3sconf/20197703002

[23] Liudmila Takaishvili Simulation models to study the development of the coal industry as energy sector component Research paper E3S Web of Conferences 77, research paper 02004 (2019) Published online: 25 January 2019 DOI: https://doi.org/10.1051/e3sconf/20197702004

[24] Agafonov G.V., Sokolov A.D, Takaishvili L.N. Modeling of coal industry development/ Proceedings of RAS. Power engineering journal. No.6, pp. 159-165. 2011, (in Russian.)

[25] Tarzanov I.G. Results of the Russian coal industry in 2017, Ugol'. 2018. No. 3. P. 58-73. (in Russian)

[26] Tsvetkov N.I. Application of the method of mathematical modeling to the integrated design of a coal basin, Ugol'. 1967. No. 2. P. 10–15. (in Russian)

[27] Methods and models of the regional energy programs development, Saneev B.G., Sokolov A.D., Agafonov G.V., et al. - Novosibirsk, Nauka, 2003. p.140, (in Russian)

[28] Amosenok E.P., Babenko T.I., Lugacheva L.I., Markova V.M., Sokolov A.V., Churashev V.N. [et al.]. Systemic modeling and analysis of meso- and microeconomic entities: Research monograph, Ed. by V.V. Kuleshov, N.I. Suslov. Novosibirsk: The publishing house of the Institute of Economics and Industrial Engineering SB RAS, 2014. 488 p. (in Russian)

[29] Sokolov A.D., Takaishvili L.N. Effect of railway tariffs on the steam coal market. The energy sector of Russia: its current state and a future outlook. Novosibirsk: Siberian publishing company of the RAS "Nauka", pp. 130-136, 1999, (in Russian.)

[30] Liudmila Takaishvili and Aleksander Sokolov Coal industry of East Siberia - prospects for development E3S Web of Conferences 77, research paper No. 03001 (2019) Published online: 25 January 2019 DOI: https://doi.org/10.1051/e3sconf/20197703001

[31] Sokolov A.D., Takaishvili L.N., Muzychuk S.Yu. Coal in the fuel and energy balance of the Irkutsk region, Vestnik Irkutskogo gosudarstvennogo tekhnicheskogo universiteta. 2017. Vol.21. No. 12 P. -185-194. http://dx.doi.org/10.21285/1814-3520-2017-12-185-194 (in Russian)

[32] Sokolov A.D., Takaishvili L.N., Petrov N.A., Pavlov N.V. Coal industry of the Republic of Sakha (Yakutia): its current state and development prospects, Vestnik IrGTU. 2010. No. 4 (44). P. 64–69. (in Russian)

[33] Sokolov A.D., Takaishvili L.N. Baikal Region Coal Industry: Current State and Development Prospects// Vestnik of Irkutsk State Technical University. 2012. № 12 (71). pp. 113–118. (in Russian)

[34] Sokolov A.D., Takaishvili L.N. Promising development trends of the coal industry in the eastern regions of Russia as a part of the fuel and energy sectorю Proceedings of Irkutsk State Technical University. 2016, vol. 20, no. 11, pp. 157–169. (In Russian) DOI: 10.21285/1814-3520-2016-11-157-169

[35] Sokolov, A.D.; Takaishvili, L.N. Tools for the research of the coal industry development prospects in the energy sector, Collected papers Energy: Management, quality, and efficiency of energy resources use, Proceedings of the VII All-Russian conference with international participation Publishing house of Amur State University, 2013. P. 375-382, (in Russian.)

[36] Sokolov A.D., Takaishvili L.N. Implementation of the information support for projections of the coal industry development in regions of Russia, Modern technologies. *System analysis*. Modeling, Issue No.1(41) p. 126-133, 2014, (in Russian.)

[37] Melentiev L.A. System studies of the energy industry. Moscow: *Nauka*, 1983. p. 455 (in Russian.)

[38] Takaishvili L.N. Consideration of system features of the coal industry as a part of the fuel and energy sector when its development modeling. Proceedings of Irkutsk State Technical University. 2017, vol. 21, no. 10, pp. 138–149. (In Russian) DOI: 10.21285/1814-3520-2017-10-138-149

[39] Analytical report "Risks of the Paris Climate Agreement implementation for the economy and national security of Russia". The Institute of Natural Monopolies Research Moscow. 2016 – 114 p. Electronic publication: https://docplayer.ru/26197083-Analiticheskiy-doklad-riski-realizacii-parizhskogo-klimaticheskogo-soglasheniya-dlya-ekonomiki-i-nacionalnoy-bezopasnosti-rossii.html (in Russian)

[40] Kondratiev N.D. Problems of economic dynamics. - Moscow: Ekonomika, p. 450, 1989, (in Russian.)

[41] Research and Development Effectiveness/Science and Education Statistics. Issue 2. Information and statistical data - Moscow: Federal state budgetary scientific institution "Federal Research Centre for Projects Evaluation and Consulting Services" research institute, p. 133, Group of authors: Berezina E.V., Lebedev K.V., Pluzhnova N.A., Prokhorova L.V., Fedin A.V., 2017, (in Russian.)

[42] Program for development of the innovative territorial cluster "Integrated coal and man-made waste processing" in the Kemerovo region. Executive summary, p. 46, (in Russian.)

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Modeling Of Facts Devices And Their Application In Intersystem Tie Lines Of The United Power System Of Central Asia

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***Abstract* — The paper analyzes the issues related to the application of flexible alternating current transmission systems (FACTS) for effective control of power flows in the electrical networks of the United Power System of Central Asia.**

***Index Terms* — power system, modeling, regulation, mode control, flexible power transmission.**

I. Introduction

The United Power System of Central Asia (UPS CA) transmits electricity to consumers in the Republic of Kyrgyzstan, the Republic of Uzbekistan, four regions of southern Kazakhstan and the "dead-end" regions of Northern Tajikistan.

In January 2019, the installed capacity of the power plants in the UPS CA was 21.7 GW, electricity output – 89.3 b kWh. The length of 220-500 kV transmission lines was 21006.6 km, including 6054 km of 500 kV overhead lines.

An analysis of the UPS operation has revealed some "weaknesses", for example, limited capabilities of parallel operation of power systems in the region due to insufficient transfer capabilities of transmission lines between neighboring power sub-systems, and problems with the voltage regulation at nodes.

II. Effective control of UPS CA

The region of Central Asia purposefully strengthens the main electric networks and increases the generating capacity to meet the growing demand.

At the same time, the power flows in the UPS do not always allow providing the levels of voltage and flows in cutsets in accordance with the standards. The technical level of emergency control is insufficient. This circumstance reduces the quality of power supply and reliability of the power system, creates prerequisites for serious disturbances of power system operation with severe consequences for the power supply to consumers.

In 2018, the voltage on the busbars of the Tashkent and Syrdaria thermal power plants dropped to 485 kV, under specified 515 kV and 525 kV, respectively.

At the Frunzenskaya substation, the voltage went down below specified 510 kV, to 478 kV, increased voltage levels were noted at the YuKGRES substation (up to 542 kV) and Almaty substation (up to 535 kV) due to insufficient operational control of net power flow through the UPS networks. There are problems with voltage regulation at 500 kV North-South transit substations. The sharply variable nature of the flows through this transit is the cause of frequent manual switchings of reactors and the operation of emergency control to switch off (on) the reactors. In some of the UPS operating conditions power flows in individual cutsets exceeded the permissible values by up to 30%.

III. Options for the control of operating conditions

Successfully developing theory and practice of applying the technology of flexible controlled AC power transmission systems, i.e. FACTS devices, make it possible to carry out the studies and develop recommendations for the adoption of this technology in the UPS of Central Asia.

One of the key elements of FACTS is a reactive power source (RPS) capable of both generating and consuming reactive power depending on the required operating parameters and specified characteristics of the power system.

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The main objectives of the FACTS technology application are [1, 5, 6, 7] to increase the transfer capability of power lines to the thermal limit; maintain a set voltage, optimize power flows in a complex heterogeneous network; and increase the static and dynamic stability of the United Power System (UPS).

The use of FACTS technology allows obtaining various corrective actions depending on the conditions of a specific control problem, reducing the gap between controlled and uncontrolled operating conditions of the UPS, by providing the dispatching personnel with additional degrees of freedom to control power flows and voltage in the network areas with power surplus and shortage.

The FACTS devices are divided into several types depending on their specific purpose. For example, SVC, STATCOM, and TCSC types are used to meet voltage constraints; TC SC, SC, and UPFC types are used to satisfy thermal limits; TCSC and SSSC are used to improve stability. Among the above types of devices, TCSC (Thyristor Controlled Series Capacitor) can be used for control in all three of these cases.

Let us consider two models of power flow calculation in three-phase networks with TCSC device with the view to increasing the efficiency of control of the operating parameters in the UPS of Central Asia.

a) A model of power flow for variable impedance control

A mathematical model of TCSC based on three-phase susceptance is obtained by combining separate single-phase TCSC modules. To control the active power flow passing through three TCSC channels, the value of the desired susceptance of BTCSC is determined using the Newton-Raphson method [4].

The TCSC admittance can be determined based on the equivalent circuit shown in Fig. 1. Assuming that index "ph" successively takes the values a, b, c, we obtain

$$\begin{pmatrix} \underline{\mathbf{I}}_1^{\mathrm{ph}} \\ \underline{\mathbf{I}}_2^{\mathrm{ph}} \end{pmatrix} = \begin{pmatrix} j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} & \underline{\mathbf{B}}_{12}^{\mathrm{ph}} \\ \underline{\mathbf{B}}_{21}^{\mathrm{ph}} & \underline{\mathbf{B}}_{22}^{\mathrm{ph}} \end{pmatrix} \begin{pmatrix} \underline{\mathbf{U}}_1^{\mathrm{ph}} \\ \underline{\mathbf{U}}_2^{\mathrm{ph}} \end{pmatrix} \quad (1)$$

Since all three TCSC modules are not related in terms of electromagnetic interaction, the matrix elements from (1)

$$\begin{pmatrix} j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} & \underline{\mathbf{B}}_{12}^{\mathrm{ph}} \\ \underline{\mathbf{B}}_{21}^{\mathrm{ph}} & \underline{\mathbf{B}}_{22}^{\mathrm{ph}} \end{pmatrix}$$

can be determined as follows:

$$\underline{\mathbf{B}}_{11}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{11}^{\mathrm{ph}} = -\frac{1}{\mathrm{X}^{\mathrm{ph}}}; \quad (2)$$

$$\underline{\mathbf{B}}_{12}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{21}^{\mathrm{ph}} = j\underline{\mathbf{B}}_{TCSC}^{\mathrm{ph}} = -\frac{1}{\mathrm{X}^{\mathrm{ph}}}, \quad (3)$$

where X^{ph} is the equivalent reactance for the fundamental frequency of the network.

In this case, the governing equation for the three-phase network is a system of three matrix equations (1), i.e.

$$\begin{pmatrix} \underline{I_1^a} \\ \underline{I_2^a} \\ \underline{I_1^b} \\ \underline{I_2^b} \\ \underline{I_1^c} \\ \underline{I_2^c} \end{pmatrix} = \begin{pmatrix} -j\frac{1}{X^a} & j\frac{1}{X^a} & 0 & 0 & 0 & 0 \\ j\frac{1}{X^a} & -j\frac{1}{X^a} & 0 & 0 & 0 & 0 \\ 0 & 0 & -j\frac{1}{X^a} & j\frac{1}{X^a} & 0 & 0 \\ 0 & 0 & j\frac{1}{X^a} & -j\frac{1}{X^a} & 0 & 0 \\ 0 & 0 & 0 & 0 & -j\frac{1}{X^a} & j\frac{1}{X^a} \\ 0 & 0 & 0 & 0 & j\frac{1}{X^a} & -j\frac{1}{X^a} \end{pmatrix} \begin{pmatrix} \underline{U_1^a} \\ \underline{U_2^a} \\ \underline{U_1^b} \\ \underline{U_2^b} \\ \underline{U_1^c} \\ \underline{U_2^c} \end{pmatrix}$$

The values of the three-phase power applied to bus 1 are defined by the following equations:

$$P_1^{\mathrm{ph}} = U_1^{\mathrm{ph}} U_2^{\mathrm{ph}} B_{12}^{\mathrm{ph}k} \sin(\delta_1^{\mathrm{ph}} - \delta_2^{\mathrm{ph}}); \quad (4)$$

$$Q_1^{\mathrm{ph}} = -(U_1^{\mathrm{ph}})^2 B_{11}^{\mathrm{ph}k} - U_1^{\mathrm{ph}} U_2^{\mathrm{ph}} B_{12}^{\mathrm{ph}k} \cos(\delta_1^{\mathrm{ph}} - \delta_2^{\mathrm{ph}}). \quad (5)$$

The equations of power at bus 2 are obtained by dual substitution of subscript 1 in equations (4), (5) by subscript 2.

Partial derivatives of power equations with respect to

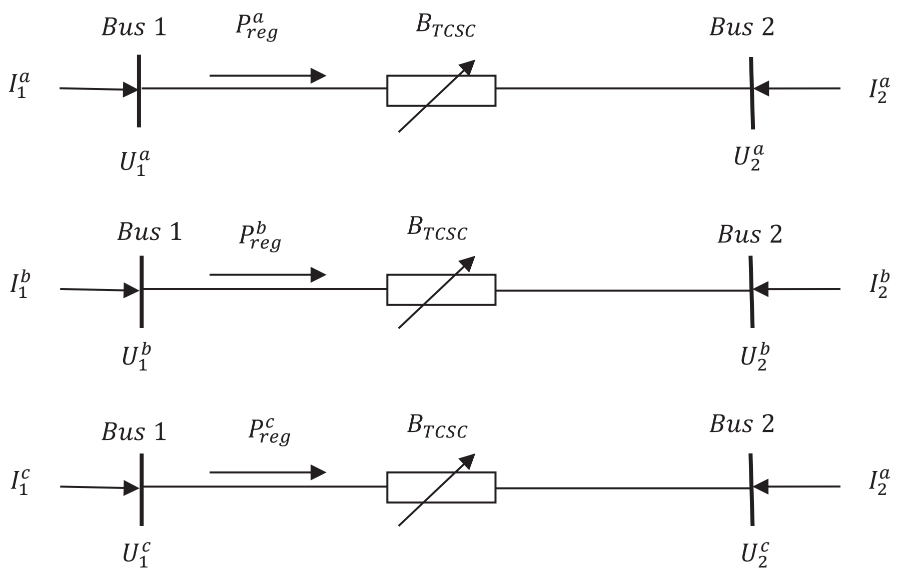

Figure 1. A TCSC equivalent circuit in a three-phase network (with a susceptance model.)

X^{ph} have the form

$$\frac{\partial P_1^{ph}}{\partial X^{ph}} X^{ph} = -P_1^{ph}, \quad \frac{\partial Q_1^{ph}}{\partial X^{ph}} X^{ph} = -Q_1^{ph}.$$

Then the process of TCSC-based control of active power flow from bus 1 to bus 2 will be described by the following iterated linearized equations:

$$\begin{pmatrix} \frac{\Delta P_1^{ph}}{\Delta P_2^{ph}} \\ \frac{\Delta Q_1^{ph}}{\Delta Q_2^{ph}} \\ \Delta P_{12}^{ph} \end{pmatrix}^{(i)} = \begin{pmatrix} \frac{\partial P_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_1^{ph}}{\partial \delta_2^{\phi}} & \frac{\partial P_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_1^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial P_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_2^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial Q_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_1^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial Q_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_2^{ph}}{\partial X^{ph}} X^{ph} \\ \frac{\partial P_{12}^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_{12}^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_{12}^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_{12}^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_{12}^{ph}}{\partial X^{ph}} X^{ph} \end{pmatrix}^{(i)} \begin{pmatrix} \frac{\Delta \delta_1^{ph}}{\delta_2^{ph}} \\ \frac{\Delta U_1^{ph}}{U_2^{ph}} \\ \frac{\Delta U_2^{ph}}{U_2^{ph}} \\ \frac{\Delta X^{ph}}{X^{ph}} \end{pmatrix}^{(i)} \quad (6)$$

Where $\Delta P_{12}^{ph.X}$ is the imbalance of active power flow calculated as $\Delta P_{12}^{ph.X} = P_{12}^{ph.Xreg} - \Delta P_{12}^{ph.X}$, ΔX^{ph} is a continuous increment of reactance of the series connected TCSC.

b) A model of power flow when controlling the advance angle

An alternative to equation (6) is the equation obtained using a three-phase model with thyristor advance angles considered as elements of the system state. Figure 2 shows the corresponding equivalent circuit of TCSC.

The reactance of TCSC at the main frequency of the network, as a function of the thyristor advance angle, can be represented by the following equation [2, 3]

$$X_{TCSC}^{ph} = -X_C^{ph} + C_1^{ph}\,(2(\pi - \beta^{ph}) + \sin(2\pi - \beta^{ph}))) -$$
$$-C_2^{ph} \cos(\pi - \beta^{ph})(\varpi\, \mathrm{tg}\varpi(\pi - \beta^{ph})) - \mathrm{tg}(\pi - \beta^{ph})),$$

where $C_1^{ph} = \frac{X_c^{ph} + X_{LC}^{ph}}{\pi}$; $C_2^{ph} = \frac{4 X_{LC}^{ph\,2}}{\pi X_l^{ph}}$; $X_{LC} = \frac{X_c X_L}{X_c - X_L}$.

The admittance matrices in each of the considered TCSC models coincide (equations (1-3)). The equations of power (4), (5) also coincide. Therefore, in equation (6) for the case of advance angles control, one should make only the corresponding changes in the matrix elements:

$$\begin{pmatrix} \frac{\Delta P_1^{ph}}{\Delta P_2^{ph}} \\ \frac{\Delta Q_1^{ph}}{\Delta Q_2^{ph}} \\ \Delta P_{12}^{phx} \end{pmatrix}^{(i)} = \begin{pmatrix} \frac{\partial P_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_1^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_1^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial P_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_2^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_2^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial Q_1^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_1^{ph}}{\partial \delta_2^{ph}} & \frac{\partial Q_1^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_1^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_1^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial Q_2^{ph}}{\partial \delta_1^{ph}} & \frac{\partial Q_2^{ph}}{\partial \delta_2^{ph}} & \frac{\partial Q_2^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial Q_2^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial Q_2^{ph}}{\partial \beta^{ph}} \beta^{ph} \\ \frac{\partial P_{12}^{ph}}{\partial \delta_1^{ph}} & \frac{\partial P_{12}^{ph}}{\partial \delta_2^{ph}} & \frac{\partial P_{12}^{ph}}{\partial U_1^{ph}} U_1^{ph} & \frac{\partial P_{12}^{ph}}{\partial U_2^{ph}} U_2^{ph} & \frac{\partial P_{12}^{ph}}{\partial \beta^{ph}} \beta^{ph} \end{pmatrix}^{(i)} \begin{pmatrix} \frac{\Delta \delta_1^{ph}}{\delta_2^{ph}} \\ \frac{\Delta U_1^{ph}}{U_1^{ph}} \\ \frac{\Delta U_2^{ph}}{U_2^{ph}} \\ \frac{\Delta \beta^{ph}}{\beta^{ph}} \end{pmatrix}^{(i)}$$

IV. Conclusion

The application of FACTS technology in power systems will open up new opportunities to control power flows in transmission lines by providing transfer capabilities of lines up to the limit of thermal resistance of the wires; to maintain voltage at nodes within standard limits; and increase the static and dynamic stability margins in the system.

The presented two models for calculation of power flow in a three-phase network help effectively control the operating parameters of the power system by providing an almost inertia-free generation of control actions to the executive elements of FACTS devices.

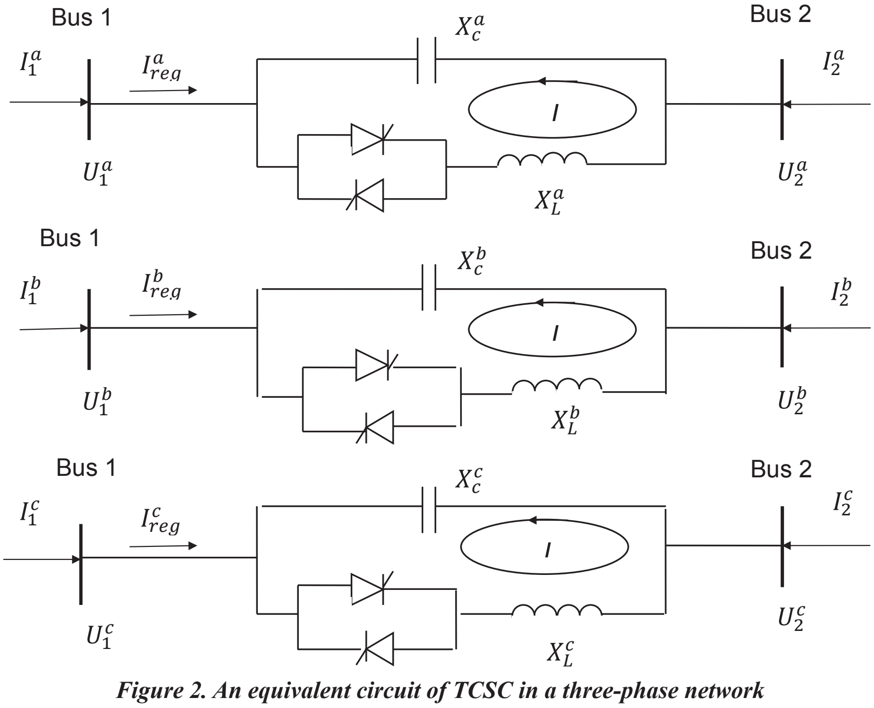

Figure 2. An equivalent circuit of TCSC in a three-phase network (with an advance angle model).

References

[1] Misrikhanov M. SH., Ryabchenko V. N., Khamidov SH. V. Calculation of power flows in electric networks with devices FACTS: Ivanovo State power engineering University. Ivanovo, p.208, 2018, (in Russian.)

[2] Acha E. A. FACTS: Modeling and Simulation in Power Networks, E. A. Acha, a.o. – *John Wiley & Sons*, 2004.

[3] Fuerte-Esquivel C. R. A Thyristor Controlled Series Compensator Model for the Power Flow Solution of Practical Power Networks, C. R. Fuerte-Esquivel, E. A. Acha, H. Ambriz-PE'rez, IEEE Trans. Power Systems, No. 15(1), pp. 58-64, 2000.

[4] Anderson P. Grid Management and stability, P. Anderson, A. Fouad. - Moscow: Energia, 1980, (in Russian.)

[5] Huang, Z. Y. Application of unified power flow controller in interconnected power systems-modeling, interface, control strategy, and case study, Z. Y. Huang [and others], *IEEE Press*, 2000, No. 2-Z. Pgs.: 817-824.

[6] Song, Y. H. Flexible AC Transmission Systems (FACTS), Y. H. Song, A. T. Johns. – London: *IEEE Press*, 1999.

[7] Hingorani N. G. Flexible AC Transmission Systems (FACTS), Overview, Hingorani N. G., Paper presented at the Panel Session of FACTS. IEEE PES 1990 Winter Meeting. Atlanta, 1990.

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Numerical Study Of Operating Parameters Of A Single-Stage Air-Steam Blown Gasification Process Of Pulverized Coal

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***Abstract* — Gasification of solid fuels is a way to improve technical and environmental efficiency of solid fuels in the energy sector. Typically, gasifiers for large power stations operate as entrained flow reactors: pulverized coal particles are carried by gasification agent and undergo conversion stages. The study examines a single-stage process of steam-air coal gasification considering preliminary high-temperature air heating. To this end, a mathematical model is used, which includes the equations of one-dimensional transport and chemical transformations of fuel and gas mixture. The calculations show the main characteristics of the gasification process and their dependence on control parameters: air heating temperature, stoichiometric ratio and steam consumption.**

***Index Terms* — coal, gasification, high-temperature air, numerical modelling.**

I. Introduction

Improvement in the technical and environmental efficiency of solid fuel in the energy sector is an important scientific and technical issue [1]. One of the ways to solve it may be a transition from a steam cycle to a more efficient integrated gasification combined cycle (IGCC) [2]. The capacity of IGCC plants in the world is constantly growing, mainly in chemical and petrochemical industries and, to a lesser extent, in coal-fired power generation [3, 4]. This is due to a number of problems, such as insufficient reliability and high capital costs.

Most of integrated coal gasification combined cycle plants use entrained-flow gasifiers in which coal dust (or coal slurry) is gasified in pressurized gaseous medium [5–7]. Oxygen-steam mixture is usually used as a gasification agent, however, there are also reactors that use air-steam mixture. Air is less commonly used in IGCC because low oxygen concentration and low flame temperature make it difficult to achieve full conversion of fuel at low stoichiometric ratios.

The latter problem can be solved by heating the gasification agent to high temperatures, similar to the processes of HiTAC and MILD combustion [8–12]. In this case, the losses associated with heating the system to the ignition temperature are reduced, and the energy costs of the endothermic reaction of the formation of combustible gases are partially compensated. On the one hand, it is possible to reduce the auxiliary power supply due to the rejection of air separation; on the other hand, the load on the compressors increases significantly and, most importantly, the thermodynamic and kinetic parameters change (due to the need to heat inert nitrogen and the decrease in the reactant gases concentration in the reaction zone of the gasifier).

High-temperature heating can be carried out using plasma sources [13] or burning additional fuel (natural gas, coal) [14, 15]. Issues of the implementation of high-temperature heaters are discussed in [16–18]. High-temperature gasification agent can also be used to gasify coal in oxyfuel conditions for efficient sequestration of CO2 [19–21]. The kinetics of high-temperature conversion of coal and semicoke was studied in [22, 23]. Methods for high-temperature air gasification of biomass and waste are proposed in [24–26]. Mathematical models for high-temperature fixed-bed and entrained-flow gasifiers were proposed in [27–34]. Conversion of coal particles and coal-water droplets in a stream of heated gases was studied in [35–39]. Efficiency of high-temperature coal-fueled power plants was estimated at [40–42].

In previous studies [31, 32], air heating effect was studied for a two-stage gasifier. However, at a sufficiently high air temperature, a one-stage process could be used.

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In this paper, using numerical simulation, we investigate coal gasification in a one-stage entrained flow reactor with heated steam-air media. Stationary operation of the gasifier under different conditions are considered, and optimal parameters in the selected parameter range are evaluated.

II. Mathematical model of coal gasification process

The model is based on the heat balance of coal particles and the gas film around them. The following assumptions are made about the course of the gasification process [43, 44]:

1. the drying rate is limited by external mass transfer of particle with gaseous medium;
2. the pyrolysis rate is proportional to the content of volatiles in the particle and depends on temperature according to the Arrhenius law;
3. the gasification rate is determined from the well-known equation of the diffusion-kinetic theory of carbon combustion.

The heat balance equation for a coal particle is written as follows:

$$c_p \frac{d\left(m_p T_p\right)}{d\tau} = \varepsilon\sigma S\left(T_w^4 - T_p^4\right) + \alpha_T S\left(T_g - T_p\right) - Q_w + Q_r.$$

Here c_p is the specific heat of the fuel, J kg^{-1} K^{-1}; m_p is current particle mass, *kg*; T_p is particle temperature, *K*; ε is the degree of the particle blackness; σ is the Stefan-Boltzmann constant, *W* (m^{-2} K^{-4}); S is a particle surface area, m^2; T^w is ambient temperature, K; α is convective heat transfer coefficient, *W* m^{-2} K^{-1}); Q_w is heat of moisture evaporation, *W*; Q_r is heat of chemical reactions, *W*.

Drying rate is calculated by the formula:

$$\frac{dm_w}{dt} = K_w S\left(C_{H_2O}^{eq} - C_{H_2O}\right)$$

Here K_w is drying rate constant, m/s; C_{H2O} is the concentration of water vapor, kg m^{-3}.

The coefficient of convective heat and mass transfer for a particle in a stream is calculated by the formula:

$$\mathrm{Nu} = \mathrm{Sh} = 2 + 0.16\,\mathrm{Re}_p^{2/3}$$

Here Nu is the Nusselt number; Sh is the Sherwood number; Re_p is the Reynolds number for the velocity of the carrier flow and current particle size.

The pyrolysis rate is described by the first-order kinetic equation:

$$\frac{dm_V}{d\tau} = -k_V^0 \exp\left(-\frac{E_V}{RT}\right) m_V$$

Here m_V is the mass of volatiles in the particle, kg; k_V^0 – pre-exponential factor, s^{-1}; E_V is the activation energy of the pyrolysis stage, J/mol; R is the universal gas constant,

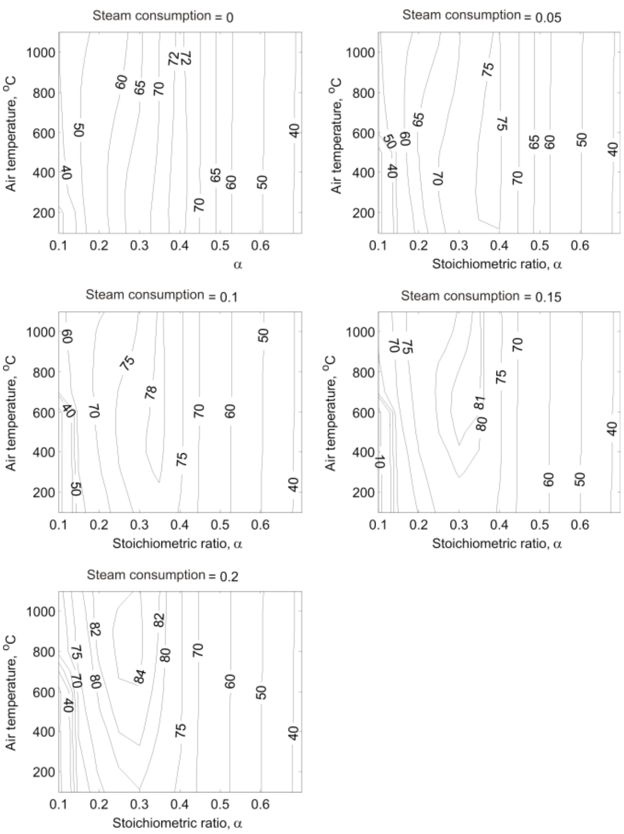

Fig. 1. The dependence of cold gas efficiency (%) on stoichiometric ratio, initial air temperature and steam consumption.

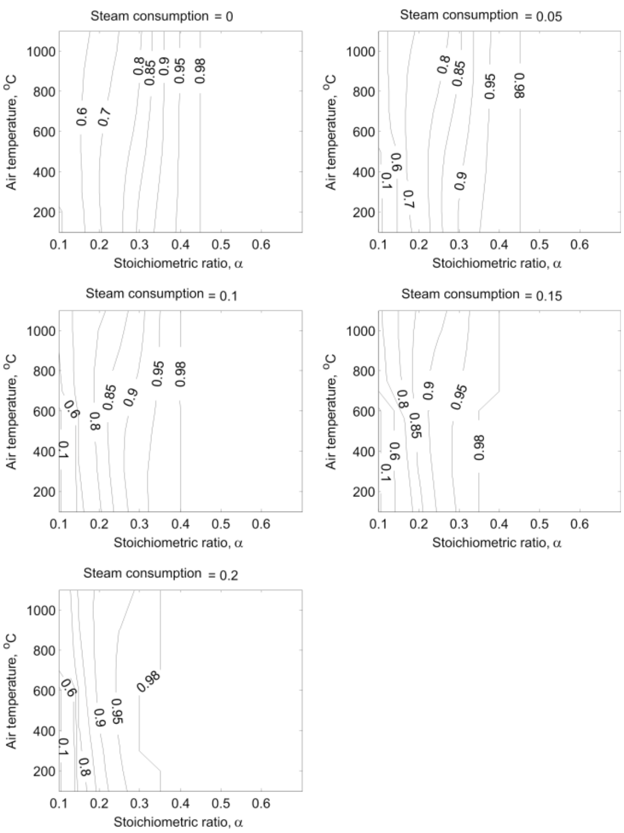

Fig. 2. The dependence of fuel conversion degree on stoichiometric ratio, initial air temperature and steam consumption.

J mol^{-1} K^{-1}. The volatiles in the model are represented by a mechanical mixture of chemical elements. After exiting the fuel particle, volatiles achieve their molecular forms according to the conditions of chemical equilibrium.

The reaction rate of the fuel with gaseous oxidizing agents is recorded as follows: $\frac{dm_C}{d\tau} = -k_{eff} S C_{ox}$

Here m_C is the mass of fuel, kg; k_{eff} is effective rate constant for heterogeneous reaction, m/s; S is a fuel surface area, m^2; C_{ox} is the oxidizer concentration, kg m^{-3}.

The effective rate constant is expressed in terms of the kinetic and mass transfer coefficients (assuming that the kinetic order of the reaction with respect to the oxidant is one) as follows [45]:

$$k_{eff} = \frac{k_C k_d}{k_C + k_d}$$

Here k_C is the kinetic rate constant for a heterogeneous reaction, m/s; k_d is the mass transfer coefficient of the particle with the flow, m/s.

The kinetic rate constant for a heterogeneous reaction depends on temperature exponentially:

$$k_C = k_C^0 \exp\left(-\frac{E_a}{RT}\right)$$

Here k_C^0 is the pre-exponential factor, m/s; E_a is activation energy, J/mol.

Overall change in particle mass is written as follows:

$$\frac{dm_p}{d\tau} = \frac{dm_w}{d\tau} + \frac{dm_V}{d\tau} + \frac{dm_C}{d\tau}$$

Chemical kinetics of reactions in the gas phase is not considered. It is assumed that substances entering the gas phase attain a state of equilibrium. Thus, chemical transformations are described using a thermodynamic model with macrokinetic constraints on the rate of heterogeneous transformations [46, 47]. This approach is applicable to high-temperature processes in which the rates of gas-phase processes are quite high compared to the rates of heterophase processes [48].

The model proposed is stationary and one-dimensional. Similar models were previously used in [49–51] to estimate characteristics of the gasification process.

III. Initial data and results

A tube reactor with a fuel capacity of 100 t/h and working pressure of 30 atm is considered. The length of the reaction zone is 15 m; inner diameter is 3 m. The temperature of the fuel entering the reactor is 27°C; steam temperature is 323°C; air temperature varies from 100°C to 1000°C (with increments of 100 degrees). Steam consumption varies from 0 to 0.2 mol/mol of carbon, stoichiometric ratio varies from 0.1 to 0.7 (with increments of 0.05). Coal characteristics are: W^r = 2%; A^d = 15.38%; V^{daf} = 29.42%; C^{daf} = 85.45%; H^{daf} = 4.86%; N^{daf} = 2.0%; S^{daf} = 0.67%.

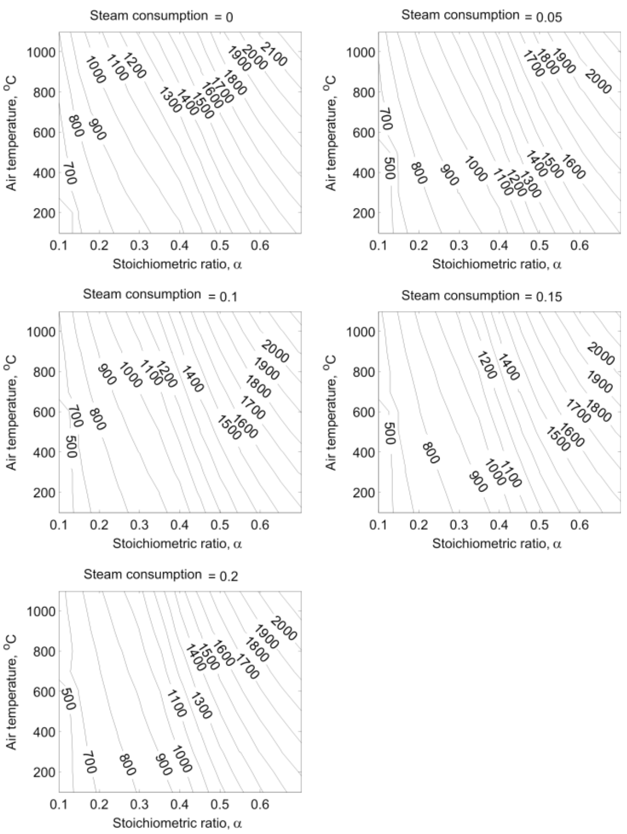

Fig. 3. The dependence of maximum combustion temperature on stoichiometric ratio, initial air temperature and steam consumption.

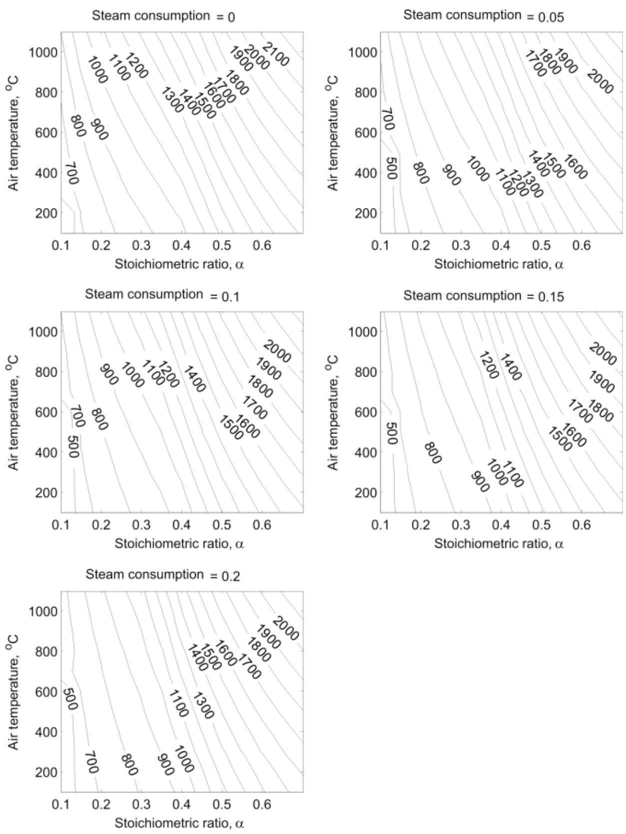

Fig. 4. The dependence of outlet gas temperature on stoichiometric ratio, initial air temperature and steam consumption.

The following characteristics were selected as key indicators: cold gas efficiency, or *CGE*, (fraction of the solid fuel combustion heat converted to the combustion heat of produced gas), maximum and final gas temperature, degree of fuel conversion, and concentration of combustible components in the produced gas.

$$CGE = \frac{Q_g G_g^{out}}{Q_f G_f^{in}} 100\%$$

The calculation results are presented in Figs. 1–6. Fig. 1 shows the contours of cold gas efficiency of the gasification process for different temperatures and specific air flow rates. A well-known pattern is observed: with a change in stoichiometry, the efficiency of the process has an extremum at fixed air initial temperature, corresponding to a complete fuel conversion (see Fig. 2) [52, 53]. An increase in air temperature enhances efficiency only if there is a sufficient amount of steam. Steam consumption of 0.2 mol/mol (C) allows increasing the cold gas efficiency of gasification from 72% (without additional steam) to 84%. Additional steam allows reducing the temperature in the core of the torch and at the reactor outlet (Figs. 3, 4).

At low stoichiometric ratio and low temperatures, the cold gas efficiency drops sharply: oxidative pyrolysis occurs under unstable temperature conditions, and large underburn is observed (Fig. 2). An increase in the stoichiometric ratio over optimal values (0.3–0.4) leads to the oxidation of combustible gaseous components, which also leads to a decrease in efficiency, and this dependence is almost the same at each steam consumption (Fig. 1). As seen in Fig. 5, the stoichiometric ratios corresponding to maximum concentration of CO are shifted toward the pyrolysis region, while the maximum of H_2 formation corresponds to the maximum of cold gas efficiency (Fig. 6).

The diagrams of the dependence of the outlet gas temperature on the gasification conditions (Fig. 4) make it possible to choose the gasification parameters considering requirements of produced gas cooling and purification systems [54, 55]. As already mentioned above, the increases in the initial temperature improves the efficiency of gasification. In this case, the optimal value of the stoichiometric ratio decreases, and also due to the decrease in the gas density, the average gas velocity changes. Therefore, at high gasification agent temperatures, the efficiency of the process begins to decline due to a decrease in particles residence time in the reactor. Therefore, the length of the reactor should be a variable parameter (for future research).

IV. CONCLUSION

A numerical study of the pulverized coal gasification process in entrained flow of heated air-steam mixture was performed. A grid of control parameters (initial air temperature, stoichiometric ratio, steam consumption) was

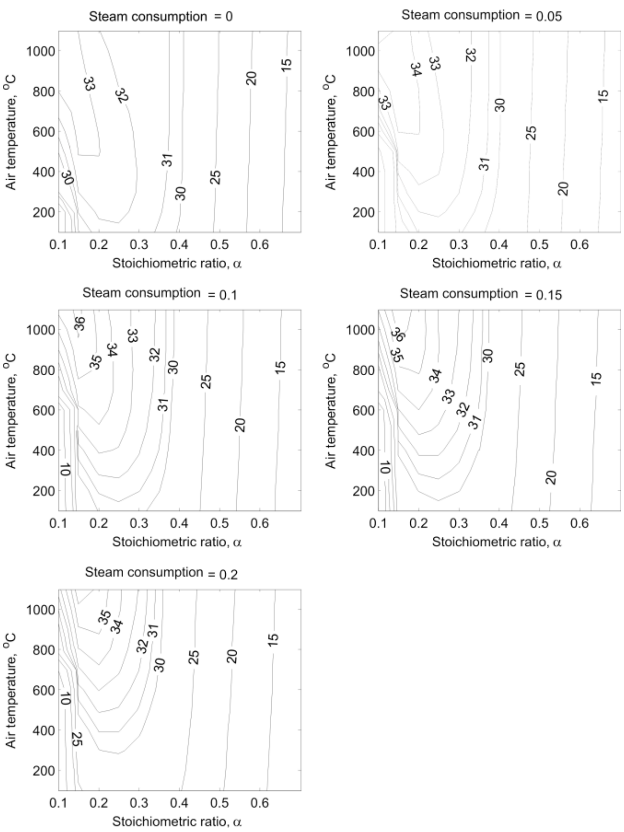

Fig. 5. The dependence of CO content in produced gas (% vol.) on stoichiometric ratio, initial air temperature and steam consumption.

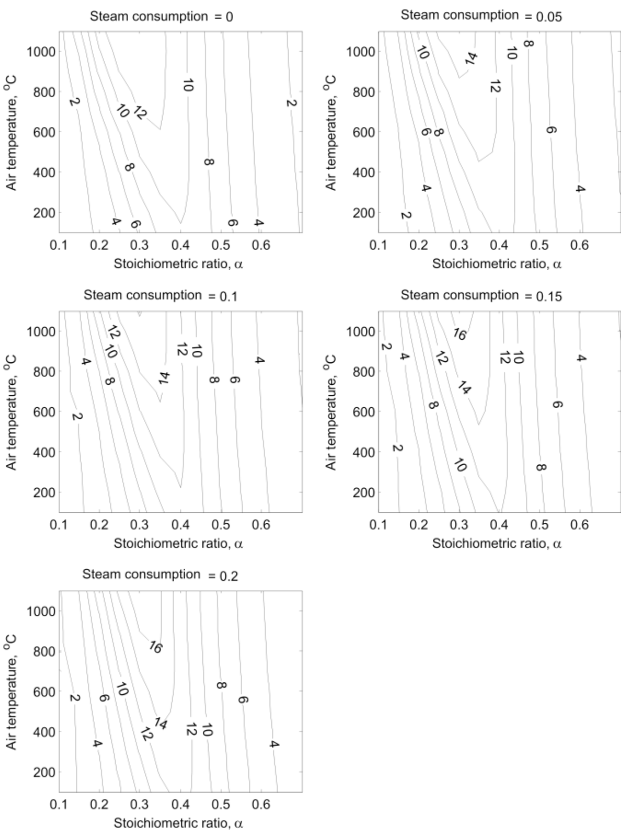

Fig. 6. The dependence of H_2 content in produced gas (% vol.) on stoichiometric ratio, initial air temperature and steam consumption.

set, in which the dependences of the main characteristics of the gasification process were obtained (cold gas efficiency, temperature, gas composition). The calculations show the possibility of enhancing the cold gas efficiency up to 84% with a steam consumption of 0.2 mol/mol of carbon fuel when air is heated to the temperatures of about 800°C.

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References

[1] H. Spliethoff, Power generation from solid fuels. Springer, 2010. 704 p. DOI: 10.1007/978-3-642-02856-4

[2] T. Wang and G. Stiegel (eds.) Integrated gasification combined cycle (IGCC) technologies. Woodhead Publ., 2017 929 p. DOI: 10.1016/B978-0-08-100167-7.00001-9

[3] Gasification technologies. ThyssenKrupp Industrial Solutions AG. Germany, 2019. 24 p.

[4] J.N. Phillips, G.S. Booras and J. Marasigan, "The History of Integrated Gasification Combined-Cycle Power Plants," in Proc. ASME Turbo Expo 2017 (June 26-30, 2017), paper no. GT2017-64507, V003T03A007. DOI: 10.1115/GT2017-64507

[5] M. Grabner, Industrial coal gasification technologies covering baseline and high-ash coal. Wiley-VCH, 2015. 376 p.

[6] A.F. Ryzhkov, T.F. Bogatova, Z. Lingyan and P.V. Osipov, "Development of entrained-flow gasification technologies in the Asia-Pacific region (review)," Thermal Engineering, vol. 63, no. 11, pp. 791-801, 2016. DOI: 10.1134/S0040601516110069

[7] G.G. Olkhovskii, "New projects for CCGTs with coal gasification (Review)," Thermal Engineering, vol. 63, no. 10, pp. 679-689, 2016. DOI: 10.1134/S0040601516100074

[8] G.S. Aslanjan, I.Ju. Ginevskaja and E.E. Shpil'rajn, "Influence of oxygen-steam blowing parameters on carbon gasification," Himija tverdogo topliva, no. 1, pp. 90-98, 1984. (in Russ.)

[9] H. Tsuji, A.K. Gupta, T. Hasewaga, M. Katsuki, K. Kishimoto and M. Morita, High temperature air combustion. From energy conservation to pollution reduction. CRC Press, 2003. 405 p. DOI: 10.1201/9781420041033

[10] S.K. Som and A. Datta, "Thermodynamic irreversibilities and exergy balance in combustion processes," Progress in Energy and Combustion Science, vol. 34, pp. 351-376, 2008. DOI: 10.1016/j.pecs.2007.09.001

[11] P.F. Li, J.C. Mi, B.B. Dally, F.F. Wang, L. Wang, Z.H. Liu, S. Chen and C.G. Zheng, "Progress and recent trend in MILD combustion," Science China. Technological Sciences, vol. 54, no. 2, pp. 255-269, 2011. DOI: 10.1007/s11431-010-4257-0

[12] C.C.P. Pian and K. Yoshikawa, "Development of a high-temperature air-blown gasification system," Bioresource Technology, vol. 79, pp. 231-241, 2001. DOI: 10.1016/S0960-8524(01)00054-2

[13] V.E. Messerle, A.B. Ustimenko and O.A. Lavrichshev, "Plasma coal conversion including mineral mass utilization," Fuel, vol. 203, pp. 877-883, 2017. DOI: 10.1016/j.fuel.2017.05.037

[14] N. Kobayashi, M. Tanaka, G. Piao, J. Kobayashi, S. Hatano, Y. Itaya and S. Mori, "High temperature air-blown woody biomass gasification model for the estimation of an entrained down-flow gasifier," Waste Management, vol. 29, no. 1, pp. 245-251, 2009. DOI: 10.1016/j.wasman.2008.04.014

[15] Y. Ueki, R. Yoshiie, I. Naruse and S. Matsuzaki, "Effect of hydrogen gas addition on combustion characteristics of pulverized coal," Fuel Processing Technology, vol. 161, pp. 289-294, 2017. DOI: 10.1016/j.fuproc.2017.02.034

[16] V.A. Mikula, A.F. Ryzhkov and N.V. Val'tsev, "Analyzing the possibility of constructing the air heating system for an integrated solid fuel gasification combined-cycle power plant," Thermal Engineering, vol. 62, no. 11, pp. 773-778, 2015. DOI: 10.1134/S0040601515110038

[17] A.M. Kler, E.A. Tyurina and A.S. Mednikov, "Coal combined-cycle plant with working medium heating in gas-turbine cycle in periodic regenerative heat exchangers," Bulletin of the Tomsk Polytechnic University, vol. 323, no. 4, pp. 75-802, 2013. (in Russ.)

[18] A.M. Kler, A.Yu. Marinchenko and Yu.M. Potanina, "Development of mathematical model of the system of high-temperature ceramic heat exchangers of periodic action," Bulletin of the Tomsk Polytechnic University, vol. 329, no. 3, pp. 26-35 2019. DOI: 10.18799/24131830/2019/3/159 (in Russ.)

[19] H. Ishi, T. Hayashi, H. Tada, K. Yokohama, R. Takashima and J. Hayashi, "Critical assessment of oxy-fuel integrated coal gasification combined cycles," Applied Energy, vol. 233-234, pp. 156-169, 2019. DOI: 10.1016/j.apenergy.2018.10.021

[20] H. Watanabe, S. Ahn, K. Tanno, "Numerical investigation of effects of CO2 recirculation in an oxy-fuel IGCC on gasification characteristics of a two-stage entrained flow coal gasifier," Energy, vol. 118, pp. 181-189, 2017. DOI: 10.1016/j.

energy.2016.12.031

[21] P.A. Ralnikov, N.A. Abaimov and A.F. Ryzhkov, "Investigation of coal entrained-flow gasification in O2-CO2 mixtures for oxy-fuel IGCC," Journal of Physics: Conference Series, vol. 1128, paper no. 012007, 2018. DOI: 10.1088/1742-6596/1128/1/012007

[22] Y. Li, R. Sun, M. Wang, Z. Wang, J. Xu and X. Ren, "Reaction kinetics of char-O2/H2O combustion under high-temperature entrained flow conditions," Fuel, vol. 243, pp. 172-184, 2019. DOI: 10.1016/j.fuel.2019.01.109

[23] Y. Li, R. Sun, J. Wu, Z. Wang, M. Wang and Z. Song, "Effect of H2O on char-nitrogen conversion during char-O2/H2O combustion under high-temperature entrained flow conditions," Combustion and Flame, vol. 207, pp. 391-405, 2019. DOI: 10.1016/j.combustflame.2019.06.013

[24] W. Yang, A. Ponzio, C. Lucas and W. Blasiak, "Performance analysis of a fixed-bed biomass gasifier using high-temperature air," Fuel Processing Technology, vol. 87, no. 3, pp. 235-245, 2006. DOI: 10.1016/j.fuproc.2005.08.004

[25] K. Qin, W. Lin, P.A. Jensen and A.D. Jensen, "High-temperature entrained flow gasification of biomass," Fuel, vol. 93, pp. 589-600, 2012. DOI: 10.1016/j.fuel.2011.10.063

[26] J. Stasiek, M. Jewartowski and W. Yang, "Small Scale Gasification of Biomass and Municipal Wastes for Heat and Electricity Production using HTAG Technology," E3S Web Conf., vol. 13, paper no. 03005, 2017. DOI: 10.1051/e3sconf/20171303005

[27] Y. Wu, Q. Zhang, W. Yang and W. Blasiak, "Two-Dimensional Computational Fluid Dynamics Simulation of Biomass Gasification in a Downdraft Fixed-Bed Gasifier with Highly Preheated Air and Steam," Energy Fuels, vol. 27, no. 6, pp. 3274–3282, 2013. DOI: 10.1021/ef4003704

[28] T.M. Ismail and M.A. El-Salam, "Parametric studies on biomass gasification process on updraft gasifier high temperature air gasification," Applied Thermal Engineering, vol. 112, pp. 1460-1473, 2017. DOI: 10.1016/j.applthermaleng.2016.10.026

[29] M.-A.Y. Jahromi, K. Atashkari and M. Kalteh, "Development of a high-temperature two-stage entrained flow gasifier model for the process of biomass gasification and syngas formation," International Journal of Energy Research, vol. 43, no. 11, pp. 5864-5878, 2019. DOI: 10.1002/er.4692

[30] V. Kuznetsov, M. Chernetskiy, N. Abaimov and A. Ryzhkov, "Study of the two-stage gasification process of pulverized coal with a combined countercurrent and concurrent flow system," MATEC Web Conf., vol. 115, paper no. 03008, 2017. DOI: 10.1051/matecconf/201711503008

[31] A.F. Ryzhkov, N.A. Abaimov, I.G. Donskoy and D.A. Svishchev, "Modernization of Air-Blown Entrained-Flow Gasifier of Integrated Gasification Combined Cycle Plant," Combustion, Explosion, and Shock Waves, vol. 54, no. 3, pp. 337-344, 2018. DOI: 10.1134/S0010508218030103

[32] I.G. Donskoy, D.A. Svishchev and A.F. Ryzhkov, "Reduced Order Modelling of Pulverized Coal Staged Gasification: Influence of Primary and Secondary Fuel Ratio," Energy Systems Research, vol. 1, no. 4, pp. 27-35, 2018. DOI: 10.25729/esr.2018.04.0003

[33] A. Ajilkumar, T. Sundararajan and U.S.P. Shet, "Numerical modeling of a steam-assisted tubular coal gasifier," International Journal of Thermal Sciences, vol. 48, no. 2, pp. 308-321, 2009. DOI: 10.1016/j.ijthermalsci.2008.08.006

[34] K. Yamamoto, T. Murota, T. Okazaki and M. Tanigichi, "Large eddy simulation of a pulverized coal jet flame ignited by a preheated gas flow," Proceedings of the Combustion Institute, vol. 33, pp. 1771-1778, 2011. DOI: 10.1016/j.proci.2010.05.113

[35] Z. Xue, Y. Gong, Q. Guo, Y. Wang and G. Yu, "Conversion characteristics of a single coal char particle with high porosity moving in a hot O2/CO2 atmosphere," Fuel, vol. 256, paper no. 115967, 2019. DOI: 10.1016/j.fuel.2019.115967

[36] S. Farazi, J. Hinrichs, M. Davidovic, T. Falkenstein, M. Bode, S. Kang, A. Attili and H. Pitsch, "Numerical investigation of coal particle stream ignition in oxy-atmosphere," Fuel, vol. 241, pp. 477-487, 2019. DOI: 10.1016/j.fuel.2018.11.108

[37] V. Salomatov, G. Kuznetsov, S. Syrodoy and N. Gutareva, "Effect of high-temperature gas flow on ignition of the water-coal fuel particles," Combustion and Flame, vol. 203, pp. 375-385, 2019. DOI: 10.1016/j.combustflame.2019.02.025

[38] S. Kriebitzsch and A. Richter, "LES simulation of char particle gasification at Reynolds numbers up to 1000," Combustion and Flame, vol. 211, pp. 185-194, 2020.DOI: 10.1016/j.combustflame.2019.08.028

[39] W. Zhang, H. Watanabe, T. Kitagawa, "Direct numerical simulation of ignition of a single particle freely moving in a uniform flow," Advanced Powder Technology, vol. 28, no. 11, pp. 2893-2902, 2017. DOI: 10.1016/j.apt.2017.08.016

[40] A.F. Ryzhkov, S.I. Gordeev, T.F. Bogatova, "Selecting the process arrangement for preparing the gas turbine working fluid for an integrated gasification combined-cycle power plant," Thermal Engineering, vol. 62, no. 11, pp. 796-801, 2015. DOI: 10.1134/S0040601515110075

[41] A. Ryzhkov, T. Bogatova and S. Gordeev,

"Technological solutions for an advanced IGCC plant," Fuel, vol. 214, pp. 63-72, 2018. DOI: 10.1016/j.fuel.2017.10.099

[42] A.M. Kler, A.Yu. Marinchenko and Yu.M. Potanina, "Optimization studies of combined cycle plant with coal gasification and high temperature heated combustion air," // Bulletin of the Tomsk Polytechnic University, vol. 330, no. 3, pp. 7-17, 2019. (in Russ.)

[43] I.G. Donskoi, "Mathematical modeling of the reaction zone of a Shell-Prenflo gasifier with the use of the models of sequential equilibrium," Solid Fuel Chemistry, vol. 50, no. 3, pp. 191-196, 2016. DOI: 10.3103/S0361521916030034

[44] I.G. Donskoy, V.A. Shamansky, A.N. Kozlov and D.A. Svishchev, "Coal gasification process simulations using combined kinetic-thermodynamic models in one-dimensional approximation," Combustion Theory and Modelling, vol. 21, no. 3, pp. 529-559, 2017. DOI: 10.1080/13647830.2016.1259505

[45] D.A. Frank-Kamenetskii, Diffusion and Heat Exchange in Chemical Kinetics, USA: Princeton Univ. Press, 2015.

[46] P. Koukkari and R. Pajarre, "Introducing mechanistic kinetics to the Lagrangian Gibbs energy calculation," Computers and Chemical Engineering, vol. 30, pp. 1189-1196, 2006. DOI: 10.1016/j.compchemeng.2006.03.001

[47] B.M. Kaganovich, A.V. Keiko and V.A. Shamansky, "Equilibrium thermodynamic modeling of dissipative macroscopic systems" in: Advances in Chemical Engineering: Thermodynamics and Kinetics of Complex Systems, ed. by D.H. West and G. Yablonsky, vol. 39, pp. 1-74, 2010. DOI: 10.1016/S0065-2377(10)39001-6

[48] A.V. Messerle, V.E. Messerle and A.B. Ustimenko, "Plasma thermochemical preparation for combustion of pulverized coal," High Temp., vol. 55, no. 3, pp. 352-360, 2017. DOI: 10.1134/S0018151X17030142

[49] R.F.D. Monaghan and A.F. Ghoniem, "A dynamic reduced order model for simulating entrained flow gasifiers. Part I: Model development and description," Fuel, vol. 91, pp. 61-80, 2012. DOI: 10.1016/j.fuel.2011.07.015

[50] M.H. Sahraei, M.A. Duchesne, D. Yandon, R.W. Hughes and L.A. Ricardez-Sandoval, "Reduced order modeling of a short-residence time gasifier," Fuel, vol. 161, pp. 222-232, 2015. DOI: 10.1016/j.fuel.2015.07.096

[51] H. Zhou, T. Xie and F. You, "On-line Simulation and Optimization of a Commercial-Scale Shell Entrained-flow Gasifier Using a Novel Dynamic Reduced Order Model," Energy, vol. 149, pp. 516-534, 2018. DOI: 10.1016/j.energy.2018.02.031

[52] M.J. Prins and K.J. Ptasinski, "Energy and exergy analyses of the oxidation and gasification of carbon," Energy, vol. 30, no. 7, pp. 982-1002, 2005. DOI: 10.1016/j.energy.2004.08.010

[53] E. Biagini, "Study of the equilibrium of air-blown gasification of biomass to coal evolution fuels," Energy Conversion and Management, vol. 128, pp. 120-133, 2016. DOI: 10.1016/j.enconman.2016.09.068

[54] Q. Zhu, High temperature syngas coolers (CCC/257). IEA Clean Coal Centre, 2015. 60 p.

[55] B.B. Botros and J.G. Brisson, "Improving high temperature heat capture for power generation in gasification plants," International Journal of Heat and Mass Transfer, vol. 61, pp. 129-137, 2013. DOI: 10.1016/j.ijheatmasstransfer.2013.01.033

Methodological Approaches To Modelling The Assessment Of Geo-Environmental Impact Of Energy Given The Quality Of Life (On The Example Of The Baikal Region And Belarusian Regions)

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***Abstract* — The paper is concerned with the results of an international project carried out together with researchers from Belarus and Armenia with the support of the EASR (The Eurasian Association for the Support of Scientific Research, established in July 2016 on the initiative of the Russian Foundation for Basic Research in cooperation with the partner organizations of Belarus, Armenia, Kyrgyzstan, and Mongolia.) Fund. The project aims to develop methods and technologies for assessing the geo-environmental impact of the energy industry in the region. The focus of the study is the negative impact on the environment and, as a consequence, a decrease in the quality of life. The study does not consider the power supply. Its priority is the development of tools for intelligent support of decision-making in this field.**

***Index Terms* — intelligent support of decision-making, energy, ecology, quality of life.**

I. Introduction

The studies on the assessment of the geoenvironmental impact of energy in the region [1, 2] are conducted within the framework of an international project implemented in cooperation with the teams of scientists from Belarus and Armenia, with the support from the EASR-RFFI funds. The focus of the paper is the main results of the project carried out by the Russian side.

The fundamental scientific problem addressed by the project is the development of methods and geo-information technologies for assessing the geo-environmental impact of energy in the region [3]. The object of research from the Russian side is the Baikal natural territory, comparable in size to Belarus and Armenia.

The paper places an emphasis on the development and integration of modern information technologies for intelligent decision-making support within the framework of the problem. To implement the project, a Web-based information system (WIS) was developed. This system integrates mathematical and semantic methods [4, 5] and tools for assessing the geo-environmental impact of energy in a region, a database, a knowledge base, and a geographic information system. Individual WIS components are implemented as agents-services [6]. The ontology of the environmental impact of energy, ontology of pollutants and WIS architecture are presented in the paper.

The project aims to develop methods and technologies for the assessment of the geoenvironmental impact of energy in the region. It fits well into the main task of geoecology.

Geoecology is understood as an interdisciplinary scientific field that unites research into the composition, structure, properties, processes, physical and geochemical fields of Earth's geospheres as a habitat for humans and other organisms. The main task of geoecology is to study changes in the life-supporting resources of the geosphere shells under the influence of natural and anthropogenic factors, their protection, rational use, and control to preserve the productive and natural environment for present and future generations [1, 2].

One of the important tasks of geoecology is to study changes in the life-supporting components of

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the environment under the influence of natural and anthropogenic factors, their protection, rational use, and control, to preserve them for the present and future generations.

The study of changes in life-supporting resources entails the management of these resources, i.e. the management of human interaction with the environment and the impact of human society on its components.

It is important to assess the impact of such an anthropogenic factor as energy on the components of the natural environment and the quality of life of the population.

The novelty of the project is determined both by its interdisciplinary nature and by the integration of modern information technologies for accomplishing the tasks set (geo-information technologies based on 3D geo-visualization; intellectual technologies of semantic modeling: ontological and cognitive modeling; BigData technology).

The developed methods and technologies can be applied to support decision-making on improving the quality of life, given the energy and environmental factors.

The relevance of the project is determined, on the one hand, by the importance of the issue of assessing the geo-environmental impact of energy in a region, and on the other hand, by its insufficient research and the need to attract modern geo-information and intelligent technologies for solving it.

In the course of the project, the main specific problems to be solved by the project were clarified and expanded. These are 1) to analyze the existing methods for estimating the air pollutant emissions from energy facilities and existing models for the spread of pollution caused by emissions from energy facilities (given the wind rose, transfer, etc.); 2) to select and justify the methods recommended for the use in the project, to modify and adapt them, and develop original methods, if necessary; 3) to identify critical facilities that affect the life-support and natural environment of the region (in the energy, water, and other sectors), to connect critical facilities with the quality of life of the population [7]; 4) to analyze the approaches to the construction of geo-information systems, design a geo-information system based on 3D geo-visualization, determine the types of interfaces for displaying and analyzing the information; 5) to determine the composition of data necessary for the use of recommended methods, identify sources of information, assess their availability and financial costs of acquiring the information; collect and structure the necessary information; design and implement a database; 6) to develop the architecture of a Web-based information system (WIS) that integrates mathematical and semantic methods and tools for assessing the geo-environmental impact of energy in the region, databases, knowledge bases and a geo-information system; to develop a knowledge base structure within WIS; 7) to develop a system of ontologies [8] for describing the domain, adapt and develop tools for semantic modeling, construct semantic models for assessing the impact of energy on geo-ecology of the region; 8) to test WIS and apply the developed methods and technologies to support making decisions on the justification and formulation of recommendations for the energy development given the requirements of geo-ecology.

II. The environmental impact of energy

In recent years, the issue of the environmental impact of energy has been widely discussed in the scientific world. Scientists try to investigate the negative consequences of the energy facilities operation for the environment and identify areas of harmful influence. The findings of the Russian and foreign scientists are considered below.

According to Vorobyov V.I. (Russia), an analysis of existing principles for the design and development of large thermal power plants (TPPs), and optimization models described by different authors shows that they do not take into account the actual air pollution effects since the specific placement of populated settlements that appear in the zone of the polluted area (especially in built-up areas) is not taken into consideration. Based on a full-scale instrumental survey of the urban area, Vorobyov V.I. determined the concentrations of harmful impurities at various distances from the pollution source (the territory of the TPPs, the sanitary protection zone, the residential development). The findings indicate that the maximum permissible concentration is exceeded at a distance of up to 18 km from the pollution source. Arslanbekova F.F. (Russia), who investigated the environmental impact of thermal power plants (TPPs) and motor vehicles, believes that the zone of the most intense air pollution by harmful impurities under torches of TPPs reaches a radius of 3-5 km. Nikiyenko Yu.V. (Russia) investigated the main points of the influence of thermal pollution on the microclimate of the adjacent territories. According to her calculations, the presence of a cooling pond in the area where NPPs and TPPs are located inevitably leads to negative environmental consequences, including maximum temperature, precipitation, and other anomalies. Kozhanov A.A. (Russia) offers methods of geo-environmental assessment of the influence of the fuel and energy system, based on establishing the relationship between natural conditions and anthropogenic impact. The studies on the interconnection of Energy, Environment, and Climate Change are also conducted in other countries, for example, [9-12]. The use of GIS-technologies and 3D-geovisualization is considered in [13, 14].

Nevertheless, the studies on the assessment of the environmental impact of energy have not considered the quality of life so far.

III. The quality of life

Scientists introduced the concept of quality of life in the 1960s when the attempts were made to model the trajectories of industrial development. There are many

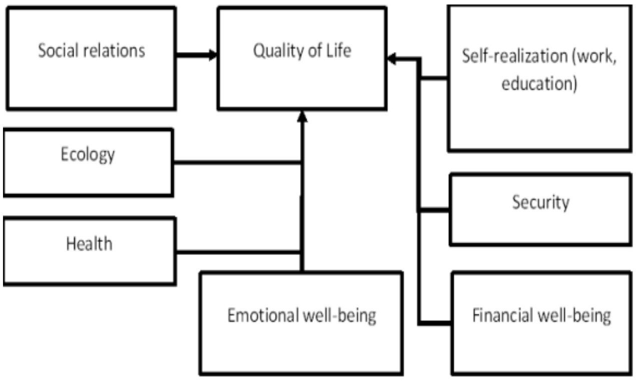

Fig. 1. Quality of life as defined by the World Health Organization.

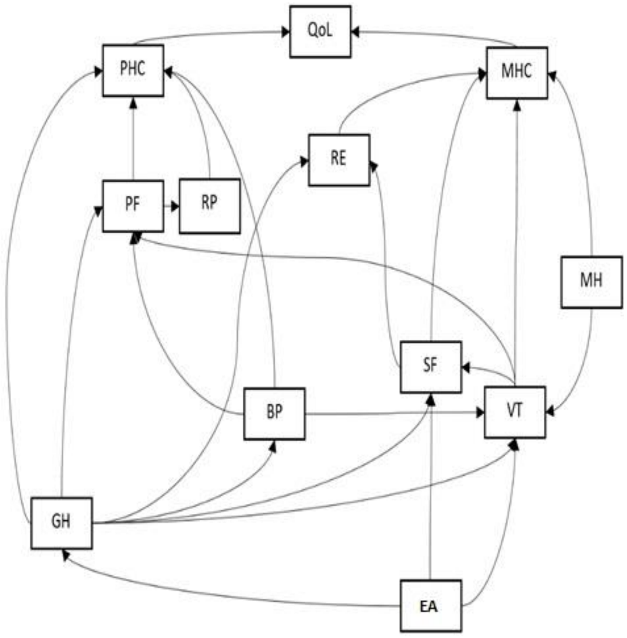

Fig. 2. A cognitive map of life quality indicators using the procedure SF-36 (all links are positive)
Story:
PF (Physical Functioning) – physical functioning.
RP (Role-Physical Functioning) – role functioning conditioned by physical state.
BP (Bodily pain) – pain intensity.
GH (General Health) – general health.
VT (Vitality) – life activity.
SF (Social Functioning) – social functioning.
RE (Role-Emotional) – role functioning preconditioned by emotional state.
MH (Mental health) – mental health.
PHC (Physical health) – general component of physical health.
MHC (Mental health) – general component of mental health.
QoL (Quality of Life) – integral index of quality of life.
(EA) – energy access.
A correlation analysis was used to test the hypothesis. The dynamic data (2011-2017) on life expectancy in the Russian Federation and emissions from stationary sources were used to build a scatter diagram (Fig. 3). The correlation coefficient was -0.79, which indicates the presence of a strong negative relationship.

different definitions of the quality of life but the most comprehensive is in the context of health care. Quality of life is understood as a set of objective and subjective parameters that characterize the maximum number of sides of an individual's life, their position in society and satisfaction with it. According to the definition of the World Health Organization [15], the factors determining the quality of life embrace not only financial well-being but the state of security, health, human position in society, ecology and, most importantly, the assessment of all these factors (Fig. 1). The integral index of the quality of life includes the indicators of health, social relations, emotional well-being, and financial well-being. In the framework of the considered project, the list of quality of life indicators includes the environmental factors.

The study conducted under the guidance of an author indicates that it is difficult to obtain an integral index using rigorous mathematical methods. The artificial intelligence methods are proposed for this purpose, namely, cognitive modeling, which is one of the directions of semantic modeling [5, 16]. Moreover, until recently, the research into the integral index of quality of life has not taken into account the impact of energy supply, whereas a shortage of energy resources can have a significant impact on both the level and quality of life. The studies also propose including the external factors in the quality of life indicators, in particular, the extent to which people are provided with energy resources (access to energy) (Fig. 2) [17].

The preliminary testing of the hypothesis about the impact of energy on the quality of life of the population shows that there is a relationship between life expectancy and the volume of air pollutant emissions from stationary sources (including energy facilities).

There were additional studies of the dynamic data (2011-2017) on life expectancy in the Republic of Belarus and emissions from stationary sources in a regional context (Fig. 4). During the study period, the values of the correlation coefficient varied from -0.33 (2016) to -0.78 (2015). The average value of the coefficient in the study period was -0.63.

The findings of the study indicate that the operation of energy facilities (in terms of emissions) has an impact on life expectancy and, consequently, on the quality of life of the population.

IV. Proposed problem-solving methods and approaches

The development of tools for intelligent support of energy and environmental decision-making in the discussed project involves the methods of geo-information technologies based on 3D geo-visualization [18], critical infrastructure research methods [7], decision-support methods, knowledge engineering methods, object approach methods (analysis, design, programming), system and application programming methods, design methods of database, methods of information and expert

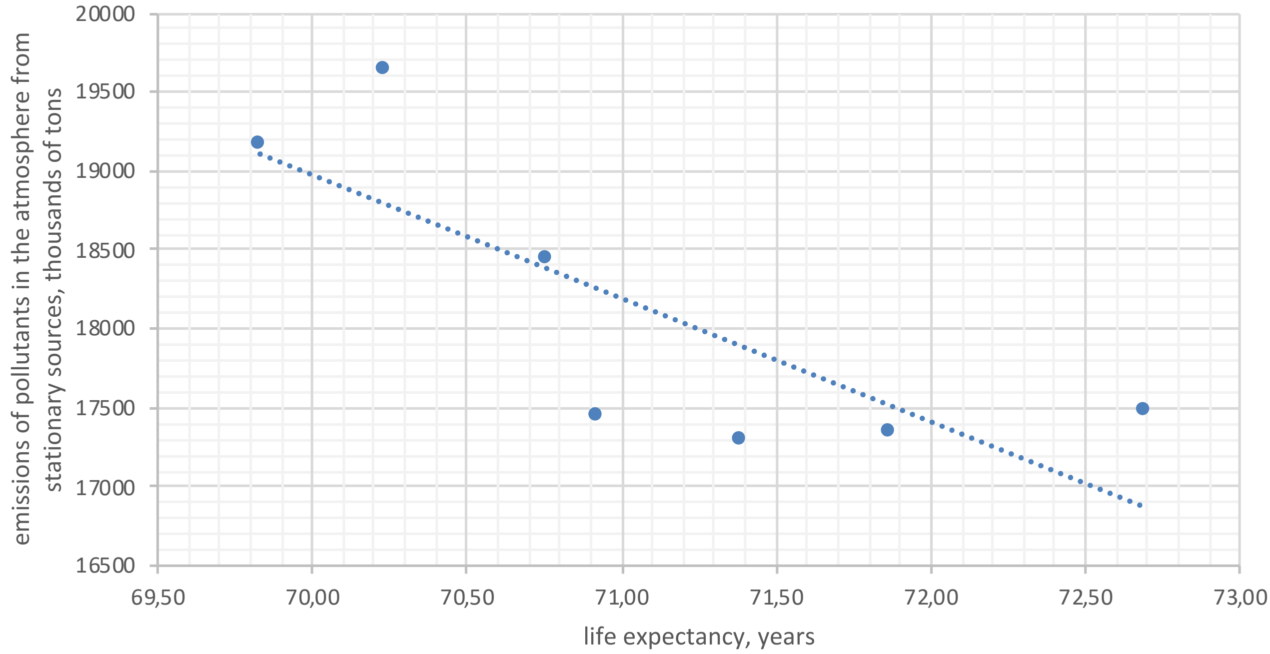

Fig. 3. Scatter diagram of data on life expectancy and emissions from stationary sources in the Russian Federation in 2011-2017.

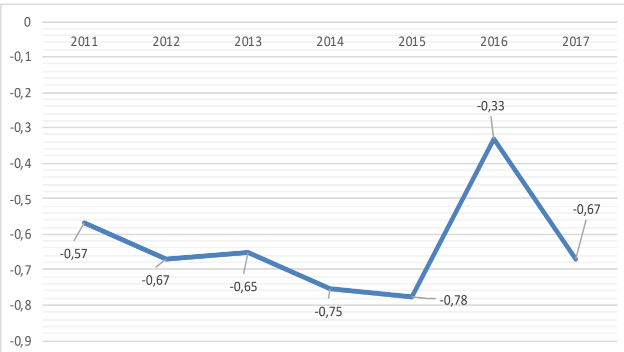

Fig. 4. Dynamics of change in the correlation coefficient of life expectancy in the Republic of Belarus and emissions from stationary sources in a regional context.

systems, as well as the methods devised by the authors, including the method of situational management, semantic modeling (primarily ontological and cognitive), and intelligent technologies for decision-making support [5]. The authors' methods of constructing an ontological space of knowledge in the field of energy; as well as the methods of semantic (ontological and cognitive) modeling in power engineering, methods of 3D-geovisualization and methods of visual analytics with elements of cognitive graphics, and the methods of intelligent systems development, which are designed to support making strategic decisions in the energy sector [19], are proposed to be developed and adapted to the project theme.

By way of illustration of the approach to constructing a system of ontologies of an applied domain, Figures 5-6 show the ontology of the environmental impact of energy (Fig. 5) and the ontology of pollutants from energy facilities (Fig. 6).

As seen in Fig. 6, the energy companies (enterprises of the electric power industry, heat power industry, and fuel and energy resources extraction and transportation companies) can pollute water, air and soil (the focus of the project is air pollution, Fig. 5). Negative impact on the quality of life of a person can be either direct or indirect (through the plant-animal relationships, i.e. through the food chain).

Figure 6 demonstrates the first version of the ontology of pollutants from energy facilities. It is built based on [20] and illustrates the way of structuring the knowledge about the subject area. The ontology can be extended or used as a hybrid one, i.e. some of its concepts can be considered as meta-concepts, which will be described by detailed ontologies. For example, the concept of "Purification" can be represented by a detailed ontology of the methods and levels of purification; the concept of the "Combustion method" can be represented by extended ontologies describing different combustion methods for small and large boiler plants, thermal power plants, etc.

As mentioned in the introduction, a Web-oriented information system (WIS) has been developed to implement the project. It integrates mathematical and semantic methods, tools for the assessment of the geoenvironmental impact of energy in the region, a database, a knowledge base, and a geographic information system. The authors' results obtained earlier are supposed to be used to study energy security problems. The individual WIS components (Geocomponent, semantic modeling support tools, individual computational modules, database access components) are implemented as agents-services [6].

WIS architecture is shown in Fig. 7. There are four levels

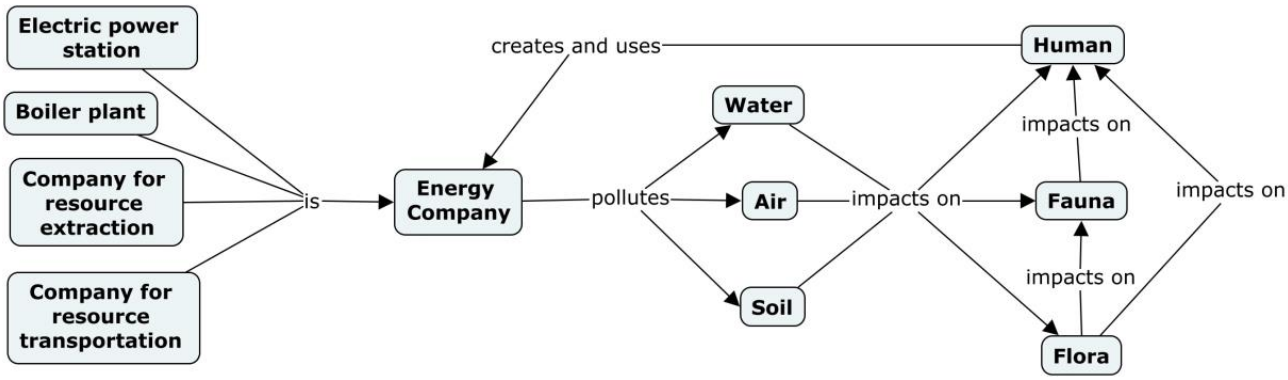

Fig. 5. Ontology of the environmental impact of the energy sector.

in the architecture: 1) the level of mathematical methods, models and software, which includes the software developed based on selected methods and models for calculating the volumes of pollutants and their impact on the quality of life of the population, and takes into account the capacity of energy facilities (energy supply) and population density in the considered territory; 2) the level of semantic modeling, which includes semantic (primarily cognitive) models for describing the interaction of factors that determine the quality of life, given the anthropotechnical factors, including availability of energy resources and the influence of pollutants from energy facilities on the environment; 3) the level of knowledge representation, which integrates the knowledge base storing descriptions of knowledge for constructing semantic models and an ontology system for describing knowledge of the subject domain; the latter can be used both for building a knowledge base and for designing a database; 4) the level of data representation, which integrates the geographic information system (GIS) and database, including geographic coordinates of energy facilities. GIS can be used both for the illustration of calculation results and for the visual interpretation of semantic models.

The meta descriptions of information presented at all four levels are stored in the Repository (its scientific prototype and tools for working with it were developed by Kopaygorodsky A.N., a member of the project team). The user interface is implemented using the components of the situational management language CML [21].

The methods listed above are used to assess the geo-environmental impact of energy in the regions (the Baikal region (Russia) and the regions of Belarus).

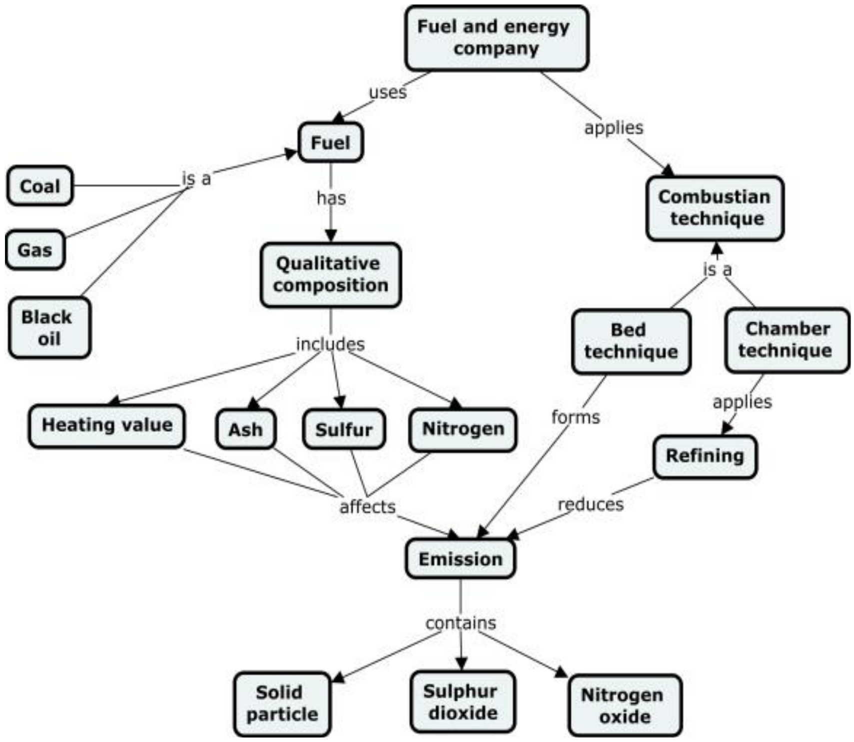

Fig. 6. Ontology of pollutants from energy facilities

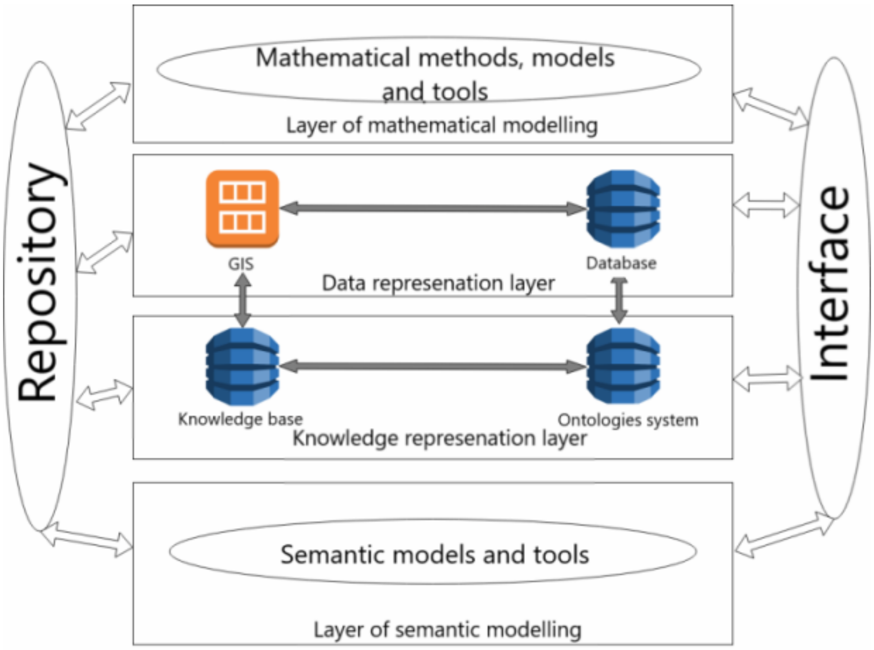

Fig. 7. The architecture of the Web-based information system (WIS) to assess the geo-environmental impact of energy in the region.

V. Characteristic of objects of the research

The main air pollutants in the Russian Federation are carbon monoxide (CO), sulfur dioxide (SO2) and nitrogen oxides (NO_x). In 2011-2017, sulfur dioxide emissions decreased by 15% and accounted for 11.83% of the total emissions in 2017, nitrogen oxide emissions decreased by 3.13% and made up 11.02% of the total emissions, carbon monoxide emissions increased by 2.08% and reached 50.42% of the total emissions (Table 1).

The main sources of pollution in the territory of the Russian Federation in 2017 were mobile sources, i.e. mobile vehicles (45.5%), as well as manufacturing and energy enterprises. An analysis of the structure of emissions from stationary sources indicates that the greatest damage to the atmospheric air of the Russian Federation is caused by the mining industry (28.14%), the processing industry (33.21%) and the energy industry (20.27%) (Table 2). The data presented in Table 2 include both the statistical data and the data provided by Russian colleagues, project team members [20]. These data were subsequently included in the database, which was designed using the proposed ontological approach and the ontology system developed during the project.

However, some regions of the Russian Federation differ in the structure of emissions from stationary sources by type of economic activity. In particular, in the territory of the Baikal region, 52.02% of air pollutant emissions are produced by stationary sources supplying electricity, gas, and steam; and by air conditioning. This indicates a significant geo-environmental impact of energy facilities in the Baikal region.

Table 1. Emissions from stationary and mobile sources of the Russian Federation, thousand tons [22].

Years	Pollutants					Total
	SO_2	nitrogen oxides	CO	volatile organic compounds	NH_3	
2011	4462	3649	15840	2977	70	32628
2012	4431	3452	16119	2563	81	32469
2013	4306	3423	15782	2834	82	32063
2014	4131	3379	15517	2741	87	31228
2015	4197	3381	15530	2716	94	31269
2016	4110	3460	15862	2756	96	31617
2017	3794	3535	16169	2742	101	32068

Fig. 8. The Baikal Region of the Russian Federation.

Table 2. Air pollutant emissions from stationary sources in the russian federation by type of economic activity for 2017 [22]

Indicators	Russian Federation, total		Republic of Buryatia		Irkutsk region		Transbaikal Territory		Total for Baikal region*	
	Thousand tons	%	Thousand tons	%	Thousand tons	%	Thousand tons	%	Thousand tons	%
Agriculture, forestry, hunting, fishing, and fish farming	248.09	1.42	0.75	0.66	4.50	0.68	0.11	0.08	6.70	0.61
Mining	4918.90	28.14	5.49	4.84	111.63	16.92	15.67	11.68	154.55	13.96
Manufacturing industries	5803.48	33.21	12.60	11.12	178.91	27.11	21.01	15.66	250.75	22.64
Electricity, gas, and steam; air conditioning	**3542.64**	**20.27**	**82.40**	**72.71**	**304.77**	**46.18**	**70.06**	**52.22**	**576.13**	**52.02**
Water supply; water disposal, organization of collection and disposal of waste, pollution control activities	492.88	2.82	2.24	1.98	4.72	0.72	0.96	0.72	10.61	0.96
Total by the studied types of economic activity	17477.47	100.00	113.32	100.00	659.93	100.00	134.16	100.00	1107.41	100.00

*Including air pollutant emissions from Mongolia, which are not shown in the Table

Table 3. Emissions of pollutants from stationary sources in the republic of belarus by type of economic activity for 2017, thousand tons [25].

Indicators	Pollutants					Total
	Solid	SO_2	CO	NO_2	Hydrocarbons	
Industry	21.0	46.5	60.3	45.9	18.4	250.4
Manufacturing industry	13.3	42.8	40.9	24.5	4.5	175.2
Chemical and petrochemical production	5.6	39.5	15.4	18.9	1.2	120.5
Production of coke and refined petroleum products	1.4	37.5	7.4	5.7	0.5	83.9
Chemical production	1.8	1.1	1.9	2.1	0.5	13.1
Production of rubber and plastic products, other non-metallic mineral products	2.4	0.9	6.1	11.1	0.2	23.5
Electricity, gas, steam, hot water and air conditioning	5.9	3.7	18.5	20.7	6.4	61.8

At the same time, the Baikal region has many unique characteristics, which is why it has been chosen as an object of the study.

The Baikal region covers the territory of the Baikal catchment area and includes three constituent entities of the Russian Federation (Irkutsk Region, Transbaikal Region and the Republic of Buryatia) and Mongolia (Fig. 8). The economic activity of these territories is carried out within the catchment area of the lake, and one way or another it affects the environmental state of Lake Baikal.

The project pays special attention to the development of the industry in the Baikal region because the bulk of it is situated in the catchment area of Lake Baikal, which is included in the list of UNESCO World Natural Heritage sites. The lake is a unique natural object of world importance. It is the deepest (1637 m) and oldest (25–30 million years old) lake of the planet.

The Law "About Protection of Lake Baikal" of April 2, 1999, provided the legal framework for the protection of Lake Baikal and outlined the Baikal Natural Territory (BNT), where the operation and development of industrial production are prohibited or limited. Within this territory are the Irkutsk-Cheremkhovo industrial area of the Irkutsk region and the main industrial zone of the Republic of Buryatia. This law imposes serious restrictions on the development of industry in the region. There is a conflict between the need to protect the environment in the zone of the World Natural Heritage site and the need to ensure a decent standard of living (especially in the case of closure of city-forming enterprises).

The territories that make up the Baikal region differ sharply in terms of the level of industrial development. The share of products from the Irkutsk region in the industry of Russia is about 1.8%, while the products from the Republic of Buryatia account for less than 0.3%, and those from the Transbaikal Territory - 0.2%. The basis for the development of industry in the Irkutsk region is the energy industry, which ensures electricity generation; coal, oil and gas production. The energy industry provides for the operation of the aluminum, pulp-and-paper, chemical, and oil refining facilities. Timber harvesting, gold mining, engineering, production of construction materials, and ferrous metallurgy are developed.

The share of the region in the production of aluminum

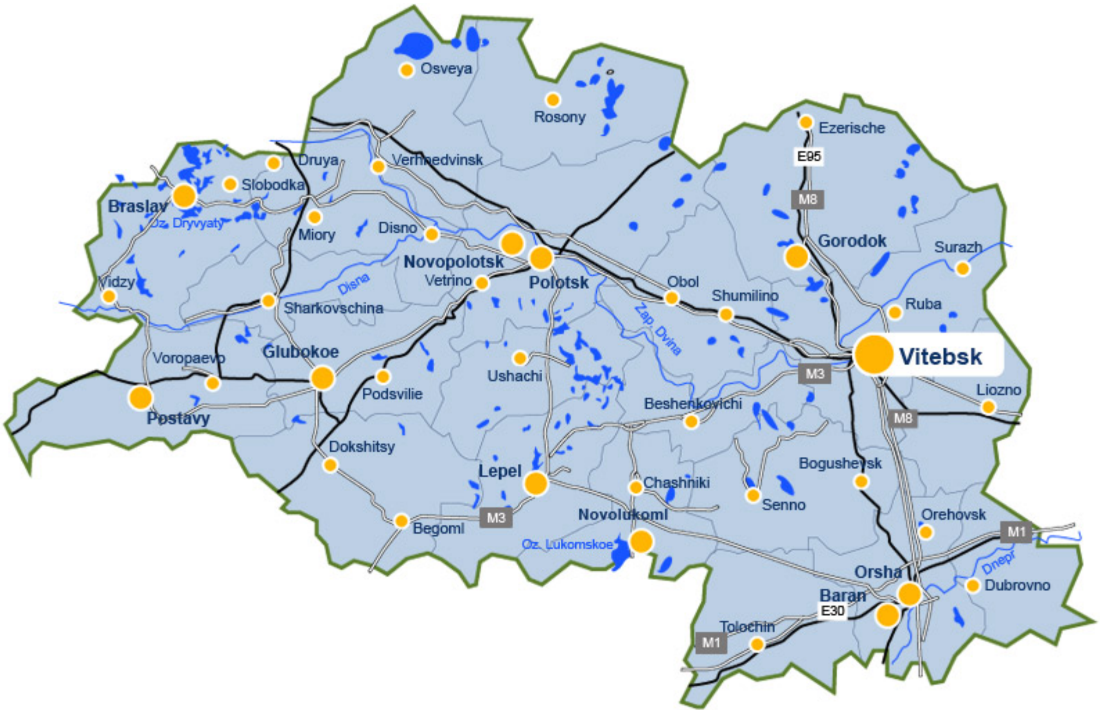

Fig. 9. The Vitebsk Region of the Republic of Belarus.

(35%), cellulose, (28%), caustic soda and chlorine (23%), plastic (12%), timber (11%), electric power (6%), radioactive materials, planes, industrial equipment, wood (15%), gold (10%) is considerable. The republic of Buryatia and Transbaikal Territory together generate electric power (using mostly coal) which is by a factor of 5 less than power generation by the Irkutsk region.

Sustainable development of the industry is impossible without the advancing growth of capacities in the energy industry. The issues of environmental protection are particularly acute here. The thermal power plants using solid fuel pollute the atmosphere and alienate significant areas under slag fields. Hydroelectric power plants damage an ecosystem by flooding considerable territories. According to short-term projections, the Irkutsk region will face a power shortage due to the development of the industry and transport, which will require new capacities to be commissioned [23].

Table 4. Air pollutant emissions in the regions of the republic of belarus for 2017, thousand tons [25]

Indicators	Air pollutant emissions		
	From stationary sources	From mobile sources	Total
Republic of Belarus	453.4	787.2	1240.6
Minsk and regions			
Brest region	50.6	116.1	166.7
Vitebsk region	102.3	88.3	190.6
Gomel region	105.6	97.8	203.4
Grodno region	60.3	94.2	154.5
Minsk	18.3	136.8	155.1
Minsk region	68.6	178.6	247.2
Mogilev region	47.7	75.4	123.1

The main air pollutants in the Republic of Belarus are mobile sources, that is, mobile vehicles, as well as industrial enterprises and thermal power plants [24].

The sectors of the economy with the largest share of air pollutant emissions are the oil refining industry - 20.5%, electricity generation, households, and utilities - 12.9% each, engineering and metalworking, agriculture, chemical and petrochemical industries, transport and communications - 6.8-8.2% (Table 3).

As seen in Table 3, 48.12% of all industrial emissions come from chemical and petrochemical production, and more than 24% are from the energy industry enterprises. As evidenced by an analysis of the spatial structure of air pollutant emissions (Table 2), the largest shares of emissions are observed in Minsk (19.93%), Gomel (16.40%) and the Vitebsk region (15.36%).

The Vitebsk region of the Republic of Belarus was selected as the object of the study (Fig. 9). This choice is due to the following factors:

- The Vitebsk region covers an area of 40.051 km², which is 19.29% of the entire territory of the country;
- The population of the Vitebsk region is 1.2 million people, that is 12.43% of the total population;
- 32.7% of all electricity (10001.9 million kWh) and 16.2% of heat (5626.6 thousand Gcal) are produced on the territory of the Vitebsk region;
- The Vitebsk region accounts for more than 45% of petroleum products produced in the Republic of Belarus. In the structure of the manufacturing industry of the region, the production of coke and petroleum products takes 51.9%;

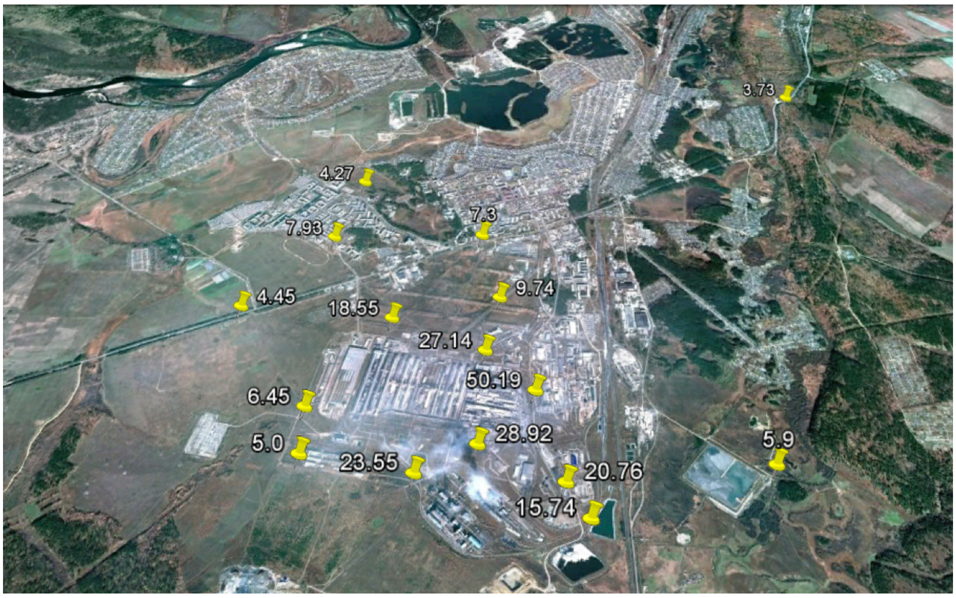

Fig 10. 3D-visualization of pollution measurement results near energy facilities (SO4 content in mg / l near the Shelekhovskaya CHP).

- Protected areas (Berezinsky Biosphere Reserve; National Park "Braslav Lakes"; Republican reserves "Yelnya", "Osveysky", "Krasny Bor", "Kozyansky", etc.) of the Vitebsk region occupy 9.5% of its area;
- The Vitebsk region ranks first in Belarus in terms of the density of the river network, the number and area of lakes. The rivers of the Vitebsk region belong mainly to the Western Dvina basin, which occupies 80% of its area. There are more than 2.8 thousand lakes in the region (Osveiskoye, Lukomlskoe, Drisvyaty, Drivyaty, Nesherdo, Snudy, Jezerishche, Strusto, Obsterno);
- The Vitebsk region ranks third in the Republic of Belarus in terms of air pollutant emissions (102.3 thousand tons from stationary sources, 88.3 thousand tons from mobile sources).

Thus, the main sources of air pollutant emissions in the Vitebsk region are the energy enterprises, the chemical industry, and vehicles.

VI. Results and discussion

The paper is devoted to an important issue of the assessment of the geoenvironmental impact of energy in the region. The environmental studies normally do not consider separately the emissions from energy facilities, because it is difficult to separate them from general environmental pollution. This makes it difficult to plan and implement measures to reduce pollution by individual energy facilities. The paper proposes an approach to solving the problem of monitoring the geo-environmental impact of the energy industry in the region, based on the integration of mathematical models, GIS technologies and modern intelligent technologies in the framework of Web-oriented information system (Fig. 10). The novelty of the project is also determined by the fact that this is the first time the assessment of the geoenvironmental impact of the energy industry has taken into account the quality of life of the population. Cognitive modeling is seen as a tool for implementing this idea. The ontology system is proposed as a basis for designing databases and knowledge bases to provide information support. The proposed Web-based system, including an improved analytical tool for estimating the emissions from energy facilities and the spread of pollution, is considered as a prototype of the intelligent decision-making support system for improving the quality of life, given the geo-environmental requirements.

VII. Conclusion

The focus of the paper is an international project, carried out under the guidance of an author with the support of the EASR - RFBR funds. The statement of the problem is formulated (the fundamental scientific task and the project objective), the relevance and expected results of the project are determined, and the methods for and approaches to its implementation are proposed. The main attention in the paper is paid to the information technology part of the project carried out by the Russian side. The illustrations of the proposed approaches are presented, including a cognitive map of indicators for assessing the quality of life, given the availability of energy resources; an ontology of the environmental impact of the energy sector; an ontology of pollutants from energy facilities; as well as the developed architecture of the web-based information system (WIS), which, together with the technology of its use, will be the final result of the project.

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References

[1] Geoecology. Geological Dictionary [in 3 volumes]. Ch. Ed. O.V. Petrov. 3rd ed., Revised. and additional. St. Petersburg: VSEGEI. - 2010. - T. 1. A-I. - P. 244. ISBN 978-5-93761-171-0 (in Russian).

[2] Geoecology. Ecological Encyclopedia: [In 6 volumes]. Ch. Ed. V.I. Danilov-Danilyan. Moscow: OOO "Izdatelstvo Encyclopedia ", 2010. V. 2. G-I. P. 22 (in Russian).

[3] Massel L.V. The problem of the assessment of the geoenvironmental impact of energy in the region: statement and solutions. Information and mathematical technologies in science and management. 2018. No. 2 (10). Pp. 5-21. DOI: 10.25729/2413-0133-2018-2-01 (in Russian).

[4] Khoroshevsky V.F. Semantic Technologies: Expectations and Trends. Proceedings of the II International Scientific and Technical Conference "Open Semantic Technologies for the Design of Intelligent Systems". - Belarus, Minsk: BSUIR. - 2012. - Pp. 143-158 (in Russian).

[5] Massel L.V., Massel A.G. Semantic technologies based on the integration of ontological, cognitive and event modeling. Proceedings of the III International Scientific and Technical Conference "Open Semantic Technologies for the Design of Intelligent Systems". Belarus, Minsk: BSUIR, Pp. 247-250 (in Russian).2013.

[6] Massel L.V., Galperov V.I. Development of multi-agent systems for the distributed solution of energy problems using agent scenarios. Izvestiya of Tomsk Polytechnic University. V. 326. No. 5. 2015. Pp. 45-53 (in Russian).

[7] Massel LV Convergence of research on critical infrastructures, quality of life and safety. Information Technologies and Systems: Proceedings of the 6th International Scientific Conference. Chelyabinsk: ChelSU. Scientific electronic publication. 2017. ISBN 978-5-7271-1417-9. Pp. 170-175. Available at: http://iit.csu.ru/content/docs/ science/itis2017.pdf (circulation date May 10, 2017) (in Russian).

[8] Gavrilova TA Ontological engineering. Electronic resource. Technologies of knowledge management. Available at: http://www.kmtec.ru/publications/ library/authors/ ontolog_engeneering.shtml (in Russian).

[9] Energy, Climate Change, Environment/ International Energy Agency. -2016. - 133 p.

[10] K. Pavlickova, A. Miklosovicova, M. Vyskupova. Effects of Sustainable Energy Facilities on Landscape: A Case Study of Slovakia. Designing Low Carbon Societies in Landscapes, Ecological Research Monographs, Chapter 7. Eds. N. Nakagoshi and J.A. Mabuhay, © Springer Japan, 2014. Pp. 109-127. DOI 10.1007/978-4-431-54819-5_7

[11] Hussey, K., and J. Pittock. The Energy-Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. Ecology and Society 17(1): 31. 2012. http://dx.doi.org/10.5751/ES-04641-170131

[12] Pfeiffer A., Millar R., Hepburn C., Beinhocker E., 2016. "Applied Energy", Elsevier, vol. 179(C). Pp. 1395-1408.

[13] Alaa Alhamwi, Wided Medjroubi, Thomas Vogt and Carsten Agert. GIS-Based Urban Energy Systems Models and Tools: Introducing a Model for the Optimisation of Flexibilisation Technologies in Urban Areas/ Applied Energy.191(1 April 2017). DOI: 10.1016/j.apenergy.2017.01.048

[14] Liang, J., Gong, J., Li, W., Ibrahim, A. N., 2014. A visualization-oriented 3d method for efficient computation of urban solar radiation based on 3d–2d surface mapping. International Journal of Geographical Information Science 28 (4), 780–798.

[15] WHO Health Impact Assessment Toolkit - Guidance on health impact assessment. World Health Organization, 2005

[16] Trakhtengerts E.A. Computer support for decision-making. Moscow: SINTEG, 1998. 376 p. (in Russian).

[17] Massel L.V., Blokhin A.A. Method of cognitive modeling of quality of life indicators taking into account external factors. Science and education. Scientific publication of the MSTU. Bauman. No. 4. 2016. Pp. 65-754. DOI: 10.7463. 0416.0839061 (13) (in Russian).

[18] Ivanova I.Yu., Ivanov R.A. The use of geovisualization in the analysis of the location of energy infrastructure facilities of the central ecological zone of the Baikal natural territory. Information and Mathematical Technologies in Science and Management. Science Magazine. No. 4/2. 2016. Pp. 80-89 (in Russian).

[19] Massel L.V. Problems of the creation of semiotic-type intelligent systems for strategic situational management in critical infrastructures. Information and Mathematical Technologies in Science and Management. Science Magazine. No.1. 2016. Pp. 7-27 (in Russian).

[20] Maysyuk E.P., Ivanova I.Yu., Ivanov R.A. Assessment of the volume and composition of emissions of pollutants from energy facilities of the central ecological zone. Proceedings of the International Scientific and Practical Conference "Current state and prospects for improving the ecology and safety

of vital activity of the Baikal region. White Nights - 2016 ". Irkutsk: Publishing House of the IRSNU. - 2016. - Pp. 475-482 (in Russian).

[21] Massel L.V., Massel A.G. Language of description and knowledge management in the intelligent system of the semiotic type. XX Baikal All-Russian Conference "Information and Mathematical Technologies in Science and Management": Proceedings, Vol. 3. Irkutsk. MESI SB RAS. 2015. Pp. 112 - 124 (in Russian).

[22] Federal State Statistics Service of the Russian Federation (Rosstat) [On-line]. 1999 - 2019. Available at: http://www.gks.ru/. (Accessed 05/10/2019).

[23] Tarakanov, M.A. Sustainable industrial development of the Baikal region. M.A. Tarakanov, A.F. Manzhigeev [Electronic resource]. News of the Irkutsk State Economic. Baikal State University of Economics and Law. Electronic journal. 2011. no. 1. Available at: http://eizvestia.isea.ru/reader/apple.aspx? id = 7528. (Accessed 05/10/2019) (in Russian).

[24] Zorina, T. Forming the strategy of sustainable energy development: monograph, Minsk: Misanta, 2016. 332 p. (in Russian).

[25] Official Statistics. National Statistical Committee of the Rep. Belarus. [On-line]. 1998 - 2019. Available at: http://www.belstat.gov.by/ofitsialnaya-statistika/. (Accessed 05/10/2019).

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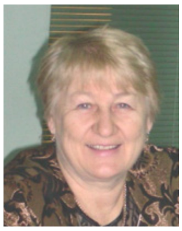

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Optimization Of The Algorithm For Finding Spanning Trees Of A Graph

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***Abstract* — The paper presents one of the possible variants of optimization of the algorithm for finding all spanning trees of the graph from the point of view of the application of the results of calculations in the topological study of complex electric power systems.**

The first stage of the topological analysis of the network is the search and determination of the values of all possible trees of the graph corresponding to a given energy system. The computational complexity of the algorithm for finding and determining the weights of all spanning graphs increases as the branches and nodes of the power grid network increase.

The main idea of optimization is to build special classes of trees. At the same time, in the process of grouping, parts of future graphs that are "parent" for groups of graphs are allocated and corresponding graphs of significantly smaller dimension are constructed. If the analysis is time-consuming, the grouping process can be applied to each graph found.

***Index Terms* — network topology, graph tree.**

I. Introduction

The need to construct all spanning trees of a given graph appears in many cases:

- when searching for an optimal tree in some sense, when the optimality criterion is so complex that the construction of an optimal tree at once is impracticable [1];
- when finding the transfer function of the system [2];
- in the topological analysis of current distribution coefficients in electric networks [3], etc.

The problem of finding all spanning trees of a graph is computationally time-consuming, since their number grows exponentially depending on the number of edges of the graph under study. Therefore, there is a need to improve the search algorithms for possible graph trees, in relation to the problems of the electric power industry. For example, to find the current distribution coefficients of electric networks, the ratio of the sum of the weights of specific trees to the sum of the weights of various trees of the graph is calculated [4]. In this case, the weight of a tree is understood as a complex product of the conductivities of its branches, taken with a sign, depending on the orientation of the branch.

In [5,6] an effective algorithm of directed search and determination of weights of possible graph trees without involvement of previously defined trees is implemented. The main idea of this algorithm is as follows. Let be a connected graph with n-nodes and m-branches. We produce a directed (excluding repetition) selection of n-1 branches from m - given. For each sample, we check for the presence of a cycle. In this case, the check is carried out from two sides, that is, from the first and last branches of the sample. If any subset of branches from the sample forms a loop, then all variants containing this subset are excluded from the search. This algorithm works successfully in the case of a weakly filled vertex neighborhood matrix (n≥0.8 m) [7]. With a more complete matrix of incidents, the execution time of the program increases many times.

In this paper, we propose an optimal algorithm for finding graph trees based on partitioning the entire set of trees, into disjoint classes, by considering several generated graphs instead of the original graph. These graphs are obtained from the original graph, by "removing" the nodes and branches selected in a certain way. The graphs obtained in this way have significantly fewer spanning trees, and from the latter, the spanning trees of the original graph are obtained by the inverse addition of "remote" branches and nodes.

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II. Optimization of the algorithm

Let be a graph with n-nodes and m-branches. The optimization process consists of several steps.

Step 1. Selection and "removal" of hanging branches with terminal vertices (nodes), as they are included in any spanning tree.

Step 2. Selecting and" gluing " paired branches, that is, branches that connect the same nodes. Since, in the end, when calculating the current distribution coefficients, only the products of the complex resistances of the branches are involved, the resistances of the paired branches simply add up.

Step 3. Let n_1– be the number of remaining nodes, m_1– be the number of remaining branches. We allocate a set of V-nodes incident to only two branches. Let R be the set of edges incident to the set of nodes V. Let the powers of these sets be |V| = α, |R|=β. It is obvious that α ≤2β.

Step 4. From the set R we choose those branches that are "repeated" twice. We also set the condition that the repeating branch is not part of a triangular cycle, although this case can be considered, if necessary, for further splitting the set of spanning trees into classes. There are cases when such repetitions go one by one, forming a chain of branches. In this case, select only one of these branches. Let $R_1 = \{r_{i,1}, r_{i,2} \dots r_{i,k}\}$ be a subset of the set R. Now, instead of the original graph, consider the graphs in which the specified branches $r_{(i,j)}, j = 1 \dots k$ of the set R_1 is either exactly there (denoted by $r_{(i,j)} = 1$), or exactly not (similarly denoted by $r_{(i,j)} = 0$). Obviously, there will be 2^k such graphs.

In the variant, where of k branches there are no *l*-branches and *k*-*l* branches there are, we will have 2^l hanging branches. And after applying step 1 to such a graph, we get a graph whose number of nodes is n^1-2^l-$(k$-$l)$ = n^1 - $(k+l)$ nodes, and the number of branches m_1-$3l$ - $(k$-$l)$ = m_1 - $(k+2l)$.

Step 5. If in some graph there is a branch $r_{(i,j)}$, which is incident to two nodes v_{j1}, v_{j2}, then instead of this graph, we can consider a graph, which instead of such two nodes will have one node, and the number of branches respectively decrease by one.

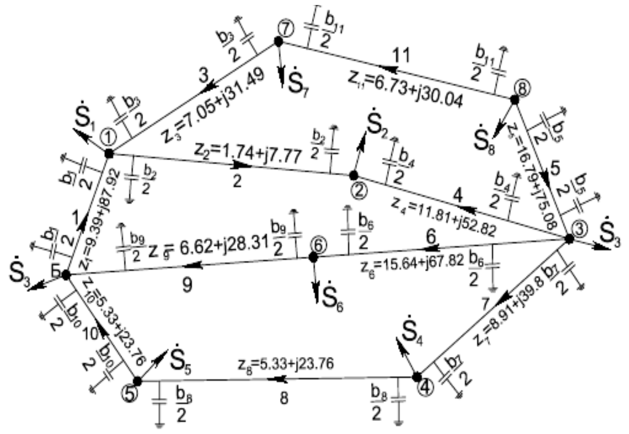

Fig. 1. Scheme of 220 kv network.

Table 1. A set of nodes incident to only two branches.

Nodes -v_i	2	4	5	6	7	8
1st branch $r_{1,i}$	2 (1)	7(3)	8(4)	6(3)	3(1)	11(7)
2nd branch $r_{2,i}$	4(3)	8(5)	10(9)	9(9)	11(8)	5(3)

As a result of constructing the subtrees of the graph with such steps we get:

1. Reducing the time spent on the study of such graphs.
2. The possibility of parallelization of the calculations of the graphs.
3. All "deleted" branches are necessarily included in the spanning tree of the original graph.
4. Adding "deleted" branches back to the spanning trees is necessary to find possible trees of the original graph.
5. The set of spanning trees corresponding to the graphs in question do not intersect and their Union yields all possible trees of the original graph.

III. An example application of the optimization process

Let's describe the optimization process on the example of the scheme (Fig. 1), is given in [7].

In this work the number of possible trees equal to 85 is obtained. In this scheme, the number of nodes n = 9, the number of branches m = 11.

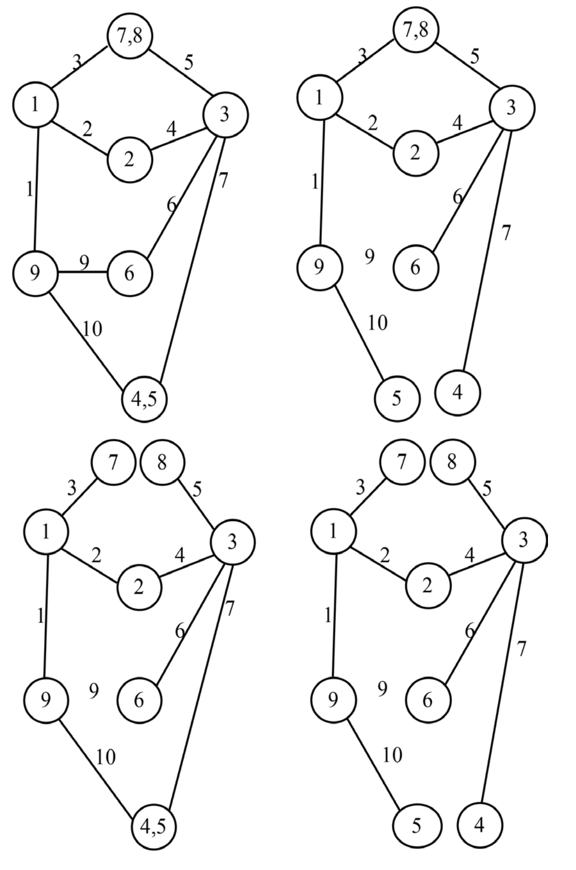

Fig. 2. Splitting the original graph into 4 graphs.

Step 1. In the scheme under consideration there are no hanging branches with terminal vertices (nodes).

Step 2. In the scheme under consideration, there are no branches linking the same nodes.

Step 3. In the scheme under consideration, $n_1 = n = 9$, $m_1 = m = 11$. For the considered scheme we have the following data given in table. 1.

The nodes associated with this branch are indicated in parentheses.

Step 4. From the set R we choose those branches that are "repeated" twice. In the above table. 1 these are branches 8 and 11. In our case $k = 2$. Thus, the original graph corresponding to the scheme shown in Fig. 1, is divided into 4 graphs (fig. 2).

In the first graph, instead of two pairs of nodes 4-5 and 7-8, there will be two nodes. Thus, the number of nodes and the number of edges will decrease by two, compared to the original graph. In the second graph, instead of a pair of nodes 4-5, there will be one node, and the 11th branch will not be, since branches 3 and 5 will become "hanging". In the third column, instead of a pair of nodes 7-8, there will be one node, and the 8th branch will not be, since branches 7 and 10 will become "hanging". In the second and third graphs, after applying step 1, the number of nodes will decrease by three, and the number of branches will decrease by 4 compared to the original graph. In the fourth graph, the graph removes branches 8 and 11, resulting in 4 hanging branches. Thus, after applying step 1, the number of nodes will decrease by 4, and the number of branches by 6 compared to the original graph.

If we calculate the number of possible spanning trees of the original graph by a known method, we get a number equal to 85. And the distribution of the number of spanning trees in the resulting four graphs will be as follows: 1 graph-48, 2 and 3 graphs - 16, the 4th graph has only 5 spanning graphs.

Similar calculations for the test 14-node scheme (IEEE) yield the following results: only one Union of nodes 10 and 11, with branch 18, is Possible. The number of trees with Union is 2182, without this branch 927. In sum, we get the known number 3909. It should be noted that, if on a simple laptop Intel Core I3-6006UCPU @ 2.00 GHZ 1.99 GHz And 4.00 GB of RAM to calculate the number of branches of the original graph 14-node scheme took 1438 milliseconds, the split for the first class took 432 milliseconds, and the second subclass 97 milliseconds.

The efficiency of this partition will be significantly manifested when considering schemes with more connected graphs. In particular, if we consider the test IEEE 30-node scheme with 41 branches, which has 7 824 000 spanning trees. If you consider that each tree has 29 branches, you need to remember the database of 453 792 000 at least two-digit numbers, and 900 times to search for the desired branches, to calculate the current distribution coefficients. Firstly, it will require large machine-time resources, and secondly, the rounding error will accumulate.

However, many trees have significant identical parts, respectively, the contribution of these parts in the calculation of current distribution coefficients is also the same, these contributions are simply summed. Therefore, the same parts can be placed outside the brackets, which significantly reduces the required number of calculations.

When splitting, parts of future trees are immediately allocated, so in the remaining parts, which are a graph with a smaller dimension, the number of search options is significantly reduced.

Note that for the specified IEEE test 30-node scheme, in which the number of possible spanning trees is 7 824 000, $k = 4$. That is, the set is divided into 16 classes. In the largest class there are 2,500,749 trees, that is 31.9% of the total number of graphs. In this case, the number of nodes of the resulting graph is 23, and the number of branches is 34. And in the most recent small class, the graph has 18 nodes and 25 branches, the number of spanning trees is 25,191 (0.3% of the total number of trees).

IV. Conclusion

1. The optimal algorithm search all possible spanning trees of a given graph based on the partitioning of many kinds of trees on disjoint classes, while additional branches of the spanning tree.

2. It is shown that such a partition significantly reduces the required number of calculations.

3. As a result of the proposed partition, the tasks are divided into several subtasks, each of which can be calculated in parallel and independently of each other.

4. Optimization efficiency is found to be essential for schemes with more filled connections.

References

[1] Christofides N. Graph Theory. Algorithmic approach. M .: Mir, 1978, - 432 p.20.

[2] Mayeda W. Graph Theory. Wiley- *Interscience*, New York, 1972.

[3] Geraskin O.T. Topological content of nodes and circuits of the electrical network and the calculation of their size with the help of a digital computer, Izvestia ANSSR. Energy and transport, 1966. №2. - pp. 59-70, (in Russian.)

[4] David Avis, Komei Fukuda. Reverse search for enumeration. *Discrete applied mathematics* 65, pp. 21-46, 1996.

[5] Akhmetbayev D.S., Aubakir D.A., Sarsikeyev Y.Zh., Bainiyazov B.A., Surkov M.A., Rozhkov V., Ansabekova G.N., Yerbolova A.S., Suleimenov A.T., Tokasheva M.S. Development of Topological Method for Calculating Current Distribution Coefficients, *Complex Power, Networks, Results in Physics*, vol. 7, pp. 1644–1649, 2017.

[6] A. R. Dzhandigulov, D. S. Akhmetbaev Finding all spanning graphs of a given graph. computer program, 2019.

[7] Akhmetbayev D., Dzhandigulov A. Development of algorithms for a new topological method for calculating current distribution coefficients in complex electrical networks, *Eurasian Journal of Mathematical and Computer Applications,* ISSN 2306–6172 Vol. 7, Issue 3, pp. 4–12, 2019.