Energy Systems Research

Volume 5 · Number 2 · 2022

Published by
Melentiev Energy Systems Institute
Siberian Branch of Russian Academy of Sciences

Available online: esrj.ru

ISSN 2618-9992

Energy Systems Research

Volume 5 • Number 2 • 2022
International scientific peer-reviewed journal
Available online: http://esrj.ru

About the journal

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.

The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

Energy Systems Research is also concerned with energy systems challenges related to the applications of information and communication technologies, including intelligent control and cyber security, modern approaches of systems analysis, modeling, forecasting, numerical computations and optimization.

The journal is published by Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences. The journal's ISSN is 2618-9992. There are 4 issues per year (special issues are available). All articles are available online on English as Open access articles.

Topics

- Energy production, conversion, transport and distribution systems
- Integrated energy systems
- Energy technologies
- International, regional, local energy systems
- Energy system protection, control and management
- Smart energy systems, smart grids
- Energy systems reliability and energy security
- Electricity, heating, cooling, gas and oil systems
- Energy system development and operation
- Demand-side management
- Energy economics and policy
- Renewable energy and clean fossil fuel based systems
- Distributed energy systems
- Sustainable energy transitions
- System problems of power and thermal engineering
- Artificial intelligence in energy systems
- Information and communication technologies in energy systems
- Energy systems analysis and modelling
- Computational methods and optimization in energy systems

Contacts

Scientific secretary:	Alexey Mikheev, Dr. of Eng.
E-mail:	info@esrj.ru
Tel:	+7 (3952) 950980 (English, Russian)
Fax:	+7 (3952) 426796
Address:	130, Lermontov str., Irkutsk, 664033, Russia

Contents

Electricity Cooperation Between Russia and Mongolia: From Bilateral Collaboration to Participation in the Northeast Asia Power System Interconnection

S.V. Podkovalnikov*

Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract — **The paper discusses the development of electricity cooperation between Russia and Mongolia. Historically, bilateral Russian-Mongolian electricity cooperation has developed along two lines. As part of the first direction, Russia designed and supplied equipment, built, and provided loans for the construction and reconstruction of electric power facilities in Mongolia. The second direction involved cross-border trade in electricity and power. To arrange bilateral electricity cooperation, the necessary regulatory framework was established in the form of cooperation agreements between government agencies and energy companies of Russia and Mongolia. The Russian-Mongolian Intergovernmental Commission acts as a kind of catalyst for the signing of these agreements and ensures contacts between the interacting parties. In the future, with the establishment of the cross-border power system interconnection in Northeast Asia and the creation of new cross-border power grid infrastructure, bilateral Russian-Mongolian contacts will be taken to the next level and grow into multilateral regional electricity cooperation within the framework of the said power interconnection. According to the optimization calculations performed in this research, the role of Mongolia as a supplier of renewable energy to the regional cross-border electricity market will increase, and electricity trading between Mongolia and Russia, Mongolia and China, and Russia and China (through Mongolia) will be dramatically strengthened for the mutual benefit of all countries within the cross-border power system interconnection.**

Index Terms: **Electricity cooperation, cross-border interconnectors and power system interconnections, electric power, capacity, agreements, expansion prospects.**

I. Introduction

Bilateral electricity cooperation between Russia and Mongolia has a long history. During the Soviet period, the USSR actively participated in the creation of Mongolia's electric power industry at the stages of designing, supplying equipment, and constructing power generation and grid facilities. The central power system (CPS) of Mongolia has been connected for parallel operation to the Interconnected Power System (IPS) of Siberia and, through it, to the Unified Energy System (UES) of the USSR since as early as the 1970s. Cross-border Soviet-Mongolian interconnectors ensured the trade in electric power and energy, improvement in the operation of power equipment, an enhancement in the efficiency of the power systems, and the power supply reliability. In the post-Soviet period, Russian-Mongolian electricity cooperation continued along the above lines.

In the future, a cross-border power system interconnection (CBPSI) is expected to be established in Northeast Asia (NEA), with Russia and Mongolia as its participants. In this regard, bilateral electricity cooperation between these countries will be transformed into multilateral one within the framework of this CBPSI. At the same time, bilateral cooperation is taken to the next level with the intensification of trade in power and electricity, using the new cross-border power grid infrastructure to be created within the framework of the Northeast Asia Power System Interconnection (NAPSI). In what follows, the issues of cross-border Russian-Mongolian electricity cooperation will be discussed in more detail.

II. Bilateral electricity cooperation

Mongolia's electric power industry was created with the active support on the part of the USSR. As a case in point,

* Corresponding author.
E-mail: spodkovalnikov@isem.irk.ru

http://dx.doi.org/10.38028/esr.2022.02.0001
Received July 05, 2022. Revised July 13, 2022.
Accepted July 28, 2022. Available online August 31, 2022.

Table 1. Electricity trading between Russia and Mongolia, GWh.

	2010	2015	2019	2020	2021
Russia–Mongolia	214	263	372	312	487
Mongolia–Russia	21	21	27	4	23

in the 1950s and 1980s, seven coal-fired thermal power plants were built there with the predominant participation of Soviet experts: four plants in Ulaanbaatar and one plant in each of the following settlements: Darkhan, Erdenet, and Choibalsan. Today, these plants, the so-called combined heat and power (CHP) plants, which generate electricity and heat, are the basis of Mongolia's centralized energy supply. They produce up to 4/5 of the country's electricity [1].

At present, as part of bilateral cooperation, Russia continues to deliver power equipment, participate in the modernization of power plants in Mongolia, and provides funding for them. For example, the modernization of Ulaanbaatar CHPP-4 was completed in 2021 [2]. The cost of the project exceeded $160 million, with funding provided in part by VEB RF [3]. The Ural Turbine Works designed and manufactured the turbines. ELSIB Research and Production Association supplied three new generators with increased capacity. The new plant units have a lifespan of at least 40 years, during which time each of the turbines will save up to $19.5 million in fuel costs annually, producing 10% fewer air emissions than the old equipment. The efficiency of the new machines increased by 9%, and their maneuverability increased by 40% [4]. As a result of the modernization, the installed capacity of CHPP-4 increased from 540 MW to 752 MW [3].

At present, the Russian energy company InterRAO-Export is developing a feasibility study for the modernization of CHPP-3 in Ulan Bator [5]. The modernization project will be financed through the Russian export credit. The modernization of CHPP-3 will improve the reliability of heat and electricity supply to the capital of Mongolia.

Electricity trading between Mongolia and Russia is an important strand of electricity cooperation between these countries. Table 1 shows the volume of electricity trading since 2010.

As seen in the Table, electricity exports from Russia exceed the transmission of electricity from Mongolia to Russia. This is due to the fact that the transmission from Mongolia is of a flow-based nature when the Mongolian base-load and low-maneuverable thermal power plants are not unloaded during the dips in daily load profiles but deliver electricity to Russia (IPS Siberia). IPS Siberia, with its considerable flexibility due to the large maneuverable hydropower capacities has the ability to reduce and redistribute the load at its power plants by receiving the flow from Mongolia. The presented scheme of interaction between the Mongolian power system and IPS Siberia is actually a description of the manifestation of the system-wide power flow effect that occurs when power systems are integrated.

Figure 1 shows the 110 kV and 220 kV tie lines between Russia and Mongolia. Work is constantly underway to modernize these interconnectors. For example, in 2015, the Russian party replaced current transformers at the 220 kV Selenduma substation of IDGC (Interregional Distribution Grid Company) of Siberia, a subsidiary of PJSC Rosseti, which made it possible to increase the maximum allowable power flow in the controlled section «Selenduma–Darkhan» from 175 MW to 245 MW. This substation is part of the 220 kV transit system that provides parallel operation of the Mongolian energy system with the UES of Russia.

In 2022, emergency control systems were put into operation at the Selenduma 220 kV substation. At the same time, the transfer capability of the grid transit line, which is used for exporting power to the Mongolian power system, increased by 100 MW to 345 MW.

Bilateral Russian-Mongolian cooperation is backed by a solid organizational and regulatory basis. There is a Russian-Mongolian intergovernmental commission on trade and economic, as well as scientific and technological cooperation, which ensures close contacts between Russian and Mongolian government agencies and power companies. These contacts are backed by various kinds of agreements. Figure 2 shows the Russian-Mongolian agreements over the past decade and beyond that have shaped the legal framework for electricity cooperation. As can be seen, these agreements are made both between government agencies and between energy companies.

The above agreements focus on the issues of power grid construction, implementation of joint projects for reconstruction and modernization of electric power facilities, construction of electric power generation facilities, including highly maneuverable regulating capacities and renewable energy sources in the Russian Federation and Mongolia. Within the framework of these agreements, the parties shall assist the economic entities of the party countries in amending or prolonging the documents, which, in particular, concerns the agreement on technical support for parallel operation, the organization of information exchange, and on the organization of metering of power flows through cross-border power lines.

It is important to note that the bilateral Russian-Mongolian electricity cooperation discussed above actually lays the foundation for multilateral cooperation in Northeast Asia. In particular, the 2019 Agreement between the Government of the Russian Federation and

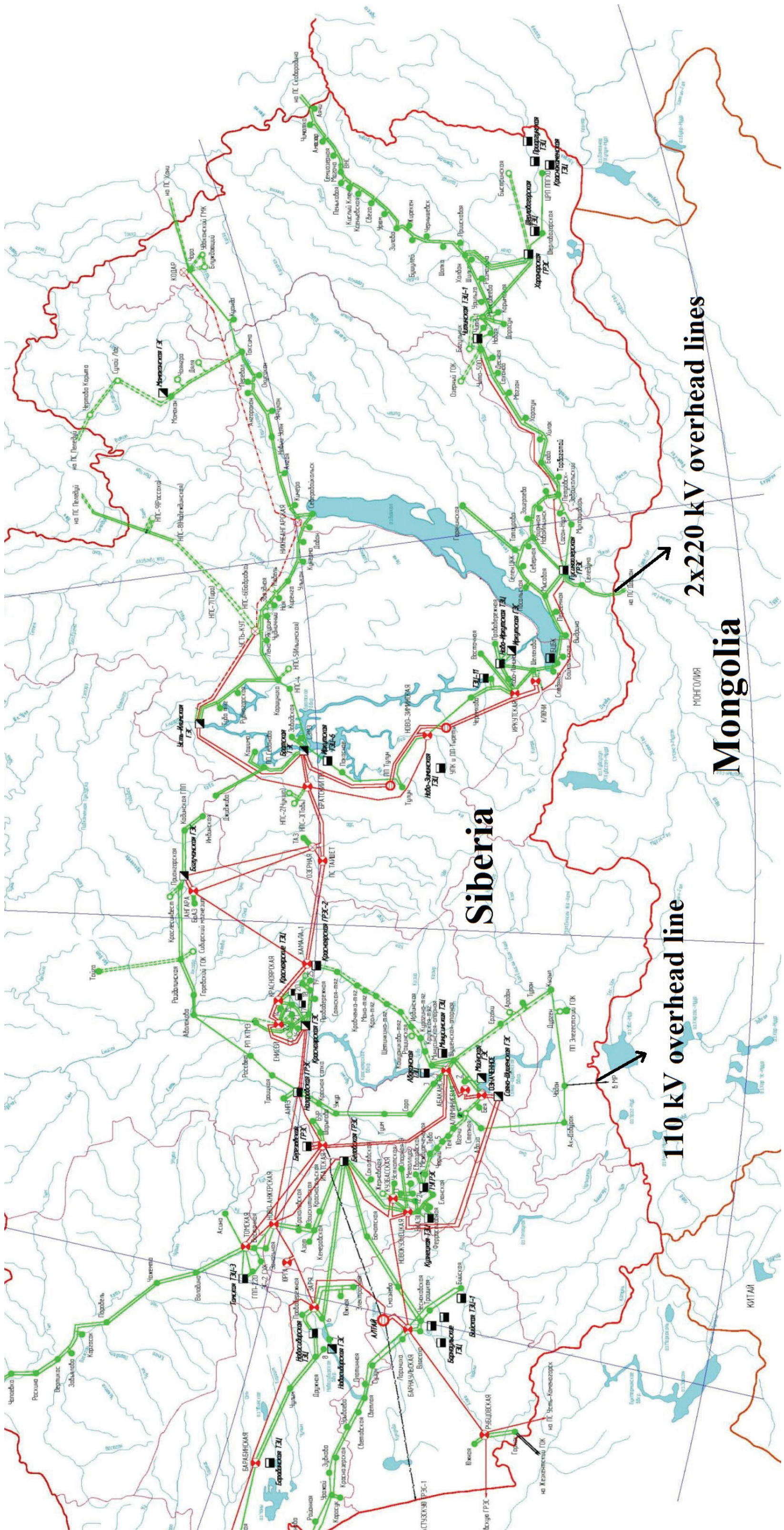


Fig. 1. Russia-Mongolia interconnectors.

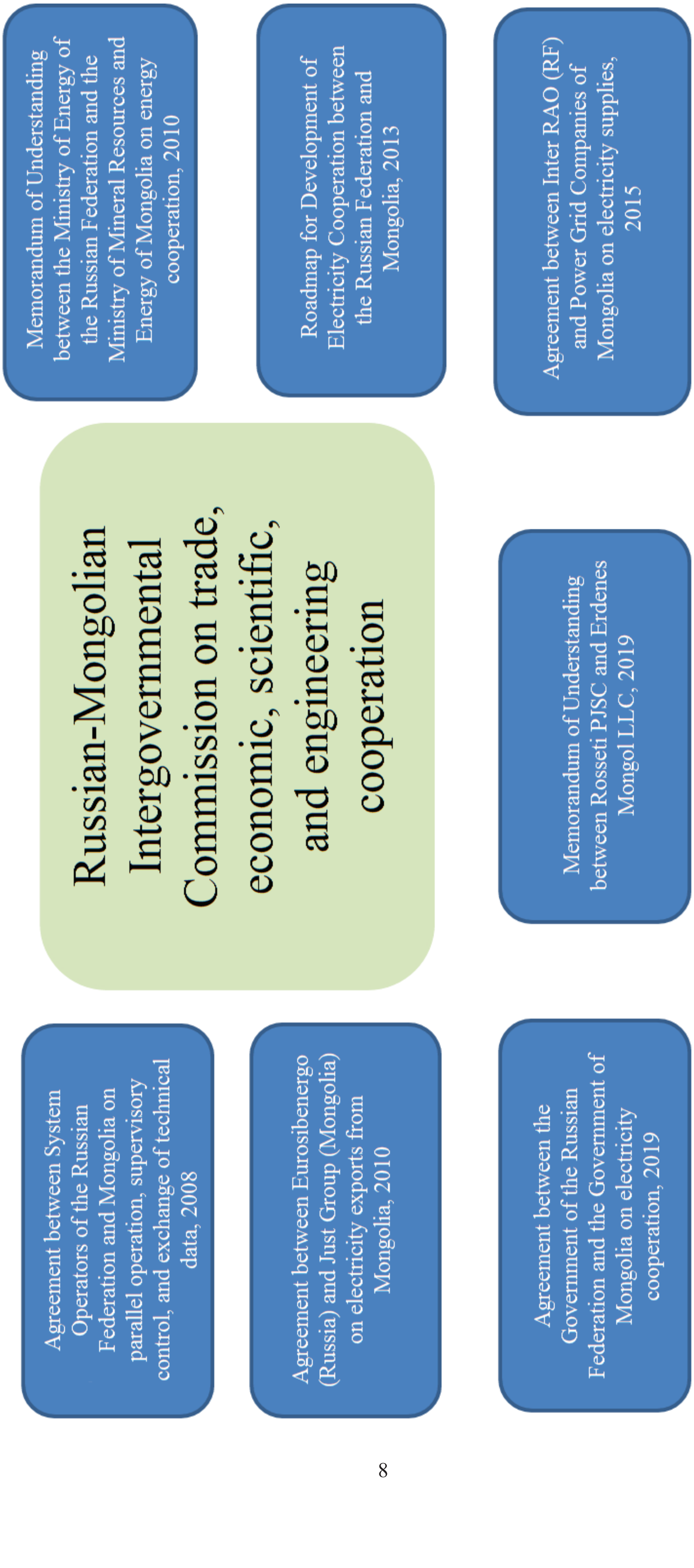


Fig. 2. Organizational and regulatory system of bilateral Russian-Mongolian electricity cooperation.

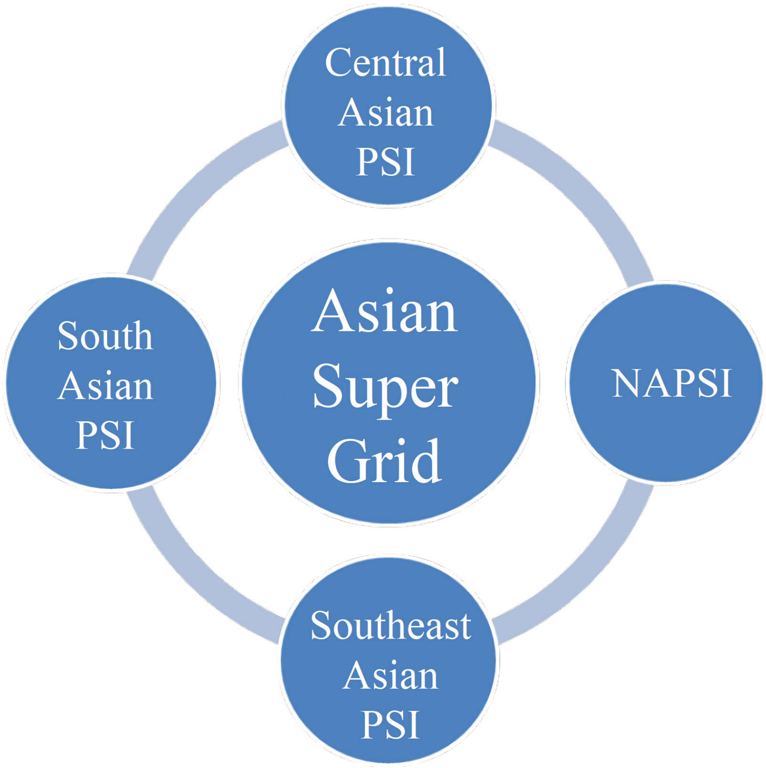


Fig. 3. Establishment of the Asian Super Grid.

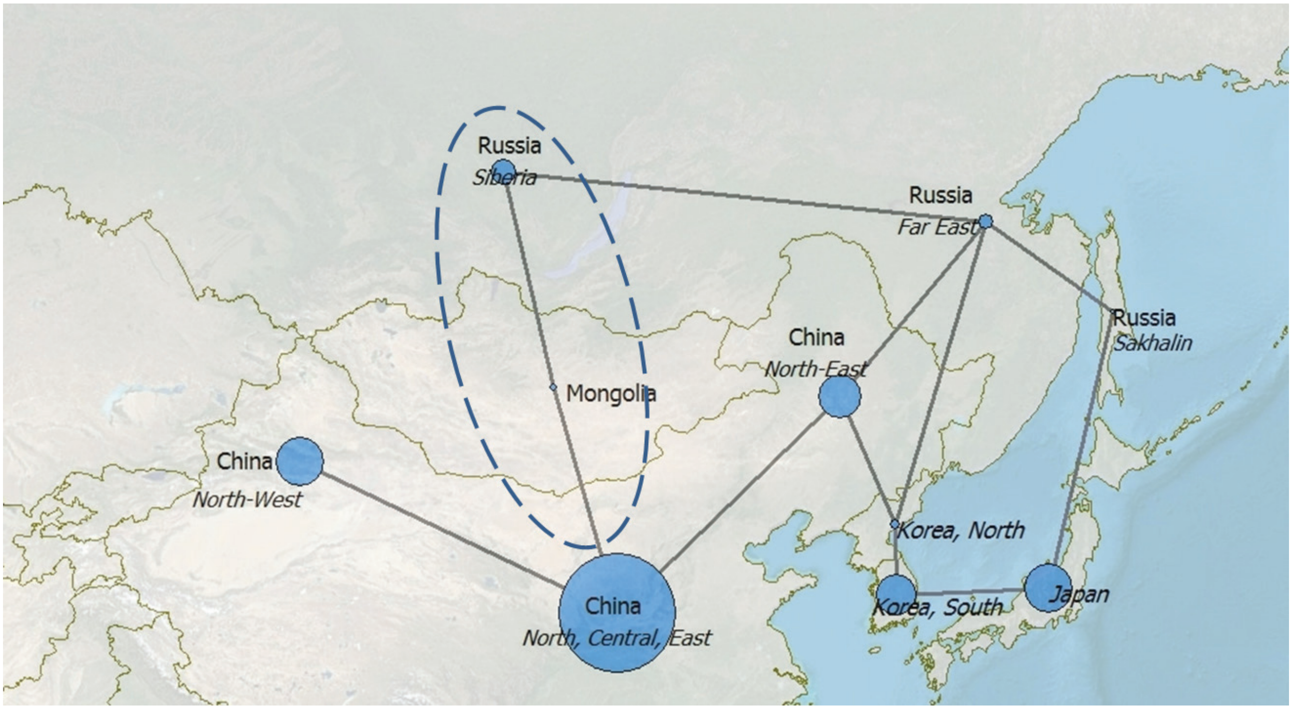


Fig. 4. Diagram of PSI in NEA.

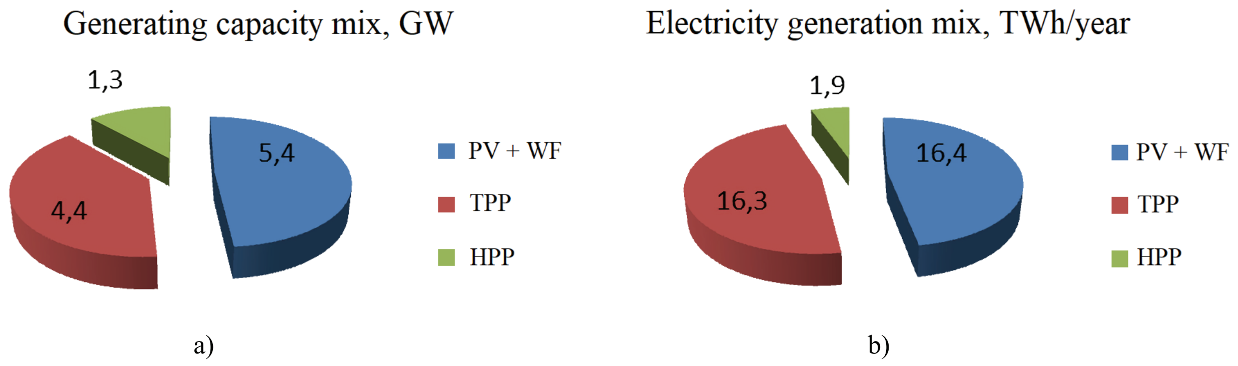


Fig. 5. Installed capacity (a), electric energy generation (b) by Mongolia, 2040, CO_2 tax = $90/t.

the Government of Mongolia on electricity cooperation notes the implementation of joint projects in electric power generation, electricity export/import to/from Mongolia, expansion planning for power grid facilities of Mongolia, including those used for the electricity transit to other countries. The document also suggests assessing the feasibility of a unified market of electric energy and power within the Russian Federation and Mongolia, and specifically as part of the integration of energy markets in Northeast Asia, etc. The 2019 Memorandum of Understanding between PJSC Rosseti and Erdenes Mongol LLC was signed for the purpose of long-term mutually beneficial cooperation in the research and development of integration links of power systems in Northeast Asia, including necessary priority measures to strengthen and improve the reliability of the power system and develop the electric power infrastructure of Mongolia. The memorandum noted that the parties agreed to form a joint working group to develop a common roadmap for the regional integration of NEA electricity markets, taking into account the modernized power system of Mongolia, conduct joint research, and conduct a feasibility study for the construction of new cross-border power lines.

III. Multilateral electricity cooperation

The conditions for multilateral electricity cooperation in Northeast Asia are currently being created. This is primarily due to the fact that the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) decided to support and promote the megaproject of an Asia Super Grid, including the CBPSI in NEA (Fig. 3).

The establishment of such a power system interconnection in the Asian region would contribute to the achievement of sustainable development goals, including carbon neutrality. In 2017, the UNESCAP established a working group on energy connectivity. This group participated in the development of a Regional Electricity Connectivity Roadmap, with strategies designed to promote cross-border interconnectors for sustainable development [6], and is currently involved in preparing a Regional Trends Report.

Studies on the NAPSI, carried out at the Melentiev ESI SB RAS [7, 8], show the technological and economic feasibility of this cross-border power system interconnection made up of six countries of the region, including Russia and Mongolia. With this interconnection, tie lines between the latter get substantially strengthened, and trading of electricity and power increases dramatically compared to the current bilateral Russian-Mongolian electricity cooperation.

Figure 4 shows a diagram of the prospective multilateral CBPSI.

It is assumed that with a multilateral CBPSI established in NEA, Mongolia will actively develop the Gobitek project based on renewable energy sources [9], which is of international importance. Its output will be transmitted to power grids in neighboring countries and will also be partially used locally to supply power to Mongolian consumers.

Below are some results of research on Russian-Mongolian electricity cooperation within the framework of the NAPSI, based on research presented in [8]. The input data and assumptions adopted were described in [8] and therefore are not given here. It is worth noting that a tax on CO_2 emissions was used to incentivize the introduction of renewable energy sources (RES) [10, 11]. The tax was assumed to be $90/ton of CO_2 emissions in order to assess the potential for the introduction of renewable energy sources in the power systems of the countries under consideration. The year 2040 was taken as the baseline year of the calculations.

Figure 5 shows the mix of installed capacity and electric energy generation in Mongolia provided this tax is introduced for the considered time frame. As can be seen, the share of RES, including only wind farms (WF) and solar photovoltaic power plants (PV), in the mix of generating capacity is about 49%, and its share in electricity generation slightly decreases, and amounts to about 47%. If conventional hydro power plants are added to wind farms and photovoltaic power plants, the share of all renewable energy sources in Mongolia will be 60% in terms of installed capacity and about 53% in terms of electricity generation.

The amounts of power, including those generated from

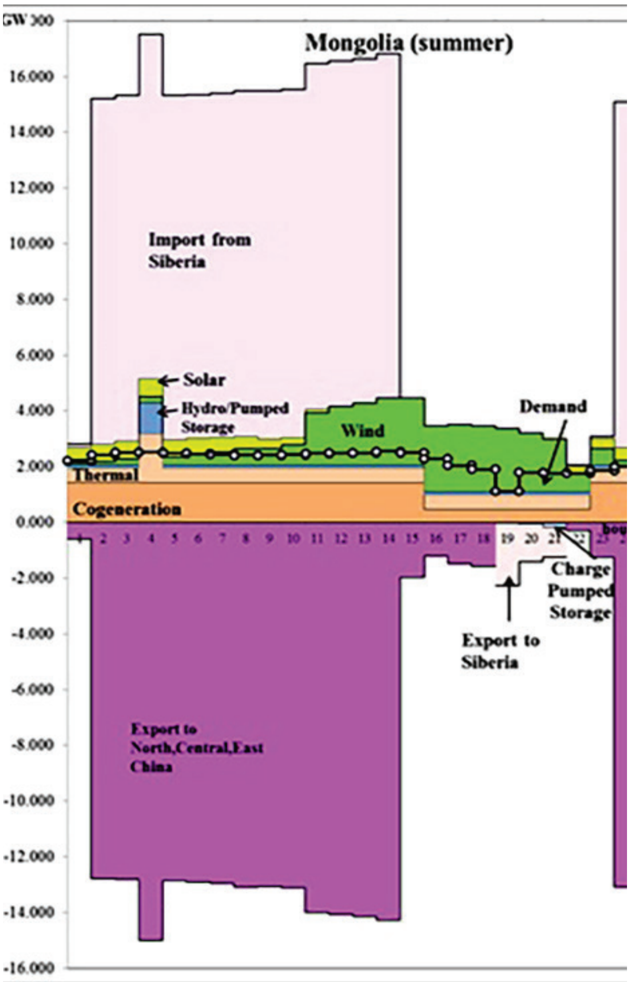


Fig. 6. Daily summer operating mode of Mongolia's power system, 2040, CO_2 tax = $90/t.

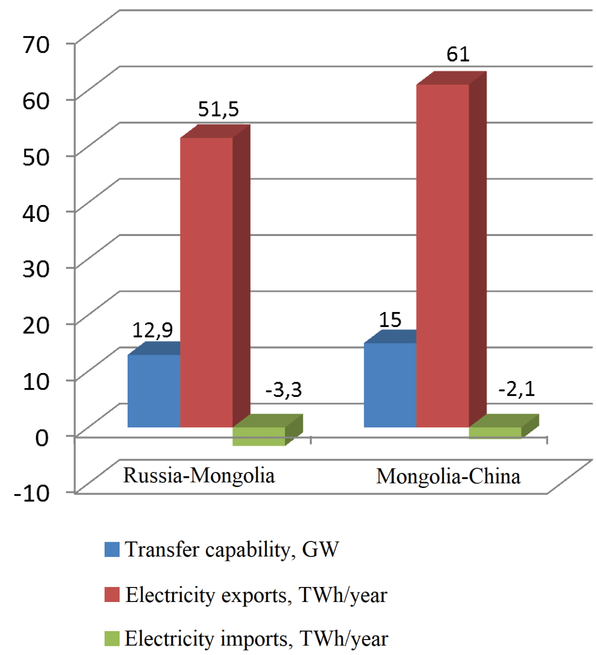


Fig. 7. Development of Russia-Mongolia interconnectors when forming a CBPSI in NEA, 2040, CO_2 tax = $90/ton.

wind and solar installations (Fig. 5) added as part of the Gobitek project, exceed the needs of Mongolia and are exported to electricity markets of neighboring countries, including Russia. These amounts were obtained by optimization calculations for the entire NAPSI for the time frame in question, and, accordingly, are optimal from the perspective of the entire power system interconnection.

Figure 6 shows the daily summer operating mode of Mongolia's power system. It also indicates electricity trading with neighboring power systems, including Russia (Siberia). As already noted, significant amounts of electricity are transmitted outside Mongolia, in particular, to Russia. A significant amount of Mongolia's energy imports come from Russia, and then this energy transits through Mongolia to China. The transfer capability of the Siberia-Mongolia interconnector in this case is about 13 GW, and that of the Mongolia-China section reaches 15 GW (see Fig. 7).

Apart from the transfer capabilities of cross-border interconnectors, Figure 7 shows the annual electricity trading between Russia and Mongolia and between Mongolia and China. Just as in the daily profile (see Fig. 6), on an annual basis (see Fig. 7), Mongolia, transmitting electricity abroad, is mainly a transit country through which energy is transmitted from Russia to China. It should be noted that the indicated diagram of flows was obtained by the optimization model considering the $90/ton tax on CO_2 emissions.

IV. Conclusion

Currently, there is active bilateral electricity cooperation between Russia and Mongolia, which is not limited to electricity trade, but also includes the participation of Russia in the design, construction, supply of power generating and electrical machinery, and financing of projects for expansion of electric power facilities in Mongolia. An appropriate regulatory and organizational infrastructure is in place to ensure such cooperation.

In the future, if the CBPSI is established in NEA, and Russia and Mongolia join it, electricity cooperation between these countries will be taken to the next (higher) level. The creation of a powerful grid infrastructure within the NAPSI will significantly strengthen interconnectors between Russia and Mongolia and increase electric energy and power trading, in particular for the more comprehensive use of highly variable and poorly predictable renewable energy sources, specifically those planned to be commissioned as part of the Gobitek project. Interconnectors with other countries will also be strengthened. Accordingly, the integration effects of the joint operation of the power systems of these countries, both bilaterally and multilaterally, will increase. All this will make a significant contribution to sustainable development and the achievement of carbon neutrality by Russia and Mongolia in the long term.

Acknowledgements

The research was carried out under a state assignment (No. FWEU-2021-0001) of the Program for Basic Research of the Russian Federation for 2021–2030 and made use of the resources of the «High-Temperature Circuit» shared research facilities center (Ministry of Education and Science of Russia, project No. 13.CKP.21.0038).

References

[1] Capacity upgrade of coal-fired CHPP-4 in Ulaanbaatar, *Energybase.ru*. Available: https://energybase.ru/news/articles/upgrading-capacity-of-coal-fired-chpp-4-in-ulaanbaatar-2021-01-14. Accessed on: Jul. 22, 2022. (In Russian)

[2] ROTEK Holding completes modernization of the largest power plant in Mongolia, *Energy News*. Available: https://novostienergetiki.ru/xolding-rotek-zavershil-modernizaciyu-krupnejshej-elektrostancii-mongolii/. Accessed on: Jul. 22, 2022. (In Russian)

[3] Inter RAO and Rotec's project to build a CHPP in Ulaanbaatar was submitted to the intergovernmental commission, *Peretok.ru. Energy in Russia and the World*. Available: https://peretok.ru/news/engineering/22705/. Accessed on: Jul. 22, 2022. (In Russian)

[4] "Rotec" completes modernization of the largest CHPP, *Peretok.ru. Energy in Russia and the World*. Available: https://peretok.ru/news/trading/23068/. Accessed on: Jul. 22, 2022. (In Russian)

[5] "Inter RAO – Export" will complete the feasibility study for the modernization of CHPP-3 in Mongolia in Q2 2022, *Energybase.ru*. Available: https://energybase.ru/news/industry/inter-rao-export-will-complete-validity-study-of-chp-3-modernization-2021-11-26. Accessed on: Jul. 22, 2022. (In Russian)

[6] *Electricity Connectivity Roadmap for Asia and the Pacific: Strategies towards interconnecting the region's grids*. Bangkok, Thailand: United Nations publication, Sales No. E.20.II.F.9, 2019, 84 p.

[7] S. V. Podkovalnikov, V. A. Savelyev, L. Yu. Chudinova, "Study of the system-wide energy and economic feasibility of forming the Northeast Asia Power System Interconnection," *Izvestiya RAN. Energetika*, no. 5, pp.16–32, 2015. (In Russian)

[8] S. Podkovalnikov, L. Chudinova, I. Trofimov, L. Trofimov, "Structural and Operating Features of the Creation of an Interstate Electric Power Interconnection in North-East Asia with Large-Scale Penetration of Renewables," *Energies*, vol. 15, iss. 10, pp. 3647–3675, 2022. DOI: 10.3390/en15103647.

[9] S. Mano, B. Ovgor, Z. Samadov, M. Publik, V. Julch, D. A. Sokolov, J. Yoon, *Gobitec and Asian super grid for renewable energies in Northeast Asia*. Sofia, Bulgaria: Spotinov print Ltd, 2014, 110 p. Available: https://www.renewable-ei.org/en/images/pdf/20140124/Gobitec_and_ASG_report_ENG_BOOK.pdf. Accessed on: Jul. 22, 2022.

[10] *World Bank Group. State and Trends of Carbon Pricing 2019*. Washington, Washington DC, USA: World Bank, 2019. DOI: 10.1596/978-1-4648-1435-8. Available: http://documents1.worldbank.org/curated/en/191801559846379845/pdf/State-and-Trends-of-Carbon-Pricing-2019.pdf. Accessed on: Jul. 22, 2022.

[11] P. Luckow, E. Stanton, B. Biewald, S. Fields, S. Jackson, J. Fisher, R. Wilson, *Spring 2016 National Carbon Dioxide Price Forecast*. Cambridge, Massachusetts, USA: Synapse Energy Economics, Inc., 2016, 38 p. Available: http://www.synapse-energy.com/sites/default/files/2016-Synapse-CO2-Price-Forecast-66-008.pdf. Accessed on: Jul. 22, 2022.

S.V. Podkovalnikov, D. Eng., Deputy Director and Head of Electric Power Systems Department, Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences. His research interests include methods for providing rationales for decisions in the energy sector under uncertainty and multiple criteria, cross-border interconnectors and interconnected power systems, expansion planning of the electric power industry in the market environment, modeling of electric power systems. He is the author and co-author of more than 200 research contributions.

Prospective Markets for Russian and Mongolian Energy Resources in the Region of North-East Asia

S.P. Popov, B.G. Saneev, D.V. Maksakova*, O.A. Baldynov

Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper shows the importance of East Asian countries for energy export from Russia and Mongolia. Groups of factors that affect the development of the global and regional energy the most and are considered in the long-term forecast of energy consumption are identified. The high-tech energy development scenario built by the Institute of Energy Economics of Japan in 2021 for China and Japan is analyzed. The scenario assumes a decrease in energy consumption in Japan and its stagnation in China. This effect is to be achieved by enhancing energy efficiency and restructuring energy consumption. Both countries will reduce coal and oil consumption, but increase the share of nuclear and renewable energy. Japan will also cut down the consumption of natural gas. The paper concludes that, given the limited resource potential in China and the "island" economies of East Asia, even in the context of a forced energy transition, there will remain favorable prospects for the export of traditional energy sources from Russia and Mongolia to these markets.**

***Index Terms*: Northeast Asia, energy forecast, energy transition, energy cooperation.**

I. Introduction

The energy resource exports are and will bSe of great importance for the development of the energy sector in Russia and Mongolia in the coming decades [1, 2]. The availability of significant resources of both traditional and renewable energy and the proximity to the world's largest energy importers (the countries of East Asia (EA)) indicate the need for a systematic update of assessments of opportunities for the development of energy cooperation in Northeast Asia (NEA – The economies of East Asia include China (with Hong Kong), Japan, Republic of Korea (R.Korea), Chinese province Taiwan, Democratic People's Republic of Korea (hereafter DPRK), and Mongolia. The economies (countries) of East Asia together with Russia constitute North-East Asia (NEA). The island economies of NEA include Japan, R.Korea, and Chinese province Taiwan.). The region has a traditionally high potential for cooperation in the trade in primary non-renewable energy resources (coal, oil, natural gas, uranium, hereafter NRER), the expansion of the relevant infrastructure, and for cooperation in the field of renewable energy [3–5] and hydrogen technologies [6, 7].

Table 1 presents several indicators that characterize the importance of the energy consumption in the EA countries for the world energy trade. China, Japan, R. Korea and Taiwan account for almost a third of world energy consumption, and their demand for NRER imports makes up a significant part of demand in the respective world markets.

For Russia and Mongolia, as the most important NRER exporters, these countries represent the most promising export market since their dependence on NRER imports in physical terms is 90–95%, see Fig. 1.

Further, we will consider three groups of NEA countries – China, island economies (Japan, R. Korea and Taiwan (or JKT)), Russia and Mongolia. The prospects for the energy development in the DPRK and its participation in the regional energy markets are not considered due to the significant uncertainty about the development of this country.

China's energy balance is characterized by the predominance of coal in primary energy consumption and an increasing dependence on oil and gas imports, while the country is self-sufficient in domestic fuel for nuclear power plants, has uranium enrichment technologies and capacities, and has achieved world-class competencies in the field of nuclear energy and renewable energy. Despite the lower level of dependence on energy imports in general compared to the JKT group, the most economically developed coastal provinces of China are energy deficient almost to the same extent as the second group of countries in the region (JKT), and generally follow the directions set

* Corresponding author.
E-mail: maksakova@isem.irk.ru

http://dx.doi.org/10.38028/esr.2022.02.0002
Received June 25, 2022. Revised July 10, 2022.
Accepted July 29, 2022. Available online August 31, 2022.

Table 1. Importance of East Asian countries in the global energy sector in 2020, percent.

Indices	Total: China, Japan, R. Korea, Taiwan	Including China
Share in total energy consumption	32	26
Share in oil imports	39	25
Share in gas imports	43	17
Share in coal imports	49	17
Solar and wind power generation	30	27

Source: [8, 9].

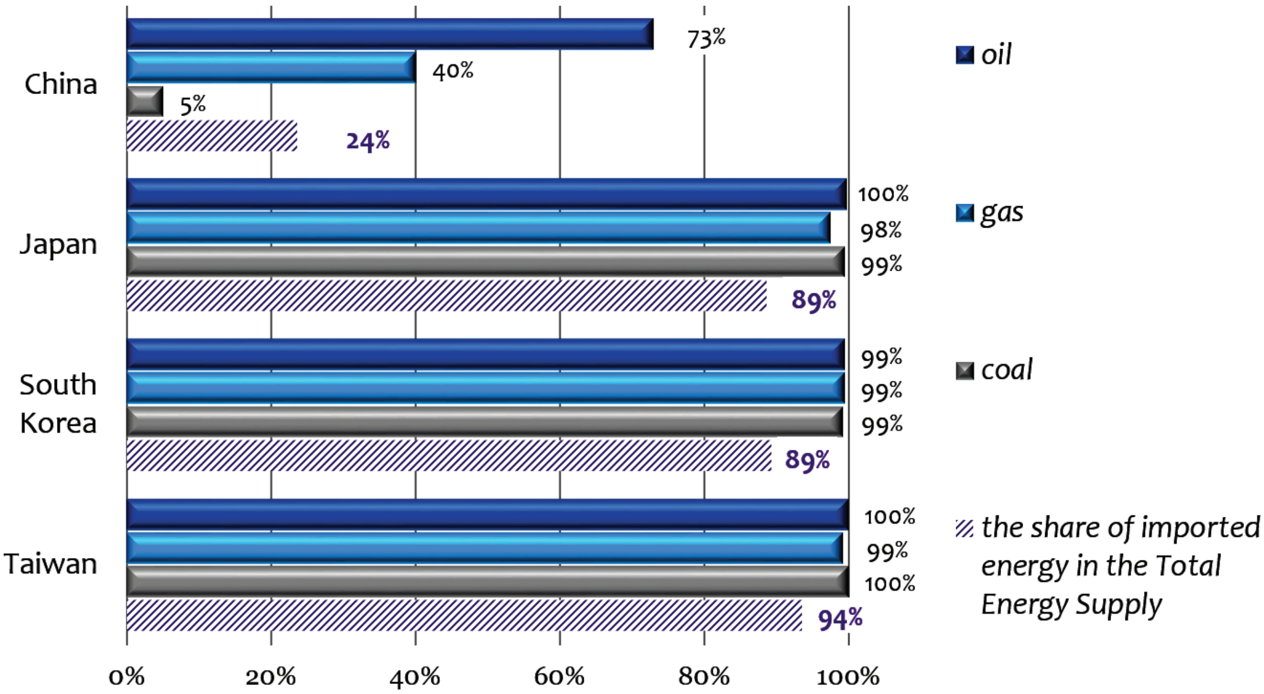


Fig. 1. Dependence of large East Asian countries on energy imports in 2020. Source: Estimated based on [8, 9].

by these countries for the development of energy systems.

The second group is characterized by the greatest degree of dependence on energy imports, and also by a higher energy efficiency of the economy. In addition, Japan and Taiwan have restrictions on the use of renewable energy resources due to elevated seismicity and high land costs.

II. World energy development trends

There are four main groups of factors that currently have the greatest impact on the development of energy sector as the most important infrastructure subsystem of human society: technological, social, economic, and political. All of them fully manifest themselves in the NEA region and the Indo-Pacific region as a whole. The following is a list of the main factors for each group, which are taken into account to predict the global and regional energy development in the long term.

Technological factors:

- Enhancement of the efficiency of energy resources at the stages of energy transportation, conversion, and final consumption;
- Growth of consumer electrification, including the electrification of the transport sector through the introduction of hybrid power plants and electric drives;
- Commercialization of solar and wind energy technologies;
- Complication of energy storage and transportation systems with an increase in the share of renewable energy sources in the structure of primary energy, accompanied by an extension of energy supply chains and, accordingly, an increase in energy losses while meeting the needs of society in energy services;
- Surge in the research on the development of hydrogen technologies for energy purposes.

Social factors:

- Change in lifestyle and increase in the consumption of energy services aimed at meeting the non-production, social, and creative needs of social development;
- Change in the demographic profile of the population in economically developed and developing countries.

Economic factors:

- Increase in the range of issues about resource support for technological development, including the transition to the development of new NRER fields, which are

Table 2. Main indices of the possible energy sector restructuring in the largest economic countries of East Asia in 2020-2050.

Indices	China		Japan		OECD	
	2019	2050	2019	2050	2019	2050
Final energy consumption, EJ, including	72	74	12	8	155	117
Electricity, %	27	46	29	42	22	37
Total energy consumption, EJ, including	142	114	17	13	219	170
Coal, %	61	30	28	13	15	5
Oil, %	19	19	38	27	35	24
Natural gas, %	7	14	22	14	29	25
Nuclear energy, %	3	11	4	19	10	14
RES, %	10	27	8	27	11	32

Source: Estimated based on [10].

Table 3. Relative change in the capacity of the energy markets of China, Japan and the developed countries of the world, % (a ratio of 2050 indices to 2020 indices).

Indices	China	Japan	OECD
Electricity consumption	144	101	127
Energy conversion, storage and transportation losses	90	110	106
Energy consumption, including	80	73	77
Coal	39	33	28
Oil	79	52	53
Natural gas	152	46	67
Nuclear energy	321	341	110
RES	222	259	218

Source: Estimated based on [10].

characterized by high production costs;

- Exacerbation of problems in building the international value chains in the context of uneven resources available in the countries and their technological development.
- *Political and geopolitical factors*:
- The beginning of a period of active transformation of all international institutions as a result of the global financial and economic crisis;
- Transformation of the architecture of world energy markets and the capital market in the face of political pressure on energy companies;
- Lobbying for "green" energy at the national and international level.

In addition to the above, it is worth noting that the importance of environmental and climatic factors increases when planning the development of energy infrastructure and substantiating investment decisions. Furthermore, the developing global financial and economic systemic crisis has raised the importance of the geopolitical factor in assessing the prospects for the transformation of global and regional energy markets.

Ahead of all Mankind are decades of hard work on building a new energy infrastructure, as one of the most crucial components of its civilizational development, which should be energy efficient, environmentally friendly, accessible to all, contributing to social and economic development. East Asian countries are at the forefront of these processes.

III. Energy Prospects for East Asia

The total impact of these factors on the energy sector of the first two groups of NEA countries will be considered using the scenario of high-tech energy development in Asian countries and the world as a whole until 2050, which was built in the framework of the world energy development forecast prepared by the Institute of Energy Economics of Japan (Table 2). The forecast was made in 2021 and does not reflect the radical changes in the institutions of world energy trade, as well as the increased influence of geopolitical factors, which fully manifested themselves in the autumn and winter of 2021–2022.

Against the backdrop of a significant decline in the final energy consumption in Japan and the OECD countries, the stagnation of this indicator for China draws attention. This is explained, apart from the integration of demographic and socio-economic factors, by the delay in the processes of China's energy sector restructuring, a decrease in the coal share in the structure of energy consumed, and the later start of the processes related to the improvement in the energy efficiency of technologies at the stages of conversion and final consumption. These conclusions are supported by the difference in the proportion of electricity in final energy consumption and changes in electricity consumption over the period under review for China, Japan and the OECD as a whole (Tables 2 and 3).

The integrated index of change in the energy efficiency differs depending on the stage of saturation with innovative energy technologies. The "Energy conversion, storage and transportation losses" index in

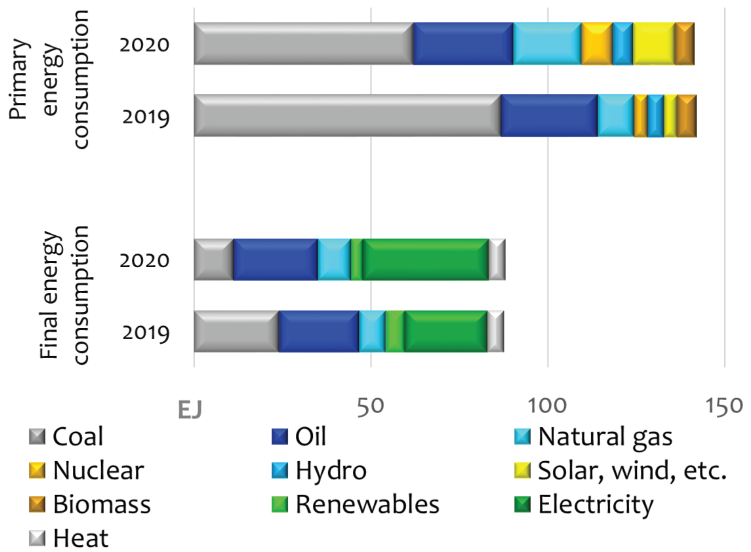


Fig. 2. China's energy consumption forecast 2019-2050. Source: Estimated based on [10].

Table 3 indicates a significant decrease in energy losses for China (by 10%, from 38% of total energy consumption in 2019 to 35% in 2050) and their growth for Japan and the OECD, respectively, by 10% (from 33% of total energy consumption in 2019 to 36% in 2050) and 6% (from 29% of total energy consumption in 2019 to 31% in 2050).

The total energy consumption for all considered subjects of the world economy will decrease. In 2050, compared to 2018, energy needs of China may decrease by 20%, the OECD – by 23%, and Japan – by 27%. At the same time, these countries will see a significant reduction in the coal and oil consumption, with a decrease in natural gas consumption in Japan and the OECD as a whole. In China, the demand for natural gas will increase by 1.5 times. The need for nuclear energy in China and Japan will rise by 2.2–2.6 times, and the consumption of RES – by 3.2–3.4 times. It is however necessary to factor in the limited natural potential of RES, the absence of natural potential of NRER (with the exception of methane hydrates) for the group of JKT countries and low economic potential for increasing natural gas production in China, which is due to the high share of hard-to-recover reserves in their overall structure. An additional limitation for the JKT countries is the absence of uranium enrichment facilities.

The forecast of changes in China's energy consumption for 2019–2050, presented in Fig. 2, reflects trends in the structure and scale of the country's final and total energy consumption. Given the available domestic NRER and RES, as well as the advances in the development of the nuclear energy industry, China will be able to ensure the highest possible level of independence from coal imports and uranium enrichment services. At the same time, the need for oil, natural gas, and unenriched uranium imports may remain at a fairly high level. The IEEJ calculations point to an increase in the energy efficiency of the total energy resources in China from 62% in 2019 to 65% in 2050. This effect will be primarily achieved through the enhanced energy efficiency at the stage of end-use. It will be crucial to replace some energy carriers with others (coal with gas, nuclear energy, and renewable energy sources) and to increase the electrification of consumers of energy services. In addition, it is assumed that after 2030, the creation of hydrogen energy industry will begin to accelerate, and after 2040–2050, there will be an accelerated construction of the infrastructure for large-scale transportation of green hydrogen and hydrogen carriers.

IV. Russia and Mongolia to support the energy export in the long term

In the context of the expected decline in the total volumes of imports of all types of NRER in the energy markets in the NEA region, Russia and Mongolia, acting as energy exporters, aim at:

- Diversifying buyers of energy carriers and energy services both in the NEA region and in adjacent markets in the Asia-Pacific and Indo-Pacific regions;
- Maintaining high competitiveness of their products, including coal and energy of RES (Russia and Mongolia), hydrocarbons and uranium enrichment services (Russia);
- Developing cooperation with purchasing and transit countries to strengthen the institutions of energy markets and expand the technological infrastructure for energy transportation.

As already mentioned, in the coming decades, the pace of transformation of the international energy infrastructure in the NEA region will be determined by political, economic, social, technological, and natural factors. Energy market institutions, both regional and international, will set the conditions for transforming the energy infrastructure. At the same time, these institutions can act as objects of influence due to the impact of new geopolitical factors created by already completed critical stages in the development of such an infrastructure. Thus, the creation of an international power interconnection in NEA requires prior political consent to such close energy cooperation, which significantly affects national security. In turn, the fact of a significant share of Russia in the supply of oil and natural gas to Japan and the Republic of Korea strongly opposes the US policy pushing the countries of the second group in the NEA region to refuse from energy cooperation with Russia.

The economic and geographical features of the NEA region favor the formation of China's transit monopoly on export routes from Mongolia to markets emerging in the countries of Indo-Pacific region. There are no river routes bypassing China, and the use of road and rail transport to deliver the products to the ports of the Russian Far East, with the obligatory stage of transshipment to sea vessels, significantly reduces the competitiveness of energy resource exports. The coastal provinces of China and the Korean Peninsula will remain areas of competition between energy supplied by land transport from Russia and Mongolia, and energy imported by sea. This situation will be most noticeable in the natural gas market, where the LNG spot market acts as a source of balancing supplies during periods of peak demand.

Land freight transport systems are immobile since they are based on the pipelines, roads and railways, the construction of which is capital-intensive, and the transportation of goods by them is an energy-intensive and costly activity often involving transit through third countries. Unlike land systems, maritime transport allows transporting energy carriers at any distance and along any route, avoiding (for the considered groups of energy importers) transit problems.

The technological factor, i.e., the commercialization of electricity generation based on renewable energy sources, primarily solar and wind energy, supplemented by storage batteries, allowed oil-importing countries, relying on transnational corporations, to put forward a new energy development paradigm, the so-called "carbon-free energy." This approach is also supported by advances in the commercialization of hydrogen technologies (fuel cells, hydrogen and hydrogen carrier storage and transportation systems). The political course towards accelerated «decarbonization» is combined with the expansion of information technologies and their wide-scale adoption. The latter involves the automation of control of almost all technological processes and even a change in social life, which rely on the creation of global communication systems (the most significant example is the Internet), and systems for collecting, storing, and processing large amounts of data.

The energy transition, which aims to provide "clean, green" energy to a technologically renewed society, is a socio-economic and political project. This project is implemented relying on the coordination of the efforts of such influential actors as transnational corporations and governments of the "most developed countries of the world," the so-called generalized West. The process of globalization at the beginning of 2022, however, shows a clear lack of unity among the actors, as well as the presence of other opinions in the world on the pace and mechanisms for the transition of mankind to a new technological base for its development.

Based on the above understanding of the Energy Transition, we will put forward a hypothesis that the pace of energy transformation will be determined by the interaction of political, economic, social, technological and natural factors. They will differ for all three previously identified groups of NEA countries at the national level (and subnational – for China and Russia). An even greater complication of the geopolitical situation in the NEA region will lead to deeper processes of transformation of the international cooperation institutions. The political factor will be aimed at changing the structure of the total energy consumption in East Asian countries and regulating the choice of partners for energy imports.

The analysis of the current situation in the energy markets in the NEA region, the prospects for restructuring energy consumption in China and the group of JKT countries, changes in the institutions of international energy cooperation in the world, in general, and in the NEA region, in particular, allows some qualitative conclusions about the prospects for energy exports from Russia and Mongolia (the third group of countries). Traditional energy sources (oil, coal, natural gas (methane), and electricity (to China)) will remain competitive. At the same time, quantitative estimates of the prospective needs of East Asian countries for energy imports and the development of regional energy markets require significant joint systematized, coordinated and regular studies.

By the end of the 2040s, the conditions for a market for green hydrogen (hydrogen carriers) and the related electro-hydrogen infrastructure can be created in the region. Given the extent to which the infrastructure for the maritime transport of oil, oil products and natural gas in the form of LNG is developed in the NEA region, one should expect the formation of a unified gas transmission system in the region to begin. This system will combine the nodes of LNG import and regasification, with developed national and, in the future, international gas pipeline systems, and the establishment of relevant international institutions for regional trade in natural gas (methane). In the event of successful development of this process, the likelihood that an international electric power (electro-hydrogen) infrastructure will appear in the NEA region will also increase since the energy security factor is critical for creating such an infrastructure.

V. Conclusion

The energy development of the industrialized economies in East Asia is aimed at transforming the infrastructure for energy supply to consumers by replacing fossil energy sources with renewable ones. Given the availability of sufficiently efficient traditional fuel energy resources, the increase in the proportion of renewable energy sources will require the accelerated development of electricity transportation and storage systems. This process contributes to a significant complication of the entire energy system and the restructuring of sectors of the economy in East Asian countries.

As the economic potential of renewable energy resources is exhausted at the national level in the countries of East Asia, the need to create a regional international infrastructure for the import of green energy will increase. Russia and Mongolia have abundant natural resources both non-renewable and renewable, which far exceed the needs of these countries. These surplus resources can be in demand in North-East, South, and South-East Asia.

Quantitative estimates of projected energy consumption can vary over a wide range depending on the assumptions made in scenario. An example of a long-term high-tech energy development scenario constructed by the Institute of Energy Economics of Japan demonstrates that the expected reduction in energy consumption within its framework is based on optimistic estimates of energy efficiency and the commercialization of some innovative technologies. The multivariate development of the energy industry and the uncertainty about the prospects for the enhancement of innovative energy technologies require that our countries have several independent think tanks able to quantitatively assess the prospective needs of East Asian countries for energy imports and conduct regular research into the development of international transport infrastructure and energy market institutions in NEA region.

Acknowledgements

The research was carried out under a state assignment (FWEU-2021-0004.) of the Program for Basic Research of the Russian Federation for 2021–2030 and made use of the resources of the «High-Temperature Circuit» shared research facilities center (Ministry of Education and Science of Russia, project No. 13.CKP.21.0038).

References

[1] S. P. Popov, D.V. Maksakova, "East Asia as an object for Russia-Mongolia energy cooperation," *Energy Systems Research*, no. 4, pp. 45–55, 2018.

[2] E. V. Batunaev, Yu. G. Grigoryeva, "Mongolia and the countries of Northeast Asia: trade, economic and integration cooperation (2009–2018)," Asia-Pacific Region: Economics, Politics, Law, no. 3, pp. 15–28, 2019. (In Russian)

[3] N. I. Voropai, S. V. Podkovalnikov, B. G. Saneev, "Interstate Energy Cooperation in Northeast Asia: Status, Potential Projects, Energy Infrastructure," *Energy Policy*, no. 2, pp. 55–65, 2014. (In Russian)

[4] A. M. Mastepanov, "Integration processes in the energy sector of Northeast Asia and the role of natural gas in their development," *Energy Policy*, no. 6, pp. 38–57, 2018. (In Russian)

[5] T. Otsuki, "Costs and benefits of large-scale deployment of wind turbines and solar PV in Mongolia for international power exports," *Renewable energy*, vol. 108, pp. 321–335, 2017. DOI: 10.1016/j.renene.2017.02.018.

[6] S. P. Popov, D. V. Maksakova, O. A. Baldynov, "Evaluation of the possibilities and directions of creating an electro-hydrogen infrastructure in Northeast Asia," *Geoeconomics of Energy*, vol. 17, no. 1, pp. 132–155, 2022. DOI: 10.48137/2687-0703_2022_17_1_132. (In Russian)

[7] S. P. Popov, "Methodological approach to the study of the electro-hydrogen system in Northeast Asia," International Journal of Hydrogen Energy, vol. 47, no. 28, pp. 13524–13531, 2022. DOI: 10.1016/j.ijhydene.2022.02.191.

[8] World Energy & Climate Statistics – Yearbook 2021. Available at: https://www.enerdata.net/publications/world-energy-statistics-supply-and-demand.html (accessed 19.03.2022).

[9] BP Statistical Review of World Energy 2021. Available at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed 19.03.2022).

[10] R. Casaubon, S. Endo, H. Hashimoto etc., *IEEJ Outlook 2022*. IEEJ: 2021. Available at: https://eneken.ieej.or.jp/data/10041.pdf (accessed 19.03.2022).

Boris Saneev is the Head of the research area "Complex Energy Problems and Regional Energy Policy" at the Melentiev Energy Systems Institute, the Siberian Branch of the Russian Academy of Sciences (MESI SB RAS). He holds the degree of Doctor of Engineering. His research interests include the issues of economic and energy development, energy cooperation between Russia and the Northeast Asian countries.

Sergei Popov is a senior researcher at MESI SB RAS. He is responsible for the analysis of the East Asian and Asia-Pacific energy markets. He joined MESI in 1982 and received the Ph.D. degree in Modeling Energy Systems at MESI in 1993. In 2004-2011, he worked in the Asia Pacific Energy Research Centre, Japan. His research interests include energy policy development and energy modeling.

Darya Maksakova joined MESI SB RAS in 2016, after receiving the Bachelor's degree in International Economics from Baikal State University, Russia. In 2018, she received the Master's degree in Finance from the same university. Now she is a junior researcher and a Ph.D. student at MESI SB RAS. Her research interests include energy economics and energy modelling tools.

Oleg Baldynov gained the Bachelor's degree in Finance in 2015 and Master's Degree in Innovation Management in 2017 from Irkutsk National Research Technical University, Russia. Since 2017, he has been a Ph.D. student at MESI SB RAS. His research interests include renewable energy sources, hydrogen energy, and energy transmission.

Directions for Transition to Low-Carbon Energy in the Baikal-Khuvsgul Transboundary Territory: Background, Conditions, Effects

I.Yu. Ivanova, V.A. Shakirov, E.P. Maysyuk*, R.A. Ivanov

Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The joint development of transboundary territories of Russia and Mongolia primarily focuses on a unique natural formation, the Baikal-Khuvsgul basin. These territories are a promising area for the expansion of cooperation in the field of environmental protection, tourism and energy. The existing energy system, however, does not provide the appropriate conditions for this, as it is characterized by low reliability and the impossibility of connecting new large consumers. Heat is supplied to consumers from numerous coal-fired and wood-fired boiler houses of small and medium capacity with outdated equipment. In the context of energy supply problems and a focus on environmentally attractive low-carbon technologies, this study examines the use of renewable energy and conversion of municipal boilers to gas. An analysis of the available resources in the territory showed a high solar energy potential for the development of generation based on photovoltaic converters. Another way to use RES in the Baikal-Khuvsgul area is to replace low-capacity coal-fired boilers with heat pump units. Conversion of boiler houses to gas does not solve completely the issue of decarbonization, since CO2 emissions, although to a lesser extent, occur during the gaseous fuel combustion. At the same time, it will significantly reduce the human-induced environmental impact through the elimination of particulate matter and sulfur dioxide emissions, and ash and slag waste. The paper presents a feasibility study of solutions for the development of electricity and heat supply with a minimum emission of greenhouse gases and pollutants in the Baikal-Khuvsgul transboundary territory.**

Index Terms: **power supply systems, environmental assessment, greenhouse gases, emissions of pollutants, ash and slag waste.**

---

* Corresponding author.
E-mail: maysyuk@isem.irk.ru

http://dx.doi.org/10.38028/esr.2022.02.0003
Received June 18, 2022. Revised July 11, 2022.
Accepted July 30, 2022. Available online August 31, 2022.

I. Introduction

The key areas of interaction between Russia and Mongolia are the joint development of the infrastructure in the transboundary territories and cooperation in the field of environmental protection, tourism, and energy (An agreement between the Government of the Russian Federation and the Government of Mongolia on support of interregional and cross-border cooperation of 03.09.2019, Ulaanbaatar).

The central part of the transboundary territory of Russia and Mongolia is occupied by a unique natural formation – the Baikal-Khuvsgul basin. The Lake Khuvsgul basin, which is one of the main stable feeding sources of the Selenga river and, consequently, that of Lake Baikal, is virtually not yet affected by human activities. Lake Baikal is recognized as the oldest and deepest lake on the planet with the largest volume of fresh water [1]. It is included in the list of UNESCO World Heritage Sites.

The Baikal-Khuvsgul transboundary territory is a favorable area for the development of international tourism. It includes the Khuvsgul aimak of Mongolia and three districts that are part of the constituent entities of the Russian Federation (the Okinsky and Tunkinsky districts of the Republic of Buryatia, and the Slyudyansky district of the Irkutsk Region) [2]. Within the boundaries of the territory at issue, there is the Tunka national park, the Khuvsgul national park, many sanatoriums, recreation centers, and places for tourism and recreation. Lakes Baikal and Khuvsgul are connected by a road passing through the Tunka Valley. The area is dominated by mid-mountain relief, and there is the highest peak of the Sayan Mountains – Mount Munku-Sardyk – on the Russian-Mongolian border, which is a popular sports tourism destination [3].

Currently, specially protected natural areas (SPNA) are actively involved in ecotourism and integrated into the socio-economic development [2]. One of the conditions for the successful sustainable development of ecotourism in the transboundary area is the creation of an environmentally friendly infrastructure to minimize environmental impact. This direction is consistent with the goals of the Strategy for the socio-economic development of the Russian Federation with a low level of greenhouse gas emissions until 2050 (Strategy for socio-economic

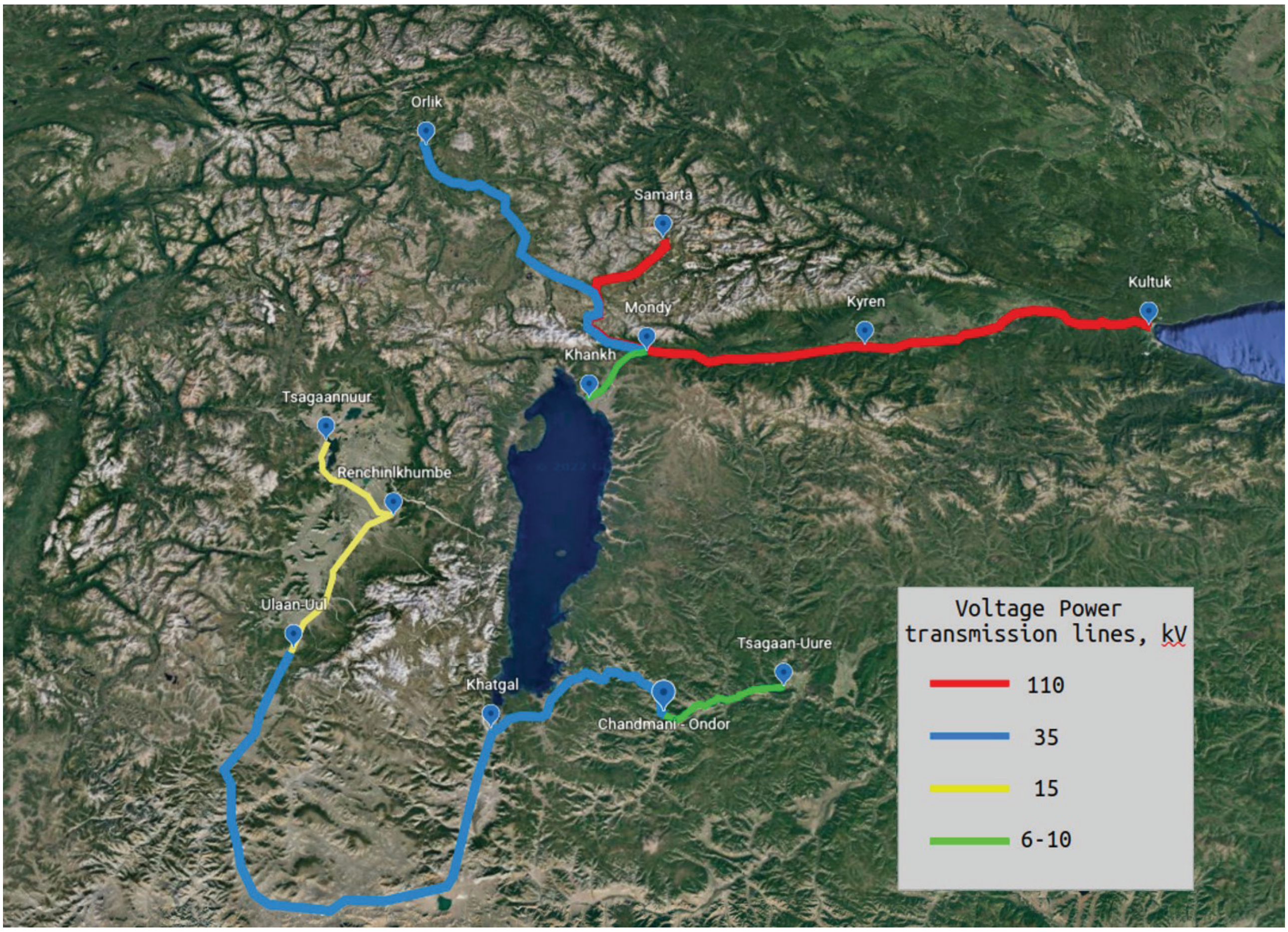


Fig. 1. Situational plan of power supply systems.

development of the Russia Federation with a low level of greenhouse gas emissions until 2050, approved by the Resolution of the Government of the Russian Federation No. 3052 of 29.102021.). The strategy measures involve replacing part of coal-fired generation with carbon-free and low-carbon ones; increasing electricity generation to meet the needs of the economy through carbon-free generation; reducing emissions from existing coal-fired generation plants through the introduction of advanced technologies.

Numerous works examine the strategies for low-carbon development of the ecotourism industry and minimization of anthropogenic impacts on protected areas. He et al. [4] models a low-carbon ecotourism system and a set of activities, including the municipal solid waste processing aimed at minimizing negative impacts on the ecosystem. Heshmati et al. [5] considers strategies for combining the development of ecotourism and the protection of natural resources using a SWOT analysis. The main proposed measures include regular patrolling and limiting destructive activities (poaching, arson, plastic waste dumping).

In [6], the findings statistically confirm a relationship between the development of tourism and the reduction in pollution. One of the key factors is the introduction of renewable energy sources. In [7], an improved decision-making tool is proposed for the technical and economic analysis of multi-energy microgrids for energy supply to infrastructure facilities in ecotourism development areas. Minaei et al. [8] consider the issue of developing energy supply to remote settlements located in protected areas, national parks and reserves, the preservation of which is essential for the sustainable development of territories and minimization of climate impacts. The electricity production based on fossil fuels and the construction of electrical networks pose a potential threat to the ecosystem in such areas. Therefore, the study considered the use of solar technologies for energy purposes.

The review of the studies shows that they focus on the identification of the influencing factors and development of a policy for low-carbon development of tourist areas and protected areas. Some investigations deal with the creation of low-carbon power supply systems.

This paper presents a study into the avenues for the transition to low-carbon energy in the Baikal-Khuvsgul transboundary territory, including a feasibility study of solutions for the development of electricity and heat supply with minimal emissions of greenhouse gases and pollutants.

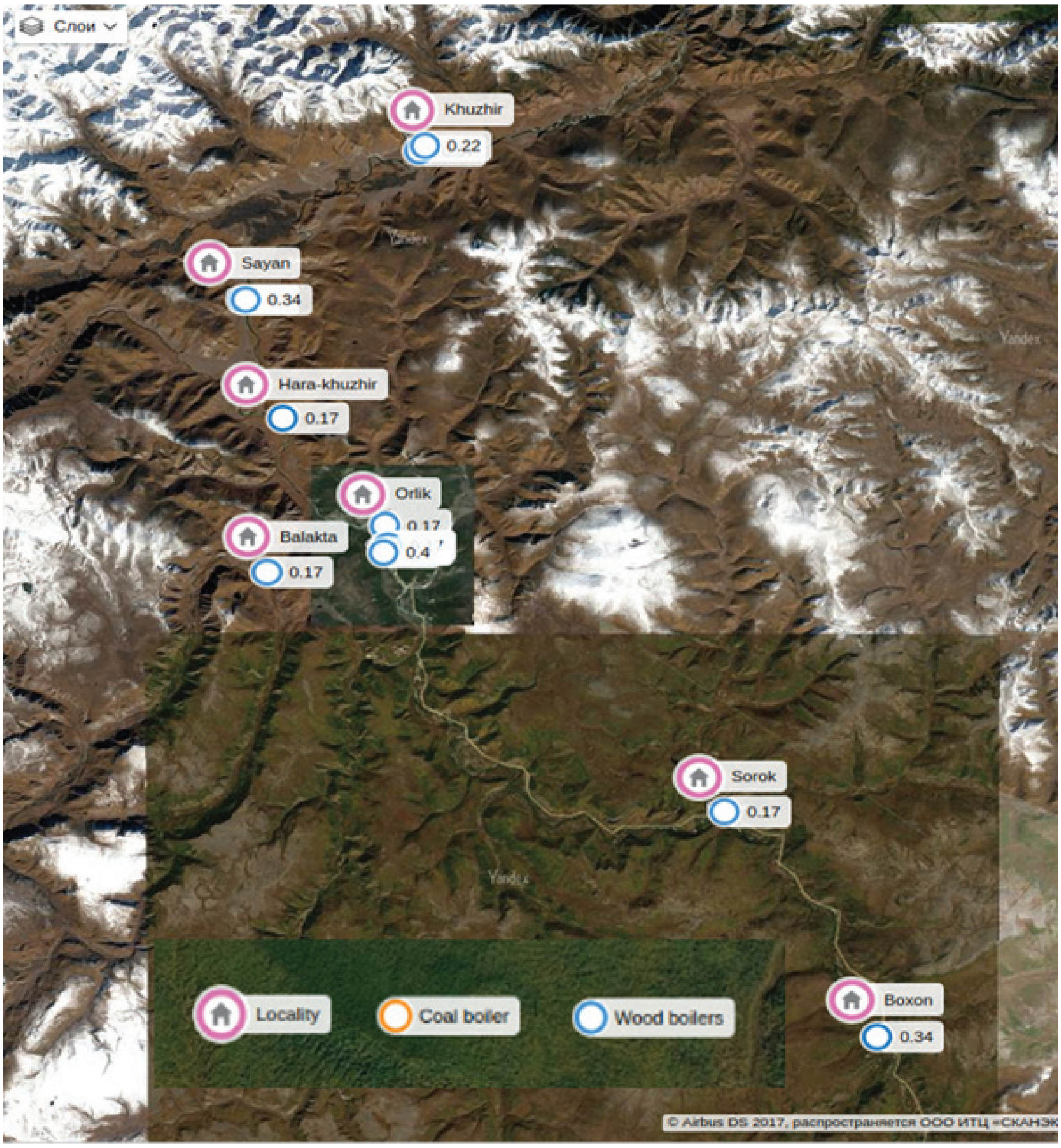


Fig. 2 Location of boiler houses in the Okinsky district with indication of installed boiler capacities, Gcal/h.

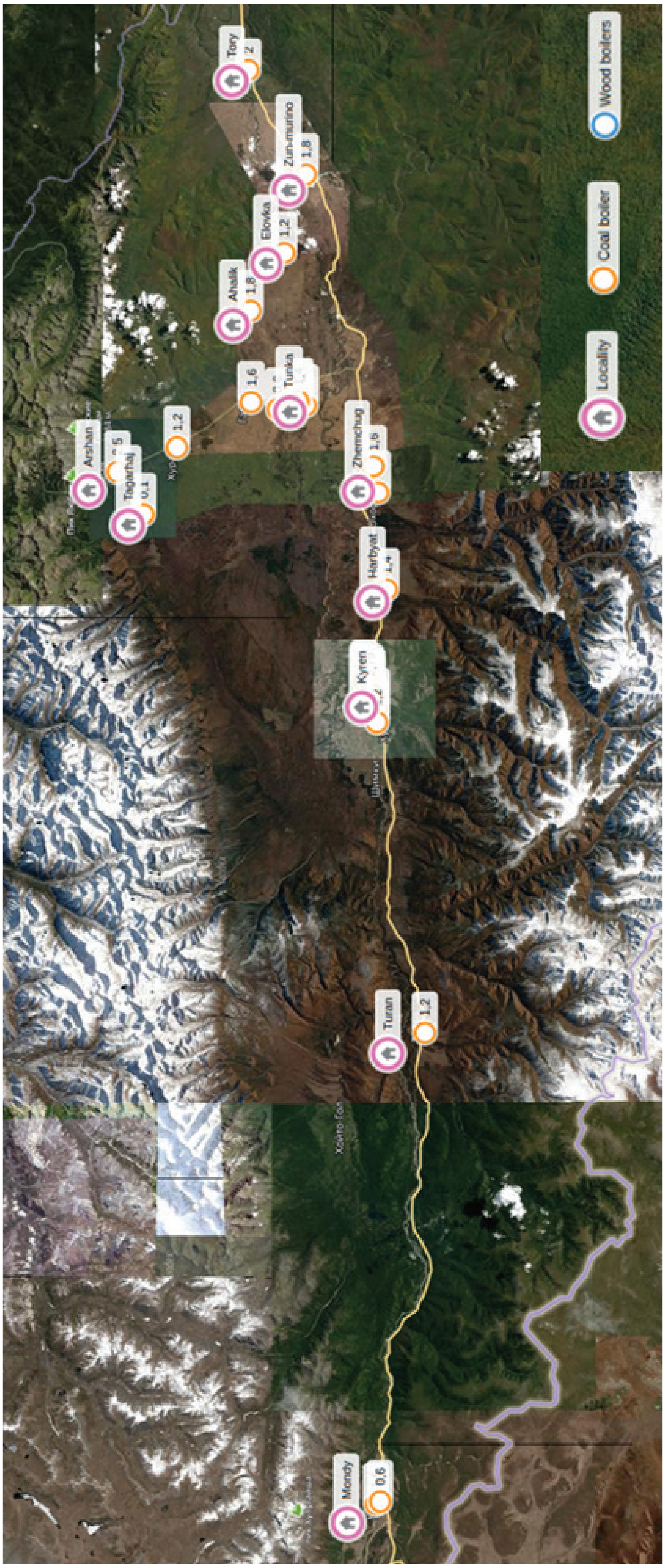


***Fig. 3.** Location of boiler houses in the Tunkinsky district with indication of installed boiler capacities, Gcal/h.*

Table 1. Estimated emissions of pollutants from municipal boilers, t/year.

Current state	District	Emissions					
		Total	Particulate matter	SO_2	NOx	CO	Greenhouse gases (CO_2)
	Okinsky	217	73	-	14	130	-
	Tunkinsky	1 516	1 236	119	15	146	10 000

II. The current state of power supply systems in the studied area

A. Power supply systems

The situational plan of a system for power supply to consumers in the Baikal-Khuvsgul transboundary territory is presented in Fig. 1. A detailed analysis of the current state of the power supply systems in this territory is given in [9–10].

Consumers in the Russian part of the territory receive power through a long single-circuit 110 kV power transmission line (TL) Kultuk - Kyren - Zun-Murino - Mondy - Samarta. Consumers located in the territory of the Khuvsgul National Park are supplied with electricity through the 10 kV interstate transmission line Mondy-Khankh, 35 km long (see Fig. 1). Power supply to consumers in the territories adjacent to Lake Khuvsgul from the eastern, western and southern sides is carried out from the central power system of Mongolia through the 110/35 kV power line Bulgan-Muren-Khatgal, 298 km long, and further through 6, 10, and 15 kV distribution networks.

Power transmission lines are characterized by significant wear and tear and frequent long outages. In the event of a long-term power outage, diesel power plants (DPPs) at some substations (for example, Orlik and Soroka substations) are used to supply consumers with power.

The large length of power lines also causes the problem of low voltage levels for consumers. The connection of new consumers in the territory at issue is limited due to the inability to provide an acceptable voltage level at remote substations.

Within the boundaries of the considered territory, there are also remote, hard-to-reach consumers, mainly tourist sites and cattle breeders, which are supplied with electricity from DPPs.

B. Heating systems

This study considers the current state of heat supply to the Baikal-Khubsugul territory focusing on the Okinsky and Tunkinsky districts of the Republic of Buryatia, which are adjacent to the Mongolian border from the Russian side. The populated settlements of the districts are mainly located along the highway, which is used to provide the population with the basic essentials. The main consumers of thermal energy from municipal boiler houses in these settlements are kindergartens, schools, administration buildings, and other social facilities. The population is supplied with heat from individual furnaces that burn mainly firewood.

In the Okinsky district, 5.5 thousand people live on an area of 26.6 thousand km^2. There are 18 municipal low-capacity boiler houses (up to 3 Gcal/h) (Fig. 2). The total installed capacity of the boiler houses is 6.9 Gcal/h, they burn 8.8 thousand tons of wood fuel annually.

In the Tunkinsky district, 20.1 thousand people live on an area of 11.8 thousand km^2. There are 24 municipal boiler houses with a total installed capacity of 38.7 Gcal/h, of which only one (in the village of Kyren) is of medium capacity – 5.2 Gcal/h, and the rest are of low capacity (Fig. 3). The main fuel is coal from the Cheremkhovskoye deposit, which is delivered from the territory of the Irkutsk region to meet an annual demand of 6.5 thousand tons/year.

C. Environmental assessment of heat supply systems

Due to the lack of information, environmental assessments in the study are given only for the systems supplying heat from municipal boiler houses in the Tunkinsky and Okinsky districts. It is worth noting that these boiler houses, along with individual furnaces, make the most significant contribution to the environmental situation in the territory, due to the predominance of coal in the fuel balance and the absence of exhaust gas purification equipment.

The emissions of pollutants into the atmosphere, which are among the main environmental characteristics of heat supply systems, were calculated based on the methods approved in Russia [11, 12]. The total emission of pollutants from municipal boilers in the two districts is estimated at 1.7 thousand tons/year, with the predominant contribution of boilers in the Tunkinsky district due to coal combustion (Table 1).

Environmental problems are local in nature and are associated not only with emissions of pollutants but also with the energy production and consumption waste, i.e., ash and slag waste (ASW). The ASW amount is calculated on the basis of existing recommendations [13–14] and makes up 861 tons/year, of which 108 tons are waste from wood fuel combustion in the Okinsky district and 753 tons are ASW from coal combustion in the Tunkinsky district.

The issue of climate change associated with greenhouse gas (CO_2) emissions is acute for thermal power facilities. According to our estimates, the rated carbon dioxide emissions at the current level of coal consumption are 10 thousand tons/year. CO_2 emissions from municipal boilers in the Okinsky district are zero, since carbon dioxide released into the air during combustion is believed to be

Table 2. The main directions and effects of the transition to low-carbon energy in the Baikal-Khuvsgul territory.

Direction	Effect
Electricity supply	
Use of renewable energy sources and reactive power compensation devices	- increasing the reliability of power supply to consumers; - ensuring the level of voltage at consumers according to the State standard requirements; - providing the opportunity to connect new consumers; - reducing diesel fuel consumption
Heat supply	
Replacement of coal with gas fuel	- excluding coal deliveries and combustion in boiler houses of the Tunkinsky district
Use of geothermal heat pumps	- replacing low-capacity boiler houses (load up to 0.4 Gcal/h) in the Tunkinsky and Okinsky districts

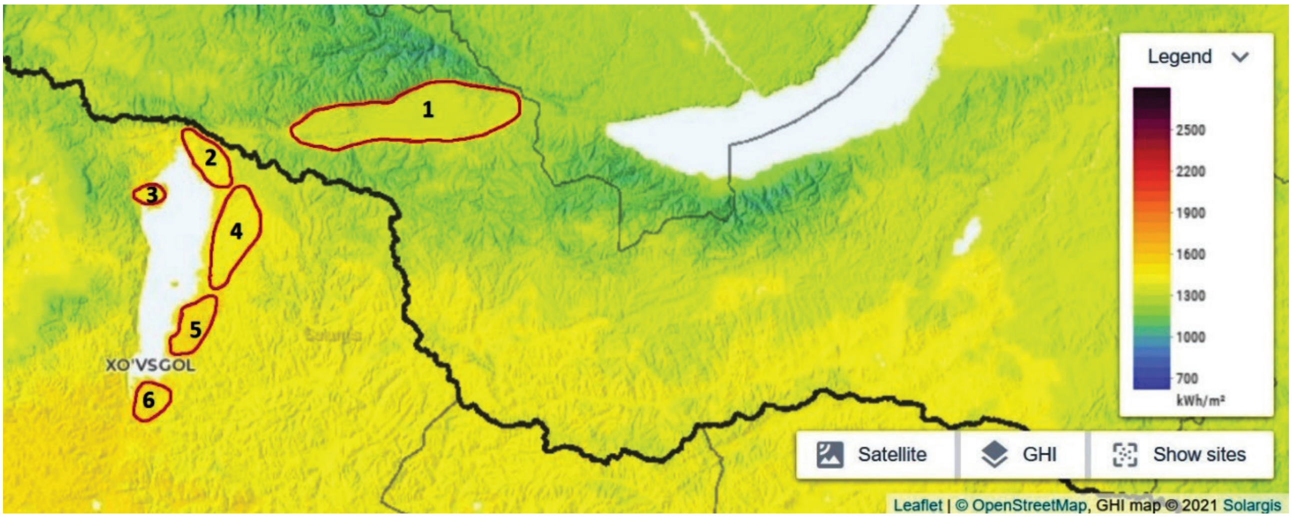


Fig. 4. Total solar radiation incident on a horizontal surface.

previously absorbed from the atmosphere by growing plants (the closed cycle formed does not lead to an increase in CO_2 concentration in the atmosphere) [15–16].

III. Main directions for transition to low-carbon energy

The issues of environmental protection, energy supply reliability and efficiency improvement can be resolved, and the transition to low-carbon energy in the considered areas can be made through the implementation of some measures related to both electricity supply and heat supply. An analysis of possible effects to be gained from these measures is presented in Table 2.

The choice of directions for the transition to low-carbon energy should be based on analysis of resource availability, and environmental and economic assessments of solutions to be adopted.

A. Resources and efficiency of wind and solar energy for electricity supply

Analysis of the wind and solar potential in the region involved geoinformation systems NASA POWER (NASA POWER- URL: https://power.larc.nasa.gov / (accessed 18.04.2022), Global solar atlas (Global solar atlas. – URL: https://globalsolaratlas.info (accessed 18.04.2022), and Global wind atlas (Global wind atlas – URL: https://globalwindatlas.info (accessed 18.04.2022).

High indicators of solar energy potential are observed in the Tunka National Park and on the shore of Lake Khuvsgul (Fig. 4). The Figure shows the areas with the highest solar energy potential. The flux of total solar radiation incident on a horizontal surface in these areas varies from 1 241 to 1 365 kW·h/m^2 per year, and on an inclined surface – from 1 456 to 1 602 kW·h/m^2 per year.

The wind energy potential of the territory is characterized by a low average annual wind speed of 3.3 to 4 m/s at a height of 10 m.

The conditions and results of a comparative analysis of the cost-effectiveness of low-capacity wind power plants (WPPs) and solar power plants (SPPs) are presented in Table 3.

The estimates obtained indicate a promising level of solar energy potential for the development of solar generation in the Baikal-Khuvsgul transboundary territory. The wind energy potential of the territory is, on the contrary, insufficient for electricity supply purposes.

The feasibility of solar energy in the Baikal-Khuvsgul territory has been assessed. The locations and installed capacity of solar power plants have been determined for

Table 3. Comparison of SPP and WPP cost-effectiveness.

Index	WPP	SPP
Specific capital investments, $/kW*	2 500–3 000	1 200–1 400
Operating costs, $/kW/year	75–90	24–28
Installed capacity utilization factor, %	7.5–10.4	18.3–19.7
Discount rate, %	7	
Estimated period, years	30	
Levelized cost of electricity generation, $/kW·h	0.31–0.51	0.07–0.09

Note – * Technical and economic estimates were obtained at a rate of 82 rubles for 1 dollar.

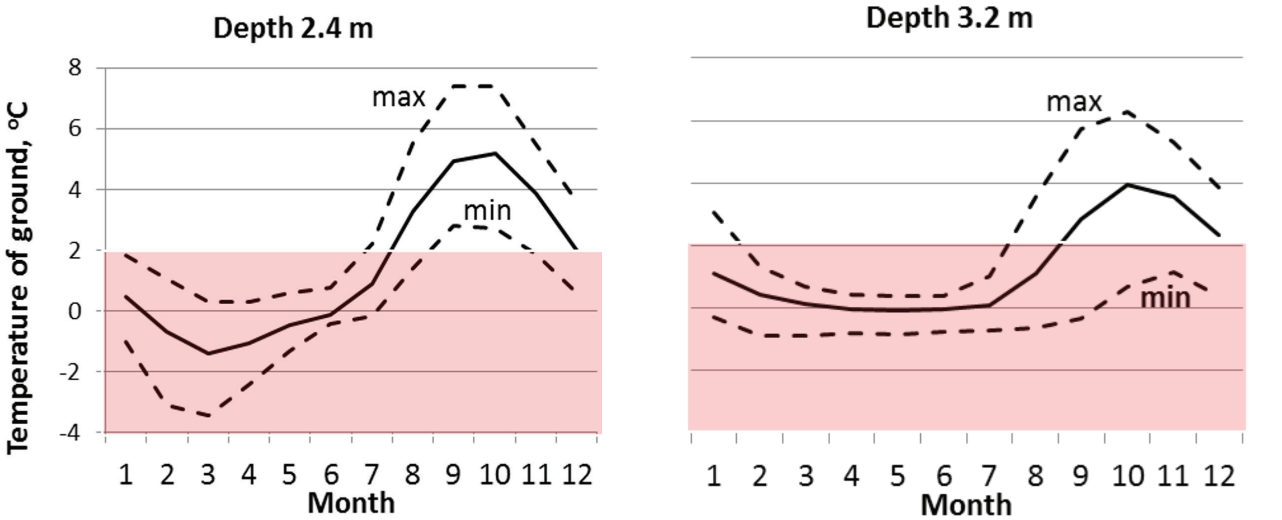


Fig. 5. Graphs of relationships between the ground temperature and the depth in the settlement of Tunka (obtained based on 1974-2012 measurements).

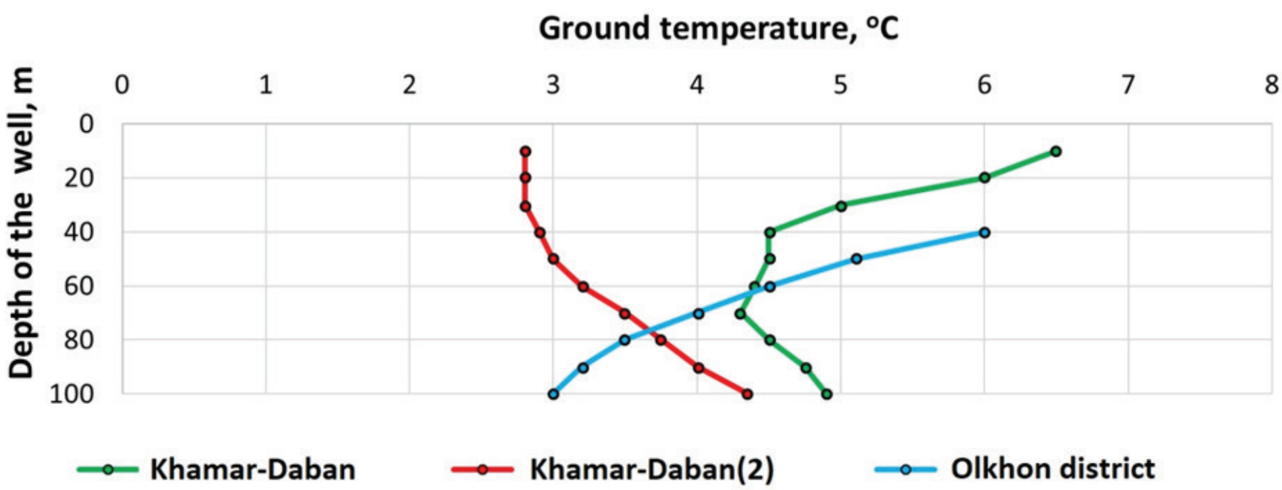


Fig. 6. Graphs of relationship between the ground temperature and the depth.

the zone of centralized power supply. These plants, given the development prospects, will provide acceptable voltage deviations for consumers and high reliability of power supply: in Khuzhir – 1.4 MW, Orlik – 0.2 MW, Forty – 0.2 MW, Police station – 0.1 MW, Mondy – 0.3 MW, and Khankh – 0.2 MW [17].

The optimal power of solar power plants in the zone of autonomous power supply is 7- 60 kW, depending on the load of the consumer, and the total required power for power supply of remote tourist sites is 250–300 kW [18].

In the southern areas of Lake Khuvsgul, it is advisable to use reactive power compensators to provide the required voltage level for the consumer [10].

B. Resources and efficiency of low-grade geothermal energy for heating purposes

The geothermal energy potential in the Baikal-Khuvsgul transboundary territory was analyzed using

Table 4. Characteristics of low-capacity coal-fired boiler houses and electricity supply conditions for consumers in the Tunkinsky and Okinsky districts.

Characteristics	Tunkinsky district	Okinsky district
Boiler houses with a load of up to 0.4 Gcal/h	22 pieces	14 pieces
Fuel type	Cheremkhovsky coal	Firewood
Consumption, tce/year	4 683	6 396 m^3
Fuel price, $*/tce	66.56	92.44
Tariff, $/kW·h	0.04 (population) 0.05–0.06 (others)	
Heat consumers	Schools, kindergartens, military commissariat, other social facilities	

Note - * at a rate of 82 rubles for 1 dollar.

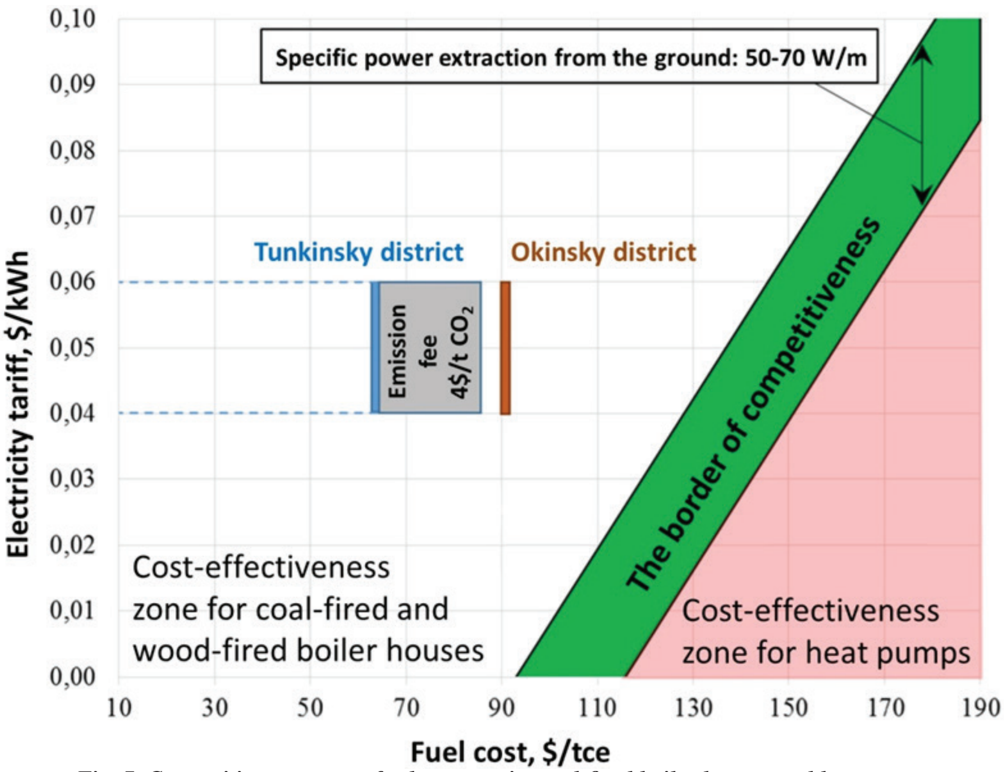


Fig. 7. Competitiveness zones for low-capacity coal-fired boiler houses and heat pumps.

the database «Specialized arrays for climate studies» (Specialized arrays for climate research – URL: http://aisori-m.meteo.ru/waisori/ (accessed 18.04.2022) and data from [19]. Due to the high cost and complexity of temperature measurements at the depth of the earth, the data are limited in terms of both the period and the number of observation points. Figures 5 and 6 show graphs of temperature changes depending on the measurement depth.

The low level of ground temperature allows considering only a limited set of geothermal energy technologies, the most promising of which are low-capacity heat pump units (HPUs).

Low-capacity heat pump units can be used to completely replace coal-fired or wood-fired low-capacity boilers (up to 0.4 Gcal/h). They are highly automated and have virtually no impact on the environment. Their widespread use, however, is limited by high capital costs for the main equipment and the system for extracting heat from the ground.

Three methods of low-potential heat extraction were analyzed for the considered area:

1. Open loop with water intake from the reservoir and subsequent return discharge.
2. Closed horizontal loop at a depth of up to 4 meters with propylene glycol as heat carrier.
3. Closed vertical loop with a borehole depth of up to 100 meters with propylene glycol as heat carrier.

An open loop with water intake from a reservoir is the most cost-effective method due to its relatively low cost [20]. However, a significant limitation is the

Table 5. Results of the feasibility study of alternative heating options.

Parameter	Value [a]
Specific capital investments in the heating system with heat pump, $/kW*	1 085
Specific capital investments in the heating system with heat pump, mln. $/Gcal/h	1.28
Discount rate, %	7
Estimated period, years	30
Discounted payback period of the heating system with heat pump	~50 years
Levelized cost of thermal energy for heat pump, $/Gcal	62.2
Levelized cost of thermal energy for low-capacity coal-fired boilers houses, $/Gcal	41.5

Note – * Technical and economic estimates were obtained at a rate of 82 rubles for 1 dollar.

Fig. 8. The route of the main gas pipeline through the territory of the Tunkinsky district.

inaccessibility of this method in areas remote from Lakes Baikal and Khuvsgul, and the difficulty of assessing the environmental impact of the project.

Heat extraction with the aid of a closed horizontal loop can also have only limited application in the coastal areas of Lakes Baikal and Khuvsgul. In the areas remote from the lakes, the ground temperature at a depth of up to 4 meters is less than 2°C for most of the year (see Fig. 5). At such a temperature of the ground, heat extraction is technically inefficient.

Heat extraction using a closed vertical loop can be implemented almost everywhere. Figure 6 shows that the ground temperature at a depth of up to 100 m in different areas of the Baikal-Khuvsgul transboundary territory is in the range of 2.8–6.5°C all year round.

The approach presented in [20] was used to assess the economic efficiency of heat pump unit to replace low-capacity coal-fired boilers in the territory at issue.

The characteristics of low-capacity boiler houses operating in the studied area are presented in Table 4. Figure 7 shows the competitiveness limits for low-capacity coal-fired boilers and heat pumps.

Table 5 shows the feasibility study results for the alternative heating options.

Based on Figure 7 and Table 5, we can conclude that under the current technical and economic conditions, coal and wood-fired boilers have a significantly higher economic efficiency compared to heat pumps. Only an increase in the fuel cost up to $135/tce will make heat pump equally economical with coal-fired boilers. The heat pump cost-effectiveness can also significantly rise with an increase in fees for emissions of pollutants into the atmosphere or the introduction of a carbon tax. Figure 7 indicates that the conditions of the Tunkinsky district approach the border of competitiveness at an emission fee of 4 $/t CO_2.

Table 6. Emissions of pollutants and greenhouse gases at conversion of boiler houses to gas in the Tunkinsky district, t/year.

Emission into the atmosphere						
Conversion to gas	Pollutants					Greenhouse gases (CO_2)
	Total	Particulate matter	SO_2	NOx	CO	
	9.5	0	0	2.5	7	4 000

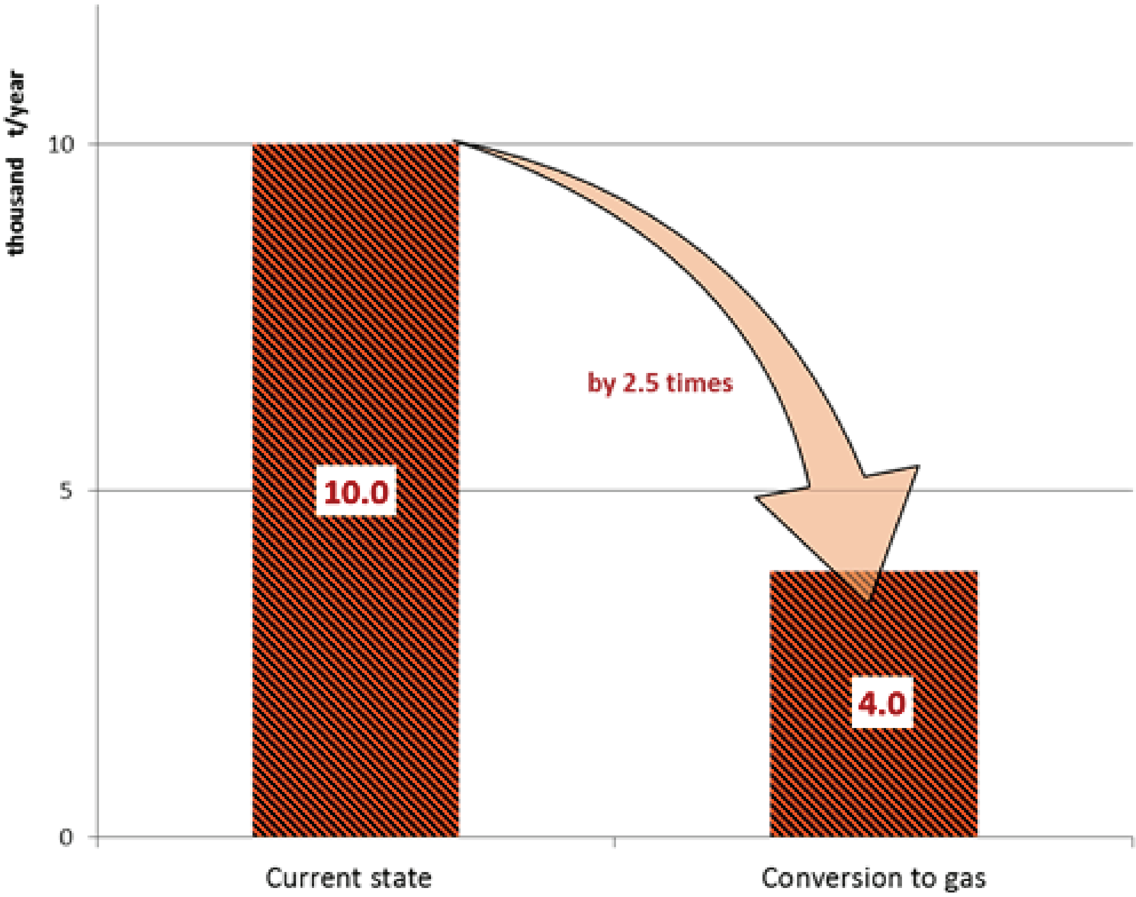


Fig. 9. Reduction in carbon dioxide emissions by converting boiler houses to gas in the Tunkinsky district.

C. Prerequisites for and efficiency of converting consumers to gas in the Tunkinsky district

One of the possible ways to reduce emissions of pollutants and greenhouse gases in the Tunkinsky district may be the transition to more environmentally friendly energy sources, namely, natural gas. As shown above, CO_2 emissions from municipal wood-fired boilers in the Okinsky district are considered to be zero.

The main preconditions for converting the Tunkinsky district to gas can be the plans of PJSC Gazprom to build the Power of Siberia 2 gas pipeline to China through Mongolia and the presence of specially protected natural areas (the Tunka and Khuvsgul national parks), where economic activity should be carried out according to the special nature management rules to meet some restrictions, especially for the areas adjacent to Lake Baikal, which is regulated by the Law on the Protection of Lake Baikal [21–22].

In accordance with the prospects for the development of the gas transmission system in the eastern regions of Russia, the main gas pipeline will pass through the territory of only four municipal districts of the Republic of Buryatia, including the Tunkinsky district. Fig. 8 presents the gas pipeline route running through the territory of the Tunkinsky district according to the assignment for engineering surveys for the project «Rationale for the investments in the construction of a gas pipeline to the People's Republic of China through Mongolia» [23].

An analysis of current prices for coal used in municipal boiler houses in the Republic of Buryatia, according to [24], shows that the Tunkinsky district has one of the highest prices among the districts of the Republic, along with the Barguzinsky and Bauntovsky districts. The assessment of competitive prices for natural gas when switching from coal to gas confirmed the effectiveness of this measure for small municipal boiler houses in the Tunkinsky district. With the

Table 7. Quantitative indicators of environmental effects.

A decrease in key environmental indicators compared to the current state, t/year	District			
Indicator:	Tunkinsky			Okinsky
	Main lines of decarbonization			
	Construction of solar power plant	Conversion to gas	Heat pump units	Heat pump units
Emissions of pollutants	12	1 507	1 091	207
Formation of ash and slag waste	-	753	542	103
Greenhouse gas emissions (CO_2)	409	6 010	7 205	-

price of coal for boiler houses of $38-44/t, competitive prices for natural gas are estimated at $146-170/1 000 m^3.

The basis for the transition to low-carbon energy should still be environmental, social, and climate effects. Estimates of the reduction in the anthropogenic load on the environment during the transition of the boiler houses to gas in the Tunkinsky district are given in Table 6.

Conversion of boiler houses to natural gas will completely eliminate emissions of particulate matter and sulfur oxides into the atmosphere, and the total emission of pollutants will be reduced by 159 times or by 99% compared to the current state. The emission of carbon dioxide will decrease by 2.5 times, from 10 to 4 thousand t/year (Fig. 9).

Moreover, a significant environmental benefit of converting to gas is the complete elimination of ash and slag waste in the Tunkinsky district.

IV. Environmental effects for various directions of transition to low-carbon energy

The implementation of the recommended directions for the transition to low-carbon energy in the Baikal-Khuvsgul transboundary territory makes it possible to gain some environmental effects associated with a reduction in the anthropogenic pressure on the natural environment. The construction of a solar power plant to replace part of diesel power plants will provide an opportunity for the Tunkinsky district to cut down diesel fuel consumption, which will decrease pollutant emissions by 12 t and carbon dioxide emissions by 409 t, yearly.

Conversion of municipal boiler houses in the Tunkinsky district to gas will reduce pollutant emissions by 1.5 thousand tons/year, greenhouse gas emissions by 6 thousand tons/year and eliminate the ASW formation. The most significant measure in the context of low-carbon energy development in the Tunkinsky district is to introduce heat pump units to replace 22 small boiler houses. As a result, only two boiler houses will supply pollutants, greenhouse gases and ASW to the elements of the natural environment. In general, the reduction in pollutant emissions will decrease from 1.5 to 0.5 thousand tons/year, CO_2 emissions - from 10 to 2.8 thousand tons, and ASW – from 753 to 211 tons/year (Table 7).

From a scientific perspective, it is of interest to compare the environmental effects for various lines of transition to low-carbon energy. The comparison for the Tunkinsky district shows that the greatest reduction in CO_2 emissions can be achieved by using heat pumps instead of numerous low-capacity boiler houses (with a load of up to 0.4 Gcal/h): heat pumps can reduce the existing emission of 10 thousand t/year by 7.2 thousand t/year, while the conversion of all heat sources in the district to gas – by 6 thousand t/year. However, conversion to gas wins when it comes to the emissions of pollutants into the atmosphere and the ASW production.

To reduce the anthropogenic pollution of the natural environment in the Okinsky district, it may be quite justified to use heat pumps instead of low-capacity boilers (only 4, out of 18, wood-burning boilers will remain in operation). Studies have shown that in this case, the emission of pollutants will decrease from 217 to 10 tons/year (22 times) and the production of ASW will drop from 108 to 5 tons/year (22 times) (see Table 7). In general, the environmental impact in this area will be virtually eliminated.

V. Conclusion

The Baikal-Khuvsgul transboundary territory is an advantageous area for the development of recreational activities and tourism. The existing energy system does not provide adequate conditions for this. The power system is characterized by low reliability and inability to connect new large consumers. Heat is supplied to consumers from many coal-fired and wood-fired boilers of small and medium capacity, which are characterized by low performance and have an inefficient exhaust gas purification system.

To improve the reliability and environmental efficiency of energy supply to consumers in the Baikal-Khuvsgul transboundary territory, the research involves studying the challenges of transitioning to low-carbon technologies. The use of RES and conversion of municipal boiler houses to gas are considered as the main avenues.

An analysis of the resources available in the territory showed a high solar energy potential for the expansion of generation based on photovoltaic converters. The levelized cost of electricity generation from low-capacity solar power plants is estimated to lie in the range of $0.07–0.09/kWh. This cost is comparable to the electricity tariff for the population of the considered territories, which reaches $0.06 /kWh. The placement of solar power plants at remote substations offers a combination of benefits: an increase in the reliability of power supply, opportunity to connect new consumers, reduction in pollutant emissions from backup diesel power plants, and elimination of fuel import and storage.

Another way of using RES in the territory at issue is to replace low-capacity coal-fired boilers with heat pumps. The geothermal energy potential is sufficient, but the capital cost of a heat pump-based heating system is high, which is why this option can be considered only if there is a significant increase in air pollution charges or a carbon tax is introduced. The levelized cost of thermal energy production from heat pump unit is \$62/Gcal, which significantly exceeds the value of this indicator for the boiler house (\$41.5/Gcal).

Conversion of municipal boiler houses to gas can become an important alternative to the transition to low-carbon technologies in the Tunkinsky district, but it will not completely resolve the issue of decarbonization, since burning of gas fuel causes CO_2 emissions too, albeit to a lesser extent. However, the implementation of this direction will significantly reduce the environmental impact from the municipal boilers: the emissions of particulate matter and sulfur dioxide will be eliminated and no ash and slag waste will be produced. This is a very important point for the creation of acceptable conditions for any type of activity in the territory of the Tunka National Park, which is a zone of special nature management. It should be emphasized once again that conversion to gas is possible only under certain conditions, if the main gas pipeline runs through the territories at issue.

However, decarbonization technologies can play an important role when they are aimed at jointly solving environmental, social, and climate problems.

The findings of the study have enabled us to make important conclusions, some of which should be highlighted:

1) The greatest environmental effect for the Tunkinsky district, as a zone of special nature management, can be provided by converting municipal boiler houses to gas;

2) The greatest decarbonization effect can be obtained by eliminating the combustion of fossil fuels;

3) It is advisable to solve the environmental problems in the considered territories by combining various avenues and technologies.

Acknowledgment

The research was carried out under State Assignment Project (no. FWEU-2021-0004) of the Fundamental Research Program of the Russian Federation 2021–2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] S. Piccolroaz, M. Toffolon, “The fate of Lake Baikal: how climate change may alter deep ventilation in the largest lake on Earth,” *Climatic Change*, 2018, no. 150, pp. 181–194. DOI: 10.1007/s10584-018-2275-2 (accessed 25.03.2022).

[2] O. V. Evstropeva, *Cross-border tourism in the adjacent regions of Russia and Mongolia*. Irkutsk, Russia: Publishing House of the V.B. Sochava Institute of Geography SB RAS, 2009, 143 p. (In Russian)

[3] D. Enhtayvan, O. Evstropeva, “Trans-boundary tourism in Mongolia,” *Service and Tourism: Current Challenges*, 2015, vol. 9 (4), pp. 37–42. DOI: 10.12737. (In Russian)

[4] Y. He, P. Huang, H. Xu, “Simulation of a dynamical ecotourism system with low carbon activity: A case from western China,” *Journal of Environmental Management*, 2018, vol. 206, pp. 1243–1252. DOI: 10.1016/j.jenvman.2017.09.008 (accessed 25.03.2022).

[5] M. Heshmati, M. Gheitury, S. Shadfar, “Factors affecting possibility of ecotourism development and sustaining natural resources using SWOT approach in west Iran,” *International Journal of Geoheritage and Parks*, 2022, vol. 10, pp. 173–183. DOI: 10.1016/j.ijgeop.2022.03.004 (accessed 25.03.2022).

[6] X.-L. Tian, F. Bélaïd, N. Ahmad, “Exploring the nexus between tourism development and environmental quality: Role of Renewable energy consumption and Income,” Structural Change and Economic Dynamics, 2021, vol. 56, pp. 53–63. DOI: 10.1016/j.strueco.2020.10.003 (accessed 25.03.2022).

[7] K. Kovačević Markov, N. Rajaković, “Multi-energy microgrids with ecotourism purposes: The impact of the power market and the connection line,” *Energy Conversion and Management*, 2019, vol. 196, pp. 1105–1112. DOI: 10.1016/j.enconman.2019.05.048 (accessed 25.03.2022).

[8] F. Minaei, M. Minaei, I. Kougias, H. Shafizadeh-Moghadam, S. A. Hosseini, “Rural electrification in protected areas: A spatial assessment of solar photovoltaic suitability using the fuzzy best worst method,” *Renewable Energy*, 2021, vol. 176, pp. 334–345. DOI: 10.1016/j.renene.2021.05.087 (accessed 25.03.2022).

[9] I. Yu. Ivanova, V. A. Shakirov, N. A. Khalgaeva, “Effects of the Adoption of Renewable Energy Sources within the “Baikal-Khövsgöl” Cross-Border Recreation Area,” *Energy systems research*, 2019, vol. 2, no. 3, pp. 11–20. DOI: 10.25729/esr.2019.03.0002 (accessed 25.03.2022).

[10] *Energy cooperation between Russia and Mongolia: the current state, a look into the future*, Collective monograph, prof. B.G. Saneev and academician of ASM S. Batmunkh, eds. Irkutsk, Russia: Melentiev Energy Systems Institute SB RAS; Ulaanbaatar, Mongolia: Mongolian State University of Science and Technology ASM, 2021, 346 p.

[11] *Methodology for determining emissions of pollutants into the atmosphere during fuel combustion in boilers with a capacity of less than 30 tons of steam per hour or less than 20 Gcal per hour.* Moscow, Russia: State Committee for Environmental Protection of the Russian Federation (with the participation of the firm «Integral», St. Petersburg), 1999, 53 p. (In Russian)

[12] *Methodological letter of the Atmosphere Research Institute No. 335 / 33-07 dated May 17, 2000 "On the calculation of emissions of harmful substances into the atmosphere according to the "Method for determining pollutant emissions into the atmosphere during fuel combustion in boilers with a capacity of less than 30 tons of steam per hour or less than 20 Gcal per hour,"* (Moscow, 1999). St. Petersburg, Russia: Atmosphere Research Institute, 2000, 20 p. (In Russian)

[13] Yu. G. Nazmeev, *Ash and slag removal systems at TPPs*. Moscow, Russia: MEI Publishing House, 2002, 572 p. (In Russian)

[14] *On the approval of some methodological documents in the field of environmental protection. Order of the Ministry of Environmental Protection of the Republic of Kazakhstan dated April 18, 2008 No. 100-p.* Available at: http://new.ecogosfond.kz/wp-content/uploads/100-ves.pdf (accessed 24.10.2021).

[15] *Methodological instructions and guidelines for the quantitative determination of greenhouse gas emissions by organizations engaged in economic and other activities in the Russian Federation*. Approved by order of the Ministry of Natural Resources of Russia dated June 30, 2015. Available at: http://sro150.ru/metodiki/371-metodika-rascheta-vybrosov-parnikovykh-gazov (accessed 25.03.2022). (In Russian)

[16] *National report on the inventory of anthropogenic emissions from sources and absorption by sinks of greenhouse gases not controlled by the Montreal Protocol for 1990-2019. Part 1.* Moscow, Russia: Rosgidromet, 2021, 459 p. (In Russian)

[17] I. Ivanova, V. Shakirov, "Multi-criteria placement and capacity selection of solar power plants in the Baikal-Khövsgöl cross-border recreation area," E3S Web of Conferences, 2020, vol. 209, Art. no. 05004.

[18] I. Yu. Ivanova, N. A. Khalgaeva, "Validation of the efficiency of using solar energy resources for autonomous power supply of the trans-border area between Russia and Mongolia," IOP Conf. Ser.: Earth Environ. Sci., 2021, vol. 629, Art. no. 012020.

[19] V. I. Verbolov, V. M. Sokolnikov, M. N. Shimaraev, *Hydrometeorological regime and thermal balance of Lake Baikal*. Moscow, Russia: Nauka, 1965, 371 p. (In Russian)

[20] I. Y. Ivanova, V. A. Shakirov, M. V. Ermakov, F. S. Bukher, "Feasibility study of using geothermal heat-pump units for substituting small-capacity coal-fired boiler houses (Taking the Baikal natural area as an example)," *Thermal Engineering*, 2020, vol. 67, no. 10, pp. 741–750. DOI: 10.1134/S0040601520100055

[21] *PJSC Gazprom Annual Report 2020*. Available at: https://www.gazprom.ru/f/posts/57/982072/gazprom-annual-report-2020-ru.pdf (accessed 25.03.2022)

[22] *Federal law "On protection of Lake Baikal"* (ed. of 14.07.2008) № 94-FL of 01.05.1999, Moscow, Russia, 1999. Available at: http://www.kremlin.ru/acts/bank/13787. (accessed 25.03.2022)

[23] T*he gas pipeline from Russia to China is planned to be laid through the Tunka National Park in Buryatia.* Available at: http://ww.infpol.ru/234646-gazoprovod-iz-rossii-v-kitay-dumayut-protyanut-cherez-tunkinskiy-natspark-v-buryatii/. (accessed 25.03.2022)

[24] *State information system of housing and communal services.* Available at: https://dom.gosuslugi.ru/#!/public-tariff/communal-resources/search (accessed 08.12.2021).

Irina Yu. Ivanova is a Ph.D. in economics, Head of the Laboratory of Energy Supply to Off-grid Consumers at Melentiev Energy Systems Institute SB RAS, Irkutsk. She is the winner of the regional competition in the field of science and technology.

Her research interests are small-scale energy, the policy of energy supply to consumers in the northern and remote areas, modeling of financial and economic activities of autonomous energy sources.

She is the author of more than 150 publications, including chapters and sections in 25 collective monographs.

SPIN 6445-7531. Hirsch index 10.

Vladislav A. Shakirov received the Ph.D. degree in engineering from Irkutsk State Transport University in 2007. Currently, he is a senior researcher of the Laboratory of Energy Supply to Off-grid Consumers at Melentiev Energy Systems Institute SB RAS. His main research interests are renewable energy, decision-making problems, and energy planning in remote areas.

Elena P. Maysuyk is a Ph.D. in economics (2002), senior researcher of the Laboratory of Energy Supply to Off-grid Consumers at Melentiev Energy Systems Institute SB RAS, Irkutsk.
Her research interests are environmental issues of energy systems development in East Siberia and the Far East. She is the author and co-author of more than 85 publications, including chapters and sections in 20 collective monographs.

Roman A. Ivanov graduated from Irkutsk Polytechnic Institute majoring in computing machines, complexes, systems and networks in 2009. He received a Ph.D. in engineering in 2013. Currently he is a researcher of the Laboratory of Energy Supply to Off-grid Consumers at Melentiev Energy Systems Institute SB RAS, Irkutsk.
His research interest are information technologies in the energy sector, visualization and analytics of the results, and development of software for decision-making in energy.

Lightning Risk Assessment Software Design for Photovoltaic Plants in Accordance with IEC 62305-2

Mohammad Parhamfar*

A freelance consultant in the power and energy field

***Abstract* — The lack of an effective protection scheme delays the integration of photovoltaic (PV) plants into distribution networks. Outdoor installation of these systems always exposes them to direct/indirect lightning strikes and consequent overvoltages. If lightning overvoltages are not limited, the PV plant equipment may be damaged. A lightning protection system (LPS) consisting of external and internal sections aims to protect the PV plant against overvoltages of the atmospheric origin. However, the lightning risk assessment for determining the need for the LPS installation and the overvoltage protection system design are complicated tasks. In the past, there was no special software for lightning risk assessment in solar power plants, and only some papers have mentioned the calculation method and software developed according to local standards. This paper develops a software application for lightning protection design of PV plants especially for risk assessment analyses according to IEC62305-2. The designed software has used a comprehensive standard compared to other software, and in addition to considering solar farms, it also covers off-grid and on-grid rooftop systems. The evaluation results show that the proposed software is a useful tool for electrical engineers and renewable energy experts who are active in the PV integration industry. Using this software, specialists will be able to easily perform complex calculations and select the suitable LPS for the projects.**

***Index Terms*: photovoltaic, lightning protection software, risk assessment, surge protective device.**

* Corresponding author.
E-mail: Info@parhamfar.com

http://dx.doi.org/10.38028/esr.2022.02.0004
Received May 05, 2022. Revised July 11, 2022.
Accepted July 30, 2022. Available online August 31, 2022.

I. Introduction

One of the important topics of electrical engineering is the study of different aspects of renewable energies. Accessibility, free primary energy, PV modules advancement, and government incentives contribute to increased attention to the PV systems among other renewable energy sources [1]. According to the international energy agency (IEA) report, despite the COVID-19 crisis, the global PV will increase every year [2]. The safe and accurate performance of the PV systems improves their offered resilience. Therefore, the enhancement of control algorithms and protection systems ensures that the PV systems remain at the forefront of renewable energy technologies.

The design of an effective protection system has always been one of the main challenges of electrical networks. Protection system should be simple and economic and detect any abnormal condition quickly to decrease damage to the network equipment (reliability and speed). It should also isolate only the faulty section (selectivity). Due to outdoor installation, the PV systems are subjected to both overcurrent due to short-circuit faults and overvoltage of atmospheric origin. A short-circuit fault results in overcurrent on the DC/AC side of the PV power plant, which is usually detected and isolated by the miniature circuit breakers (MCBs) or molded case circuit breakers (MCCBs). A ground fault is detected by the ground fault protection device. On the other hand, lightning may result in overvoltages in the PV system equipment. In some research, computer programs for risk calculations in solar power plants have been developed based on local and old standards [3]. Software developed by the world's largest companies does not provide the evaluation of solar power plants separately [4, 5].

Little work has been done as yet to design software to assess the risk of lightning strikes on photovoltaic installations. In [6], a comprehensive review of the superior modeling methods of PV systems during lightning strikes is presented. The paper displays various platforms to simulate the transient effects of lightning strikes on PV systems. This paper also gives some recommendations about the modeling methods and protection of PV systems during lightning strikes. A computer program for lightning strike risk assessment and design of lightning protection system for the photovoltaic system is also proposed in [7].

In this paper, a developed software for risk assessment calculation according to IEC62305-2 and LPS design for PV plants is introduced and investigated. By using this software, an engineer can evaluate various lightning protection system designs in a short time. This software helps to understand the concepts of lightning protection design and to view the result of their design without performing numerous calculations.

II. Fundamentals of Lightning Protection System Design for PV Systems

1.1. Basic Principles

Lightning overvoltage protection is one of the main modules of protection schemes of PV power plants, especially in countries with stormy and cloudy climates [8]. If an overvoltage condition is not detected and isolated, the PV system equipment may be damaged, which will lead to an increase in the return time of investment. PV systems are subjected to both direct and indirect overvoltages. In the former case, the lightning strikes the PV structure while in the latter case, lightning falls near the structure, or signaling/electrical lines entering the structure are affected by the lightning. When lightning strikes near the structure, the resultant variable magnetic field induces the overvoltages on the building circuit (inductive coupling) while when lightning strikes the entering lines, through the line characteristic impedance, the lightning current results in overvoltage (resistive coupling). If an overvoltage exceeds the impulse withstand voltage of equipment, it is damaged and even poses a risk of fire hazard.

An LPS consists of external and internal protection systems. The external protection system protects the PV system against direct strikes by using the air-termination system (ATS), down-conductor system, and earth-termination system for intercepting the lightning, conducting the current to the ground, and distributing the current in the ground, respectively. The internal protection system protects the PV system against sparking inside the structure by implementing equipotential bonding or keeping a separation distance between the LPS components and other conductive elements of the structure.

In the case of direct lightning, there can be three conditions [9]:

1. Rooftop PV plant without LPS: If the PV installation does not change the building outline, the frequency of the threat does not change, and consequently, no measures are required. Otherwise, the risk assessment should be performed.
2. Rooftop PV plant with LPS: If the PV plant does not significantly change the building outline and the minimum distance d between the available LPS and PV system is greater than safety distance s, no measures are required. However, if d is less than s, the LPS should be extended and connected to the PV metal structure. If the PV installation changes the building outline, a new risk assessment is required.
3. Ground PV plant: In this case, there is no fire threat due to direct strike.

In the case of indirect lightning strikes, the circuits are shielded to decrease the magnetic field. In addition, the module conductors are twisted and the live conductors are kept near to protective earth conductor to decrease the induced circuit turn area.

Even for limited overvoltages, surge protective devices (SPDs) are required to discharge them to the ground. An SPD presents a high impedance at the nominal voltage while its impedance significantly decreases in the case of an overvoltage, making a low-impedance path to the ground. Thus, the lightning current is discharged to the ground and the PV plant equipment is protected against overvoltage.

1.2. Risk Assessment Based on IEC 62305-2

According to IEC 62305-2 standard [7], risk assessment requires that source of damage, type of damage, and type of losses be determined. The primary source of damage is the lightning current. There are four damage sources: lightning strike to a structure (S1), lightning strike near a structure (S2), lightning strike to a line (S3), and lightning strike near a line (S4). Depending on the structure characteristic, there are three damage types: electric shock and the resultant injury to living beings (D1), physical damage (D2), and failure of electronic and electrical systems (D3). There are four types of loss in the structure resultant from various types of damage: human life loss, including permanent injury (L1); public service loss (L2); cultural heritage loss (L3), and economic value loss (L4).

The total potential risk in a structure is calculated as [8]

$$R = R_1 + R_2 + R_3 + R_4, \quad (1)$$

where R_1 is the risk of L1 as

$$R_1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z, \quad (2)$$

R_2 is the risk of L2 as

$$R_2 = R_B + R_C + R_M + R_V + R_W + R_Z, \quad (3)$$

R_3 is the risk of L3 as

$$R_3 = R_B + R_V, \quad (4)$$

R_4 is the risk of L4 as

$$R_4 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z, \quad (5)$$

and

- R_A is related to the injury to living beings resulting from step and touch voltages in the case of a direct strike,
- R_B is related to the physical damage resulting from sparking inside the structure, which triggers explosion or fire in the case of a direct strike,
- R_C is related to the internal system's failure resulting from lightning electromagnetic impulse (LEMP) in the case of a direct strike,

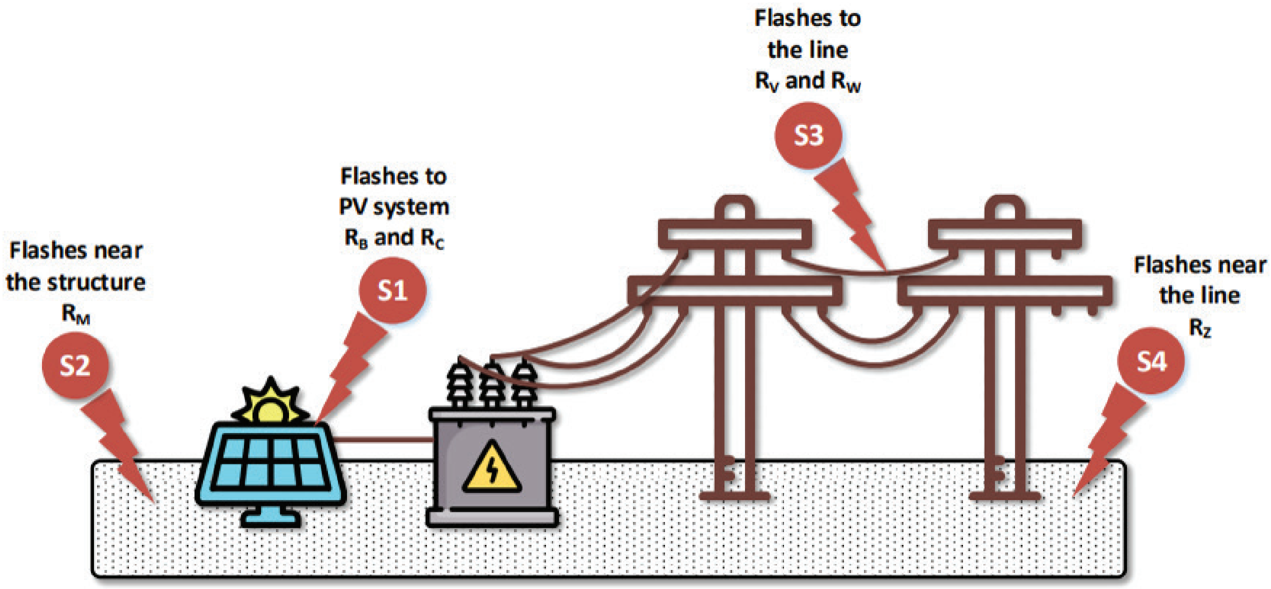


Fig. 1. Risk components of a PV system.

- R_M is related to the internal system's failure resulting from LEMP in the case of indirect strike,
- R_U is related to the injury to living beings resulting from step and touch voltages in the case of a strike to a line connected to the structure,
- R_V is related to the physical damage resulting from sparking between metallic parts and external installation due to transmitted lightning current through incoming services in the case of a strike to a line connected to the structure,
- R_W is related to the internal systems' failure resulting from induced overvoltage on incoming lines and transmitted to the structure in the case of a strike to a line connected to the structure, and
- R_Z is related to the internal systems' failure resulting from induced overvoltage on incoming lines and transmitted to the structure in the case of a strike near a line connected to the structure.

All risk components of R_A to R_Z are calculated as

$$R_x = N_x \times P_x \times L_x, \quad (6)$$

where N_x is the number of dangerous events (Year^{-1}), P_x is the structure damage probability, and L_x is the consequent loss. Due to space limitation, the detailed procedure of determining R_x is not presented; this procedure is available in [9].

If $R \le R_T$ where R_T is the tolerable risk, there is no need for lightning protection. While, if $R > R_T$, protection measures should be adopted in such a way that $R \le R_T$ for all risks threatening the structure. The tolerable risk for human life or permanent injury loss, public service loss, cultural heritage loss, and economic loss are 10^{-5}, 10^{-3}, 10^{-3}, and 10^{-3} (Year^{-1}), respectively.

1.3. Risk Assessment for PV Plants

In the risk assessment of PV systems, there is no need to consider some risks [10]. Since the structure of PV systems is nonflammable, the fire hazard can be neglected. In addition, most of the rooftop PV systems are installed on small buildings; thus, the probability of a direct strike is low. Moreover, there are no people in a large PV power plant. Consequently, human life loss risk (R1) is not considered. On the other hand, due to the small capacity of PV systems, even in the case of PV power plants, the public service is not affected by their failure. Thus, risk R2 can also be neglected. Moreover, the PV systems are not usually installed in historical places; thus, cultural heritage loss risk (R3) can be neglected.

Consequently, economic value loss is the only risk that should be considered in the risk assessment for PV systems. The risk components of R_4, R_A and R_U are related to the cases where animals may be lost. Due to installing PV systems on rooftop or enclosing the PV power plants, these risk components are neglected and only R_B, R_C, R_M, R_V, R_W, and R_Z are considered. According to [8], among these components, R_M, R_W, and R_Z are more relevant than others in the case of rooftop PV systems. Figure 1 shows the risk components of a PV system.

Since there is only one risk in the risk assessment of PV plants, $R = R_4$. The following measures can be implemented to decrease the total risk of a PV system to a tolerable level:

- reduction in R_W and R_Z by installing a coordinated SPD in the low voltage (LV) line entering the building;
- reduction in R_M by installing a coordinated SPD in the DC line of the PV system.

In the case of a PV power plant, in addition to the above-mentioned protections, an external lightning protection system can be installed to reduce R. Figure 2 shows the flowchart of the risk assessment for PV systems.

The above section was aimed at calculating Risk assessment for solar farms. In addition, the developed software can be used to make calculations for off-grid and

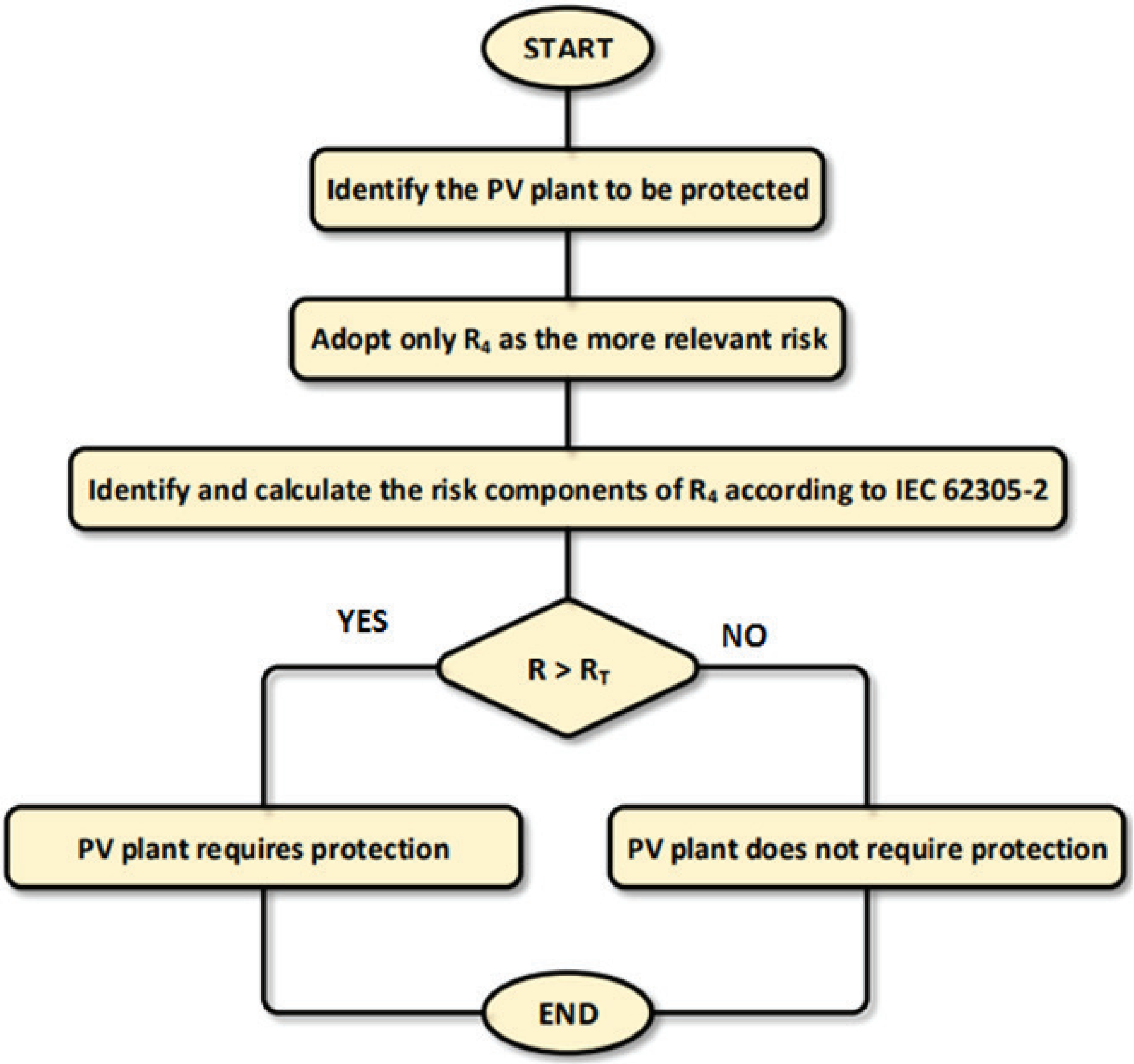


Fig. 2. Flowchart of risk assessment for solar farms.

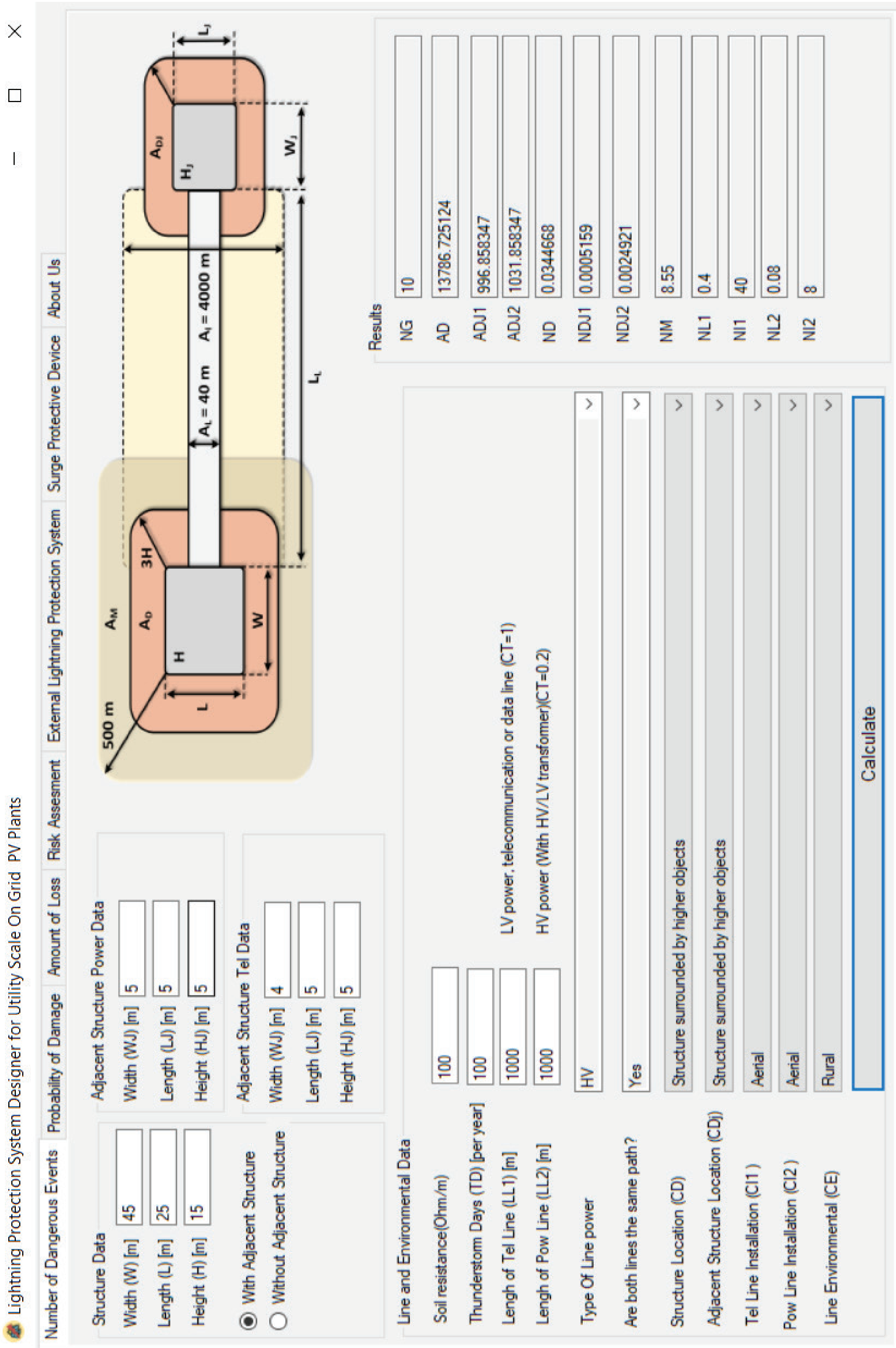


Fig. 3. The main page of the developed overvoltage protection software design.

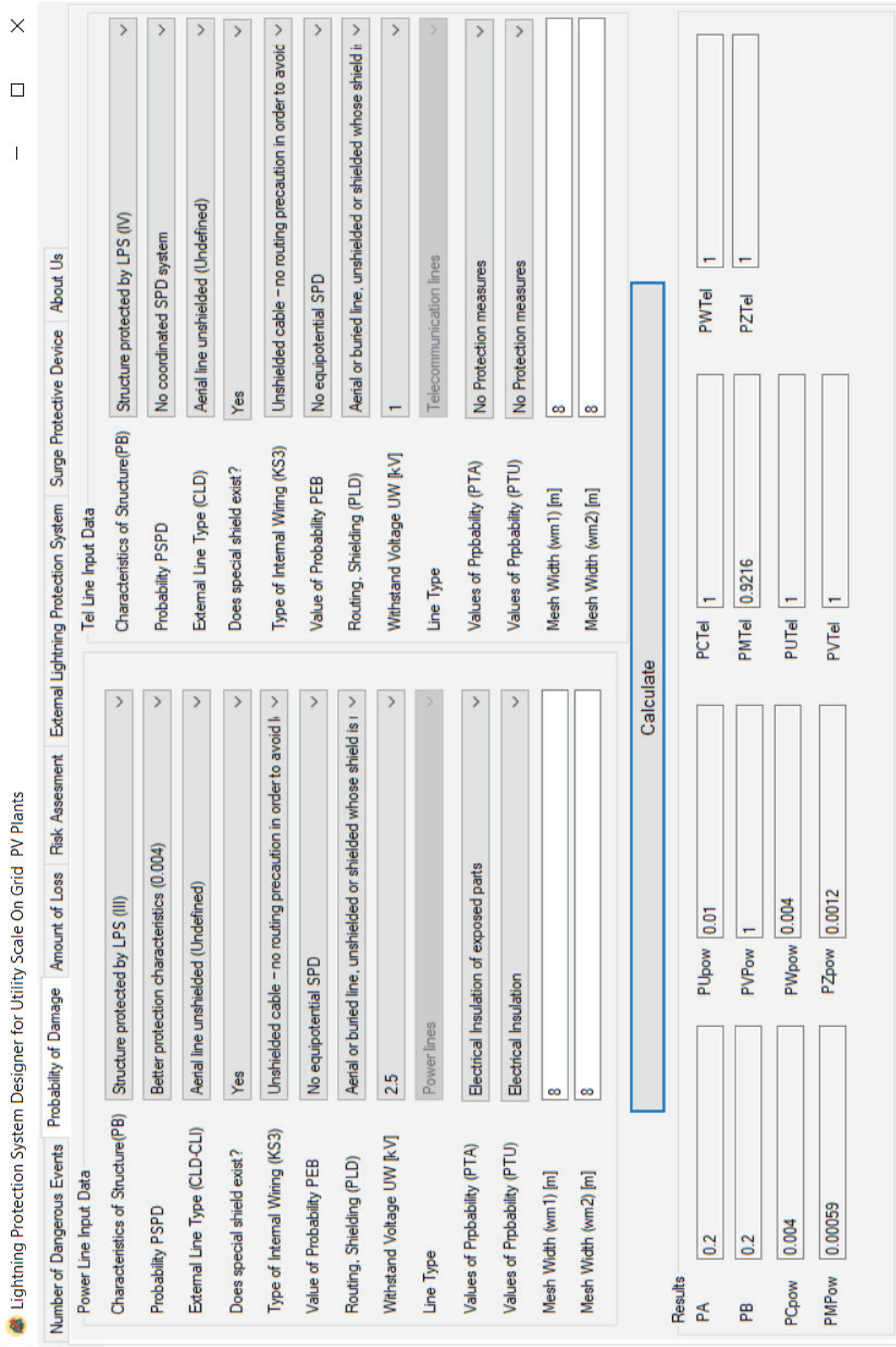


Fig. 4. The Probability of Damage Menu of the developed overvoltage protection design software.

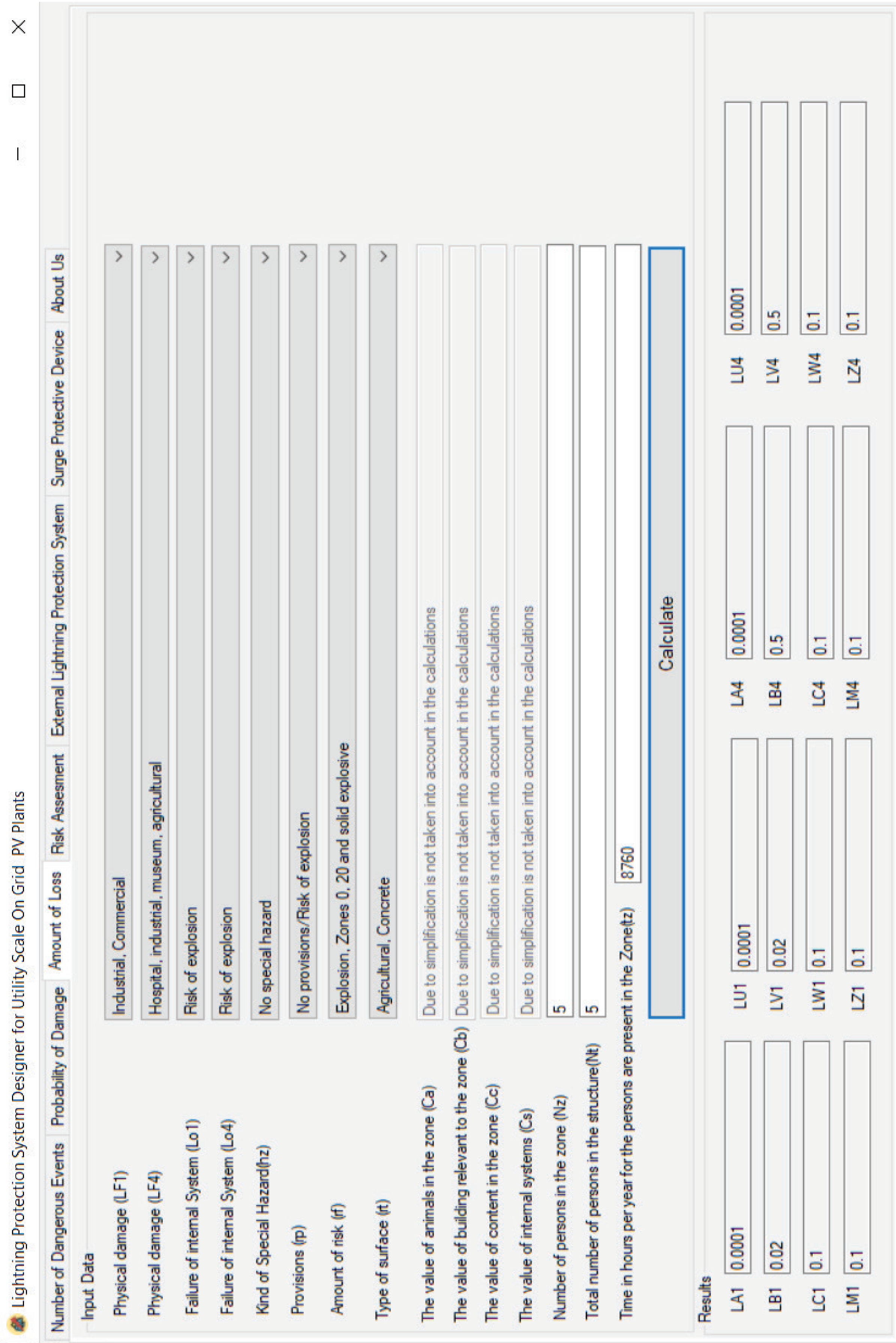


Fig. 5. The Amount of Loss Menu of the developed overvoltage protection design software.

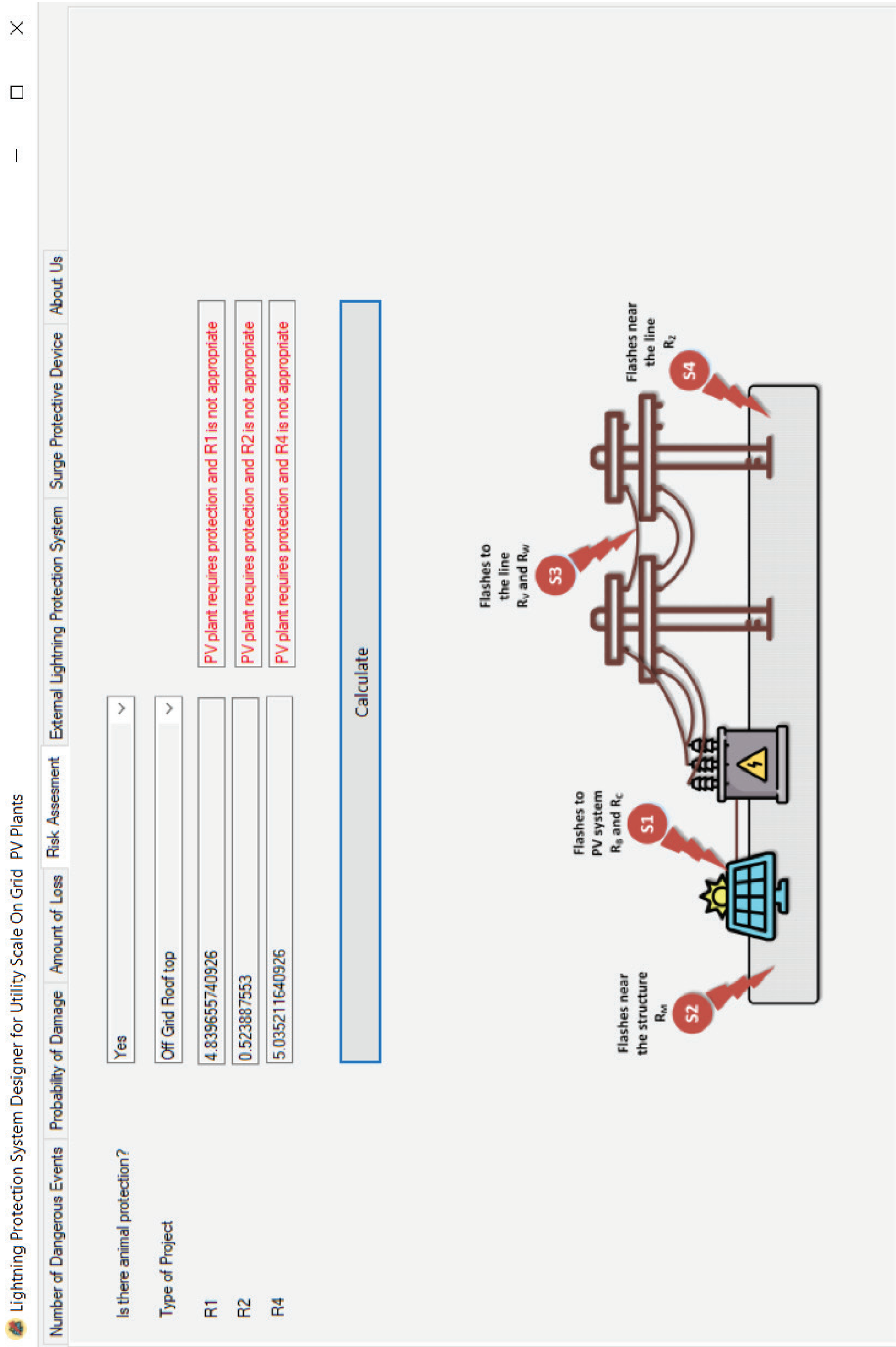


Fig. 6. The Risk Assessment Menu of the developed overvoltage protection design software.

Fig. 7. The External Lightning Protection System section.

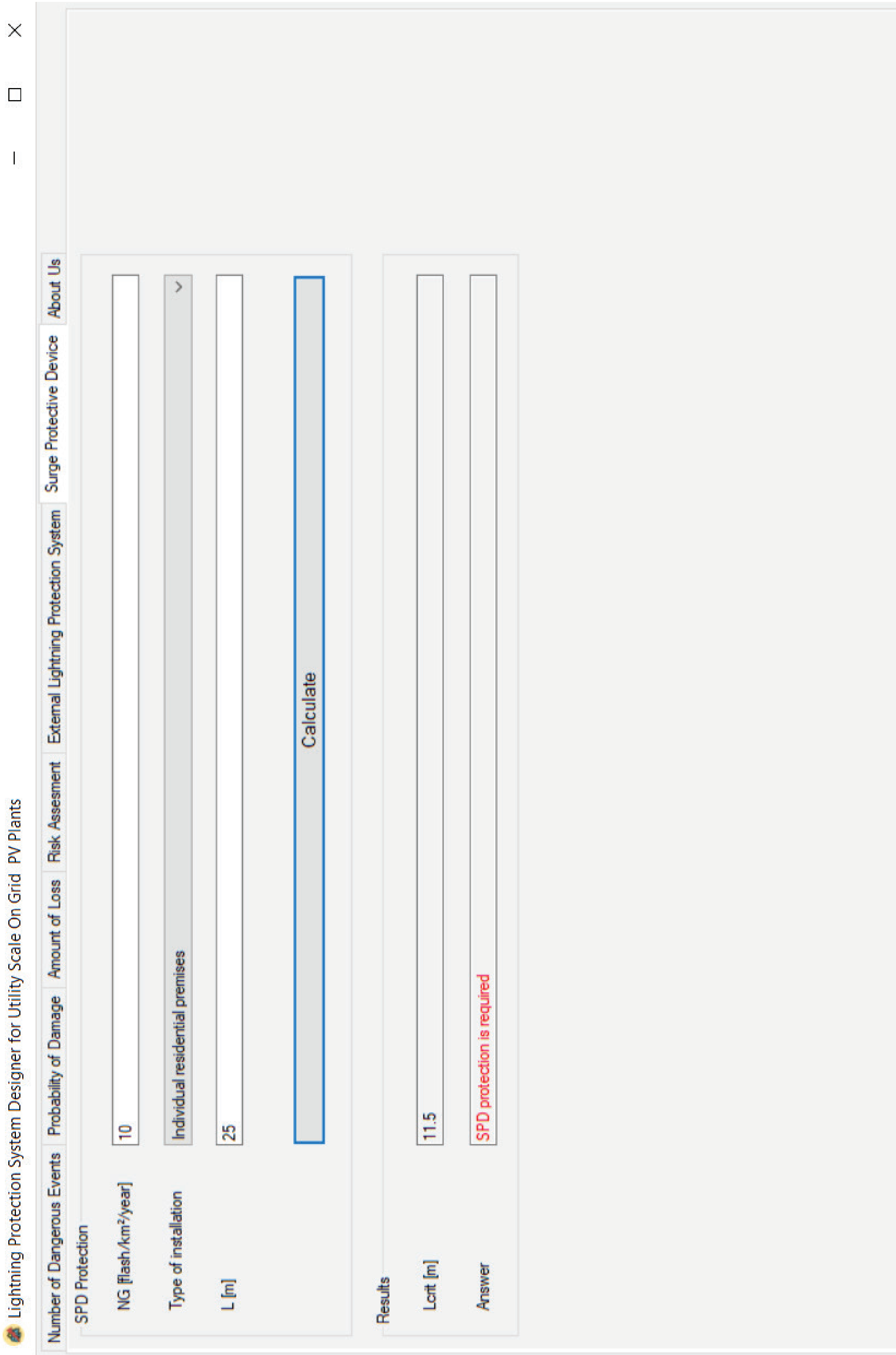


Fig. 8. The Surge Protective Device Menu.

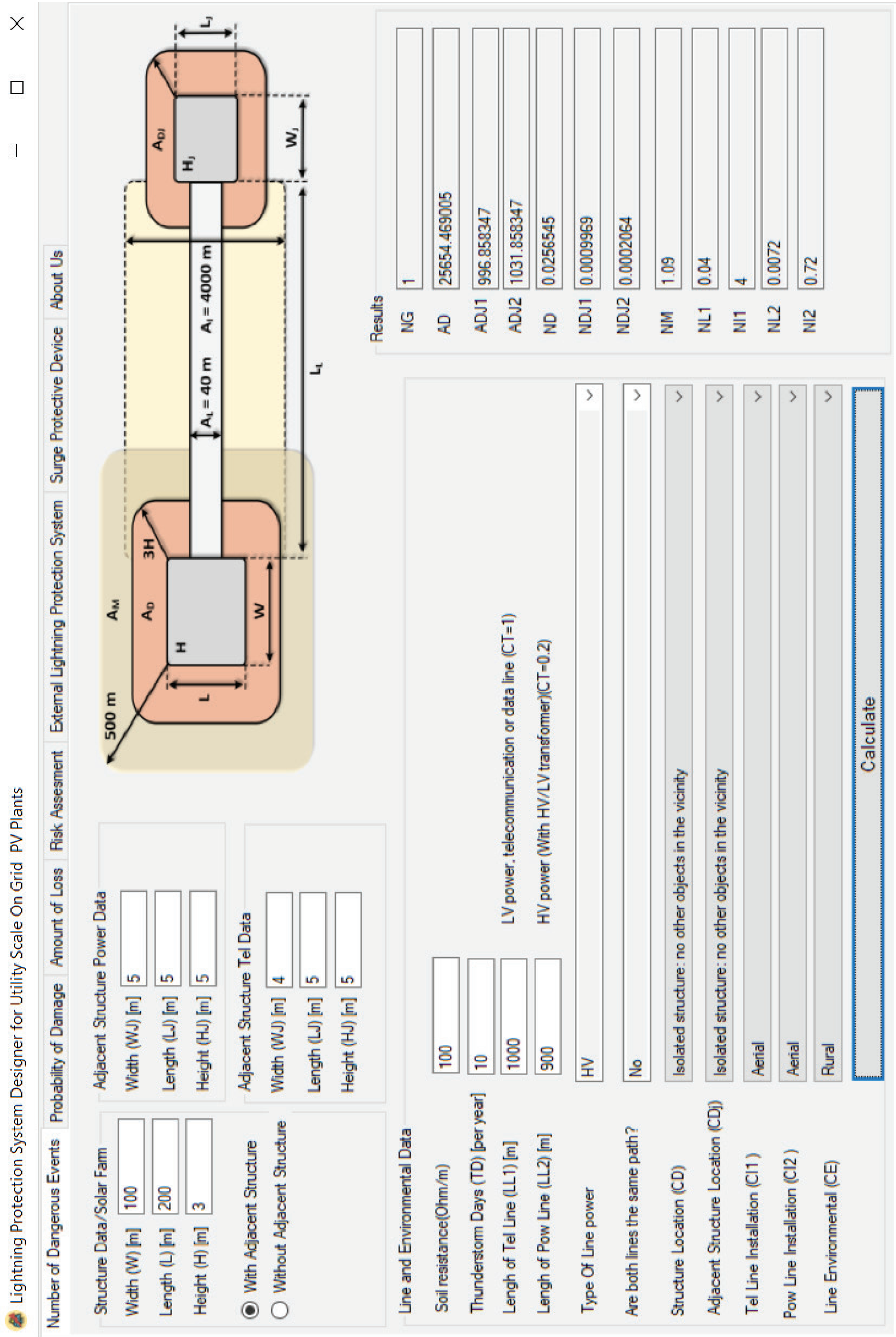


Fig. 9. The Number of Dangerous Events Menu.

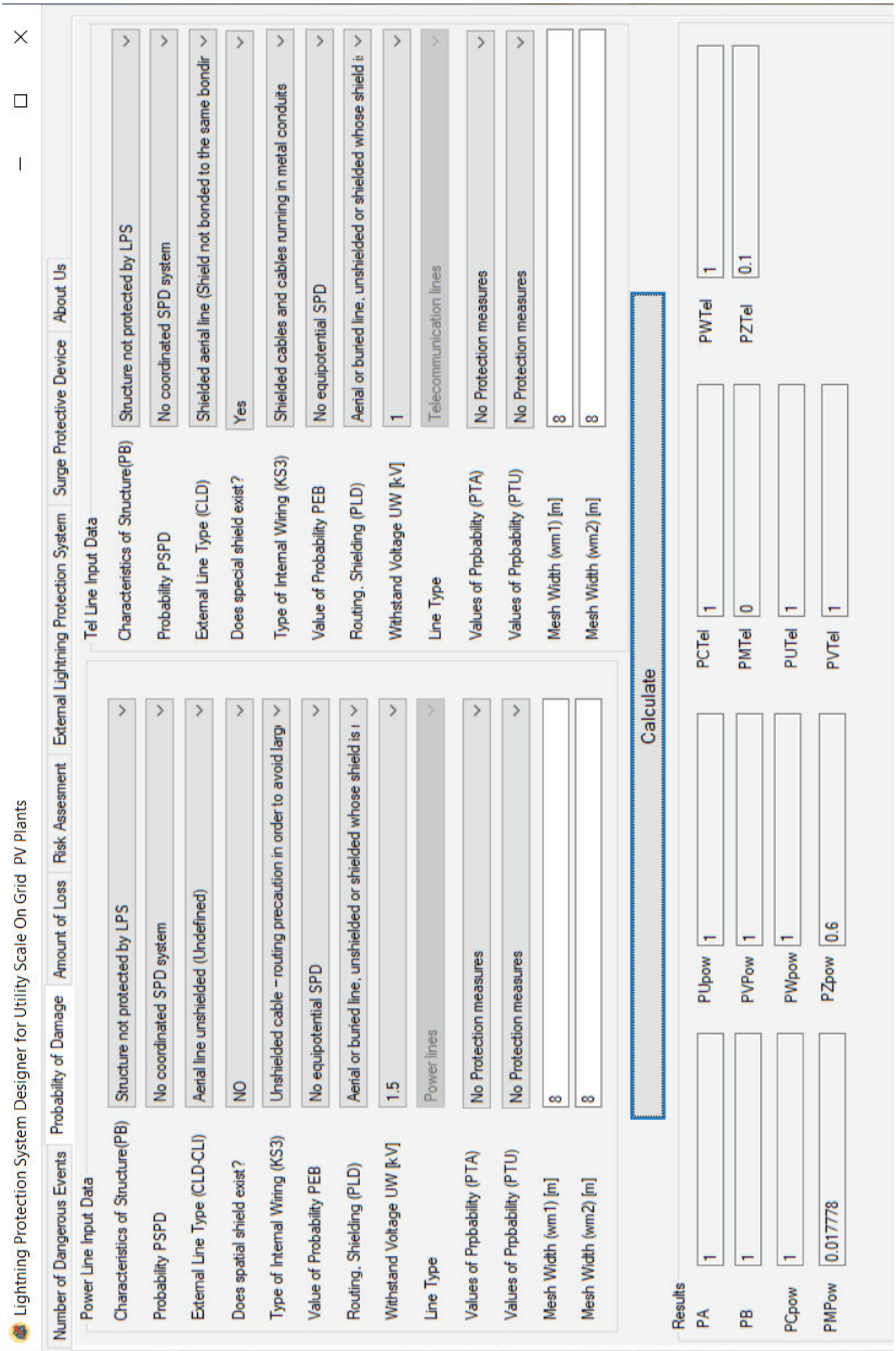


Fig. 10. The Probability of Damage Menu.

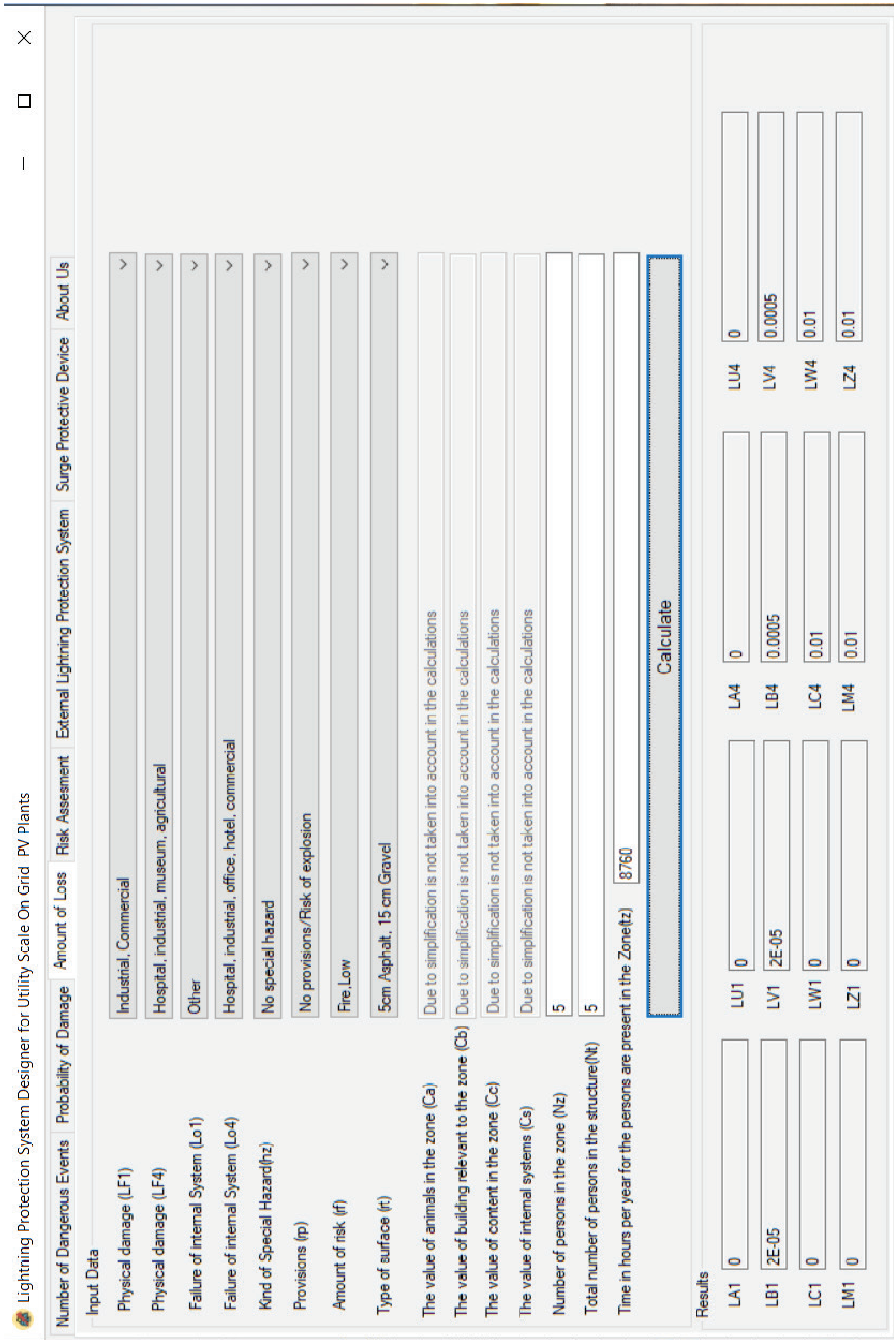


Fig. 11. The Amount of Loss Menu.

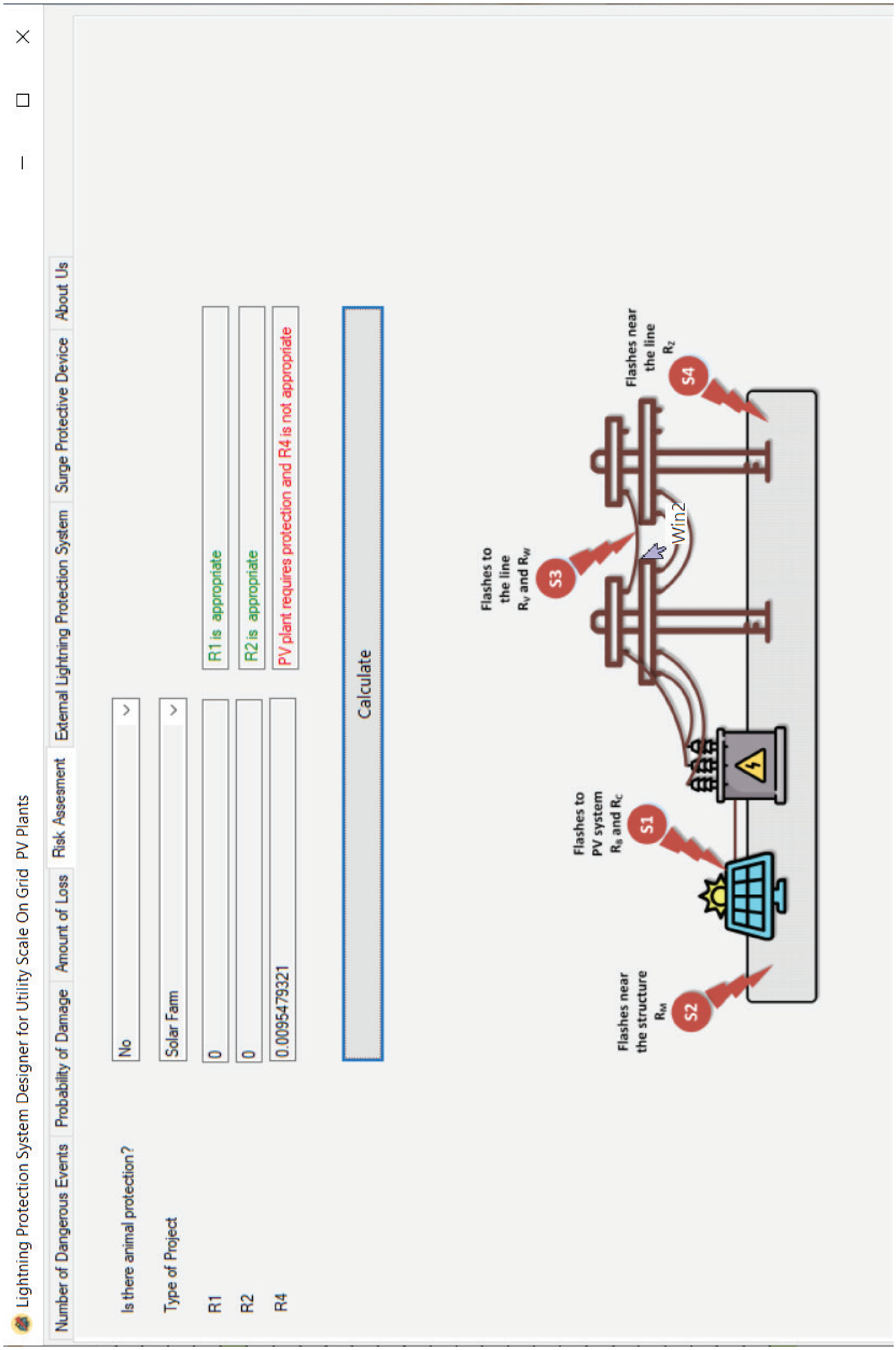


Fig. 12. The Risk Assessment Menu.

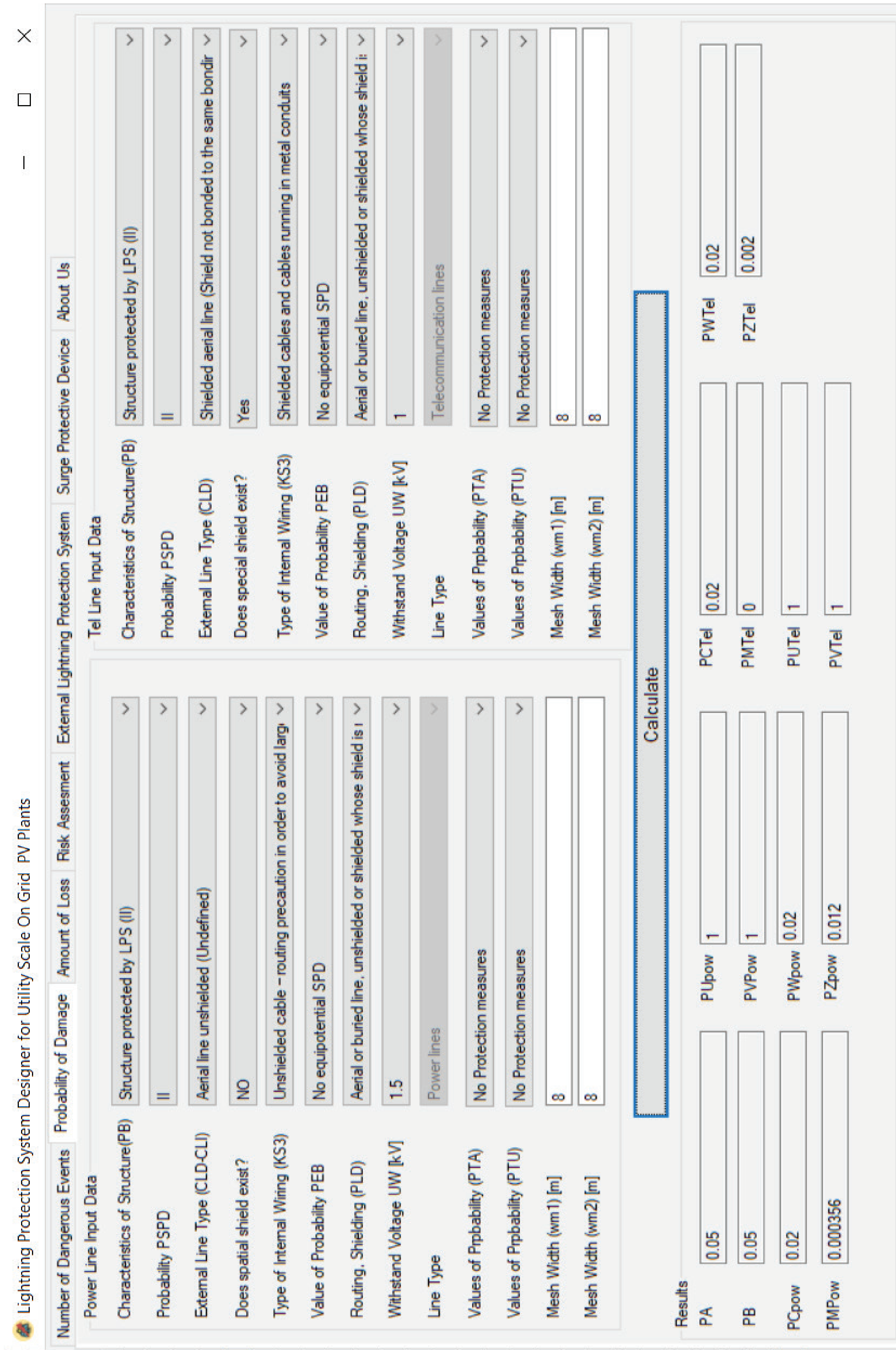


Fig. 13. The Probability of Damage Menu with new settings.

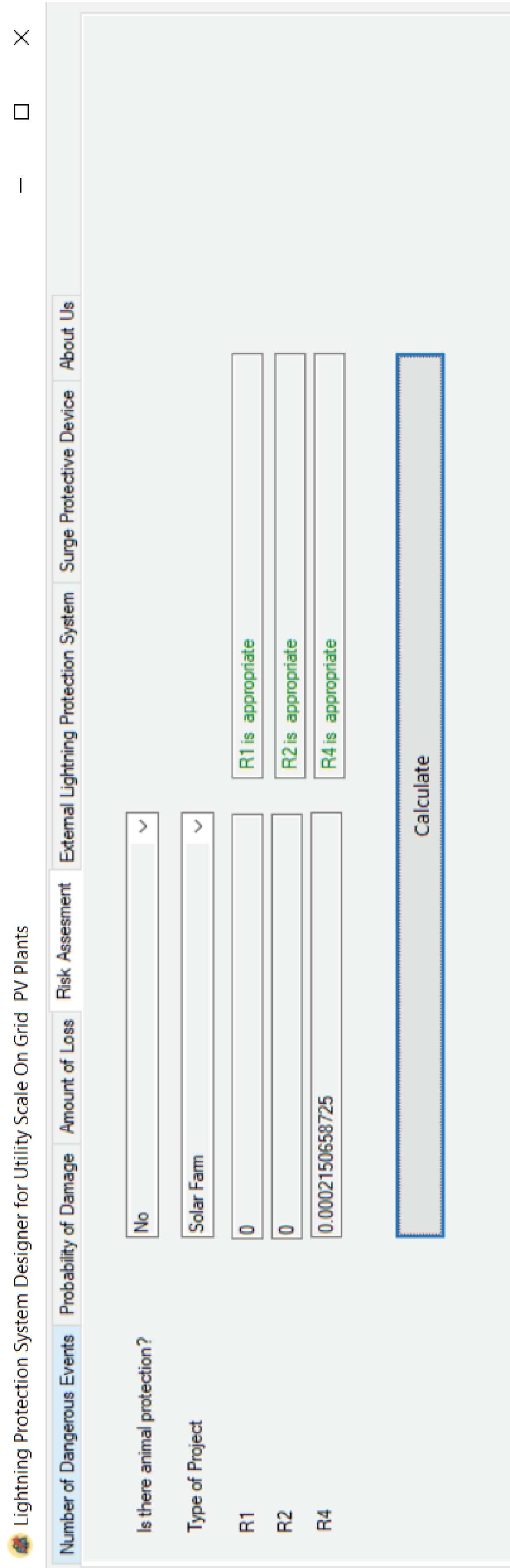


Fig. 14. The Risk Assessment Menu with new calculation.

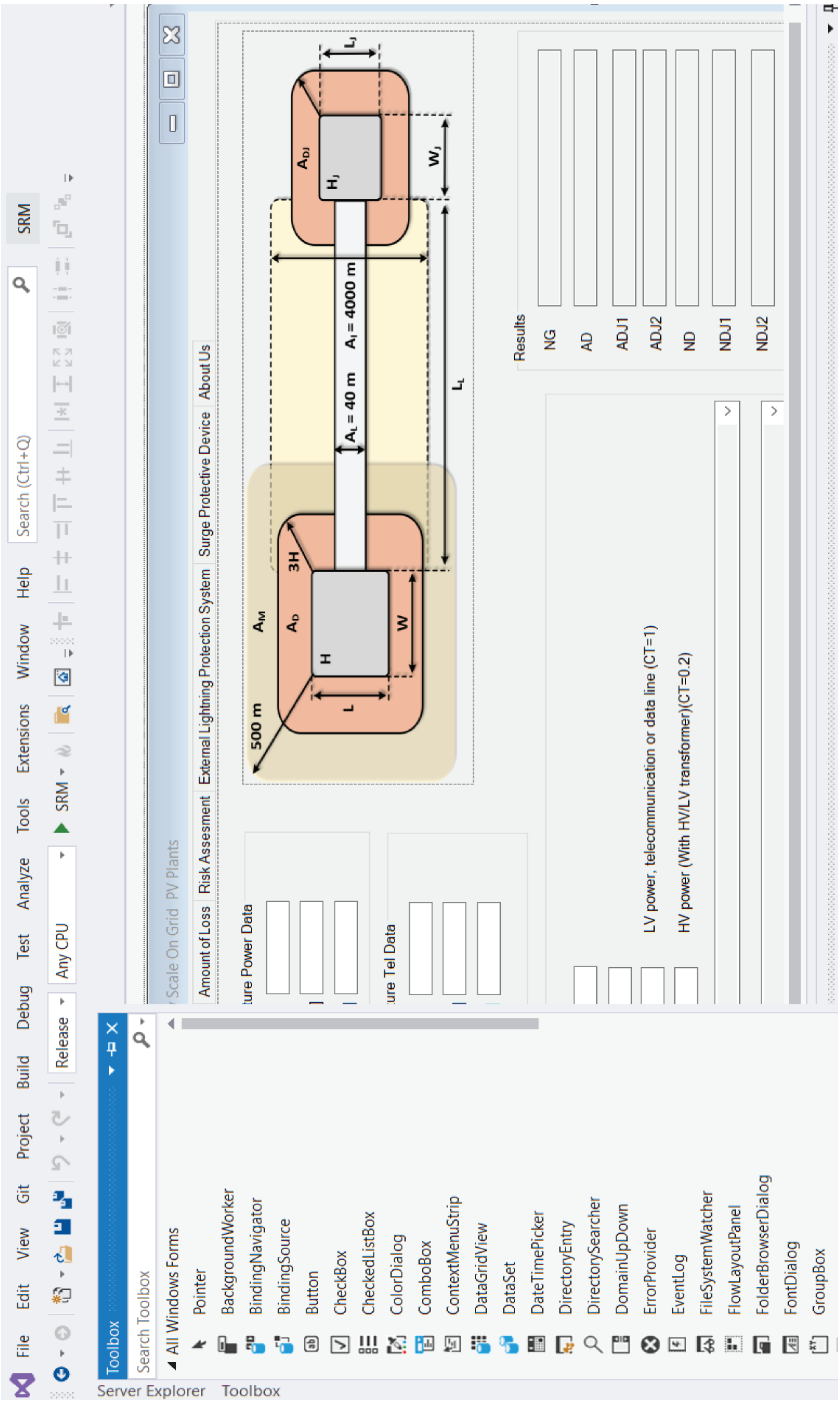


Fig. 15. Designed Software Window by Visual Studio.

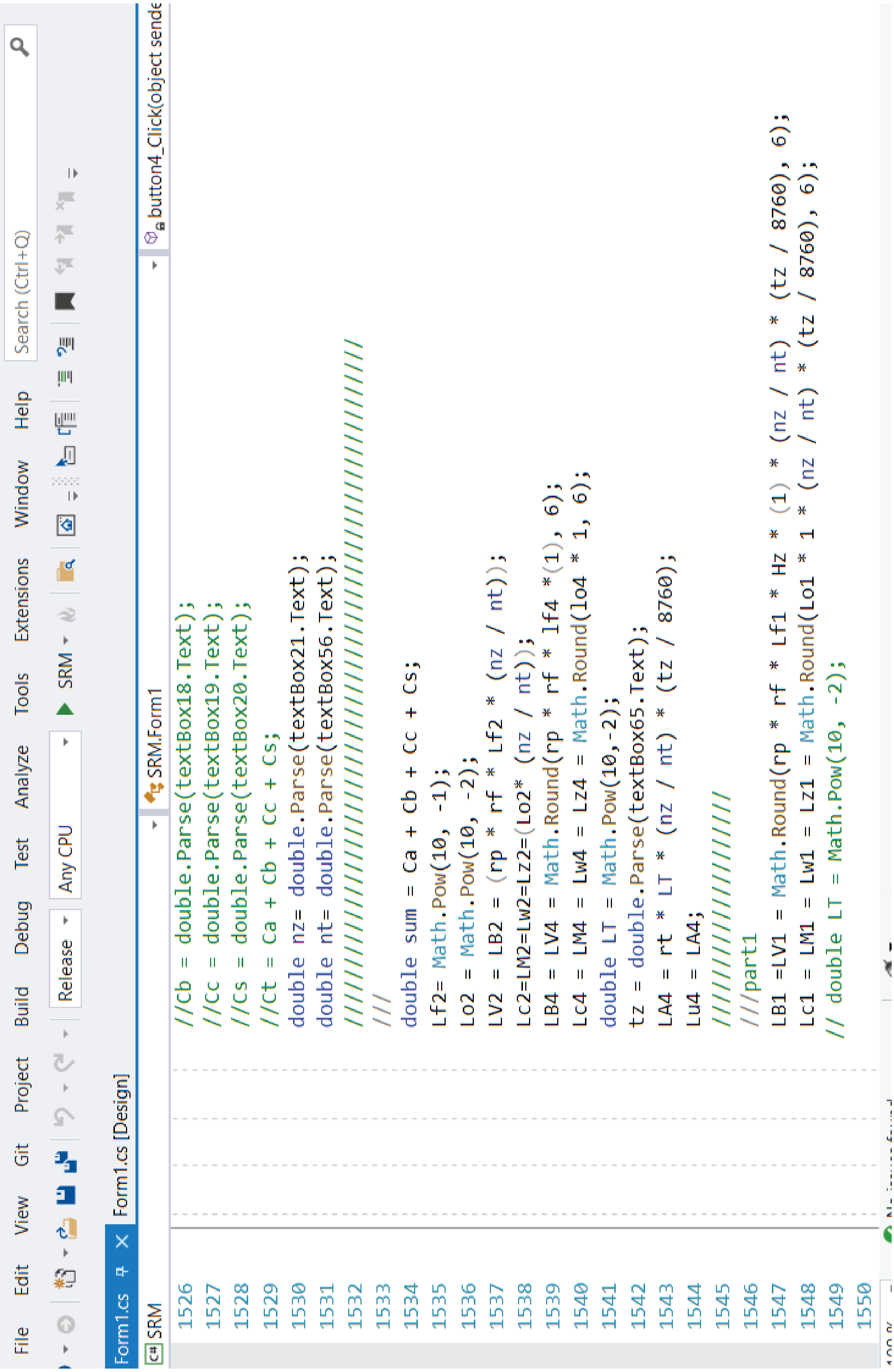


Fig. 16. Part of the Software Codes.

on-grid rooftop projects. In off-grid solar systems, risk R3 can be excluded because they are rarely used in heritage buildings. In systems connected to the solar network, we can eliminate the risk of public services and heritage buildings (R2, R3). Briefly, the following parameters have been considered for various solar power plants:

1. Solar Farms: R4.
2. Off-grid projects: R1+R2+R4.
3. On-grid rooftop projects: R1+R4.

1.4. External Lightning Protection System

As mentioned in the previous subsection, an external LPS may be required to reduce the total risk of a PV power plant. One of the most important parts of the external LPS is the air-termination system (ATS), which can consist of catenary wires (horizontal conductors), rods, and meshed conductors (Faraday cage) [11]. The ATS prevents direct flashes on the PV structure. The proper design of ATS reduces damage to the area to be protected. There are three methods to determine an ATS protection area [12]:

- Rolling sphere method: It is a universal technique, especially for complicated applications.
- Protective angle method: It is proper for simple-shaped buildings, but it has a limitation of the ATS height.
- Mesh method: It is suitable to protect the plane surfaces (for buildings).

The rolling sphere technique is an acceptable method for designing ATS. In this method, given the lightning rod height and highest piece of rooftop power plant project, the protective radius r_p of each rod is calculated as follows [13]:

$$r_p = \begin{cases} r_s + \sqrt{2h_e r_s - h_e^2}, & h_r \geq r_s, \\ \sqrt{2r_s h_r - h_r^2} - \sqrt{2h_e r_s - h_e^2}, & h_r \leq r_s, \end{cases} \tag{7}$$

where r_s is the rolling sphere radius, and h_e and h_r are the maximum height of the equipment and rod height, respectively.

1.5. Surge Protective Device on DC Side Based on IEC 60364-7-712

IEC 60364-7-712 standard [14] determines whether the DC side of a PV plant requires SPD or not. According to this standard, the critical length L_{crit} is calculated as

$$L_{\text{crit}} = \begin{cases} \dfrac{115}{N_G}, & \text{for rooftop PV system}, \\ \dfrac{120}{N_G}, & \text{for PV power plant}, \end{cases} \tag{8}$$

where N_G is the density of lightning ground flash (flash/km^2/year) which depends on the location of the structures and power lines. L_{crit} is compared with maximum route length between the connection points of PV modules of the different strings and the plant inverter L. If $L < L_{\text{crit}}$, there is no need for installing SPDs on the DC side; otherwise, the overvoltage protection system should be equipped with SPDs on the DC side.

III. Developed PV Lightning Protection System Design Software

In the studies, the standard IEC62305-2 was thoroughly analyzed, the effect of various parameters in solar power plants was studied, and software was designed based on solar power plants' features. In addition, other standards [15, 16] were examined and compared to other sources. The major purpose of developers has been the simplicity of calculations for fast and accurate design. Sometimes, the complexity of the calculations forces the experts to overlook the design of the lightning protection, which can cause irreparable damage in the event of a lightning strike and delay the return on investment of projects that have been supported by the off-taker.

The lightning protection design for a PV system, including risk assessment, is a challenging task due to numerous variables. There are also many tables in the IEC-62305-2 for the calculation of R_xs. To address this problem, a software application is developed using C# environment. It provides a user-friendly graphical interface to simplify LPS calculations. Figure 3 shows the main page of the "Lightning Overvoltage Protection Designer for PV Plants" software. It consists of the following six sections:

1. The number of dangerous events calculations;
2. The probability of damage calculations;
3. The amount of loss calculations;
4. The risk assessment;
5. The external lightning protection system calculations; and
6. The surge protective device calculations.

Upon opening the software, the "Number of Dangerous Events" section appears. The user enters the dimensions of the structure and solar farm to be protected. In addition, if available, the dimensions of the adjacent structure are specified. Finally, the user enters the line and environmental data. By clicking on the "calculate" button, the numbers of various dangerous events due to flashes are calculated according to IEC 62305-2. The second section is dedicated to calculating the probability of damage resulting from the lightning strike, as shown in Fig. 4. In this section, after entering the required data such as structure characteristic, line type, and whether a coordinated SPD is provided, the results are shown.

Figure 5 shows the "Amount of Loss" section of the software. In this section, the user specifies the input data such as the amount of risk and various values to calculate the consequent losses. The fourth section of the developed software is dedicated to assessing the risk of the PV plant, as shown in Figure 6. Using the data entered in the previous tabs, the total risk R is calculated. Then, based on Fig. 2, it is determined whether the PV plant requires protection or not.

As mentioned in subsection 2.3, it may be required to equip a PV power plant with the external LPS. The "External Lightning Protection System" section of the software calculates the number and coverage area of ATS rods based on the rolling sphere method. In this section, the user enters the dimension of plant and protection overlap percentage. Figure 7 shows the fifth section of the developed software. Finally, the sixth section is dedicated to determining whether SPD is required on the DC side or not, as shown in Fig. 8. In this section, the density of lightning ground flash is transferred from the first tab or the user enters it; also, the installation type and *L* are entered. By clicking on the "calculate" button, the critical length is calculated and the answer is shown according to Subsection 2.5.

IV. Performance Evaluation

This section is dedicated to investigating the performance of the developed software in both 1 MW power plant systems. The main data of 1 MW PV power plant project implemented in the north-west of Iran are presented as follows:

- Length = 200 m, Width = 100 m, Height = 3 m;
- Adjacent structure power data information: Length = 5 m, Width = 5 m, H = 5 m;
- Adjacent structure telecom data information: Length = 4 m, Width = 5 m, H = 5 m;
- Thunderstorm Days (TD) = 10;
- Complete length of power line = 1000 m;
- Complete length of data line = 900 m;

Other input information is shown in Fig. 8, 9, 10, and 11

Figure 10 indicates the risk parameters with little consideration at first.

- According to the input information in the previous menus, the results can be viewed. Figure 12 shows the Risk Assessment menu with the selection of solar farm option first and then calculation. As it turned out, the risk of R4 was identified with red color, which is not acceptable. For this reason, according to Fig. 13, we have used class 2 LPS and SPD. After the new calculation, the results have been shown in green color (Fig. 14), which indicates that the solar farm is protected with this design. In the same way, one can see the effect of different parameters using the software and do the best design.

When selecting lightning protection measures, one must examine whether the risk R determined for the relevant types of loss exceeds a tolerable value (R_T). According to the IEC 62305-2, the acceptable values are programmed in the software and compared to the desired values.

According to the simulation results (Fig. 12), 0.0095479321 is obtained for the first time, which indicates that this solar farm is not protected. The designer may need to reconsider the calculations to check various parameters to find the appropriate protection according to Fig. 13 and 14, which may take a lot of time but this software has increased the accuracy and speed of calculations and reached the desired result of 0.00021506.

V. Overview of the methods

The developed software is programmed in the C# language. In order to develop such software, at first comprehensive studies must be done to prepare computational and optimization algorithms. After the algorithms are developed, according to the Visual Studio product, we can design the software and reach the desired results by using C# codes. As mentioned in the paper, there are applications in this field that do not have the features of the designed software.

About 4000 lines of code were written for the development of this software in 9 months. Figures 15 and 16 show a designed software window with some codes.

VI. Conclusion

This paper was motivated by the complicated procedure of risk assessment and lightning protection of PV plants for engineers. The developed software provides risk assessment for PV plants to determine the necessity of the LPS. The number of ATS rods and the necessity to install SPD on the DC side are also determined. By adopting various combinations of inputs, the users can evaluate various LPS designs. The developed software can be used as a helpful tool to increase the LPS design understanding. In addition, compared to previous research, this study presents software designed based on a comprehensive standard and considers three different categories of solar farms, off-grid systems and on-grid rooftop systems. In addition, compared to other software designed, this software determines the number of air terminals and provides risk calculations for SPD, especially for solar power plants. By using this software, simplifying calculations and designing protection against lightning, the power plant will be safe in the event of a lightning accident. If the owner sells the electricity to the network and off-taker, the return period of its investment will be reduced.

This software can be used in countries with many lightning strikes such as East Asian countries and some European countries.

Declarations

Ethical Approval and Consent to participate

I morally accept the rules of the journal and Ethical conditions.

Consent for Publication

I express my consent to the publication of the full paper by the journal and state that I will not submit this paper to any other journal.

Availability of Supporting Data

Paper information is available and can be provided if needed.

Competing Interests

I have done this project as free research and this problem existed in the past. The only solution for fast computing has been provided. The owner and developer of this software is Mohammad Parhamfar. Thus, there are no Competing interests.

Funding

There was no special funding for this project. I have requested that the cost of publishing the paper be waived due to the Iran conditions.

Authors' Contributions

Mohammad Parhamfar has proposed the idea and developed the software using C# language. The paper has been written by him.

Acknowledgements

I appreciate Mr. Ezatolah Partovi Shal, Dr. Mohsen Niasati and Mohammad Reza Farahani for sincere cooperation.

References

[1] A. Khoshnami and I. Sadeghkhani, "Sample entropy-based fault detection for photovoltaic arrays," *IET Renewable Power Generation*, vol. 12, no. 16, pp. 1966–1976, 2018. DOI: 10.1049/iet-rpg.2018.5220.

[2] International Energy Agency (IEA), "Renewables 2020 – solar PV," Available at: https://www.iea.org/reports/renewables-2020/solar-pv.

[3] S. Ittarat, S. Hiranvarodom, B. Plangklang, "A computer program for evaluating the risk of lightning impact and for designing the installation of lightning rod protection for photovoltaic system," *Energy Procedia*, vol. 34, pp. 318–325, 2013. DOI: 10.1016/j.egypro.2013.06.760.

[4] M. M. Mounir, A. E. Mahmoud, "Development of lightning risk assessment software in accordance with IEC 62305–2," in *2013 International Conference on Computing, Electrical and Electronic Engineering (ICCEEE)*, Khartoum, Sudan, Aug 26-28, 2013, pp. 178-182. DOI: 10.1109/ICCEEE.2013.6633928.

[5] C. H. Liu, Y. B. Muna, Y. T. Chen, C. C. Kuo, H. Y. Chang, "Risk analysis of lightning and surge protection devices for power energy structures," *Energies*, vol. 11(8), pp. 1999–2014, 2018. DOI: 10.3390/EN11081999.

[6] I. Hetita, A. S. Zalhaf, D.-E. A. Mansour, Y. Han, P. Yang, C. Wang. "Modeling and protection of photovoltaic systems during lightning strikes: A review," *Renewable Energy*, vol. 184, pp. 134–148, 2022. DOI: 10.1016/j.renene.2021.11.083.

[7] S. Ittarat, S. Hiranvarodom, B. Plangklang, "A computer program for evaluating the risk of lightning impact and for designing the installation of lightning rod protection for photovoltaic system," *Energy Procedia*, vol. 34, pp. 318–325, 2013. DOI: 10.1016/j.egypro.2013.06.760.

[8] Technical application papers no. 10 photovoltaic plants, ABB, Tech. Rep., 2010.

[9] Lightning protection guide, DEHN + SO¨ HNE, Tech. Rep., 2014.

[10] IEC 62305-2: Protection against lightning – Part *2*: Risk management, 2nd ed., 2010.

[11] E. Pons, R. Tommasini, "Lightning protection of PV systems," in *2013 4th International Youth Conference on Energy (IYCE)*, Siófok, Hungary, Jun 6-8, 2013, pp. 1-5. DOI: 10.1109/IYCE.2013.6604209.

[12] P. Velmurugan, K. Dhayalasundaram, K. Ilangovan, "Application of IEC 62305 to a large power and desalination plant-lightning protection system," in *1st International Conference on Electrical Energy Systems*, Chennai, India, 2011, pp. 308–313. DOI: 10.1109/ICEES.2011.5725348.

[13] P. H. Tan and C. K. Gan, "Methods of lightning protection for the PV power plant," in *IEEE Student Conference on Research and Development*, Putrajaya, Malaysia, 2013, pp. 221–226. DOI: 10.1109/SCORED.2013.7002575.

[14] IEC 60364-7-712: Low voltage electrical installations – Part 7-712: Requirements for special installations or locations – Solar photovoltaic (PV) power supply systems, 2nd ed., 2017.

[15] UNE 21186:2011-12-21 Protection against lighting: Surge arresters using early streamer emission air terminals.

[16] NFC 17-102 "Protection against lightning early streamer emission lightning protection systems."

M. Parhamfar received his B.Sc. degree in Electrical Engineering and M.Sc. degree in Renewable Energy from the Islamic Azad University, Najaf Abad, Isfahan, Iran, in 2007 and 2019, respectively. He also held a DBA certificate in 2021. He is currently working as a freelance consultant in the power and energy field. His research interests are renewable energy, solar power plants, software development, artificial intelligence, lightning protection, and earthing.

Trends and Prospects for Coal Deliveries from Russia's Eastern Regions

L. Takaishvili*, A. Sokolov, G. Agafonov

Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract **— The coal industry in the eastern regions of Russia is of great economic and social importance. An analysis of the dynamics of coal deliveries from the eastern regions of Russia in 2010–2020 attested to a significant increase in exports while indicating reduced supplies to the domestic market. The eastern direction contributed most to the growth in coal exports. The eastern regions account for about 45% of Russia's coal balance reserves and have a significant potential for the expansion of mining the coal suitable for different uses: export, power generation, coke manufacturing and coke by-product recovery, and coal chemical industry. Based on the existing production capacity and coal mining development projects, the production of coal in the eastern regions is expected to reach up to 195–275 million tons by 2035 and its export volumes are estimated at 75–130 million tons. The expansion of coal supplies is influenced by a variety of factors, including the demand for coal; the condition and capabilities of transport infrastructure; the availability of coal balance reserves and production capacities; the decarbonization of the world's economies; geographical, climatic, geopolitical, and other conditions. The minimum levels of coal supplies correspond to their insignificant growth in the domestic market with moderate growth in exports, and the maximum levels correspond to the maximum possible growth of exports and the commissioning of coal-fired thermal power plants. The potential of the region to supply coal far exceeds the demand for it.**

Index Terms: **coal, coal balance reserves, eastern regions of Russia, supplies, mining, development of coal mining, projects, reserves-to-production ratio, trends.**

* Corresponding author.
E-mail: luci@isem.irk.ru

http://dx.doi.org/10.38028/esr.2022.02.0005
Received July 06, 2022. Revised July 21, 2022.
Accepted July 30, 2022. Available online August 31, 2022.

I. Introduction

The eastern regions of Russia include the federal entities of the Russian Far East and Eastern Siberia. For the economy of Russia as a whole and its eastern regions, coal delivery to the domestic and international coal markets is important. In the domestic market, coal consumers are power facilities (power plants and boilers), coke manufacturing and coke by-product recovery plants, households, and others. The policy prioritizing the conversion of Russia's regions to gas can lead to a significant reduction in coal consumption.

Coal exports from the eastern regions increase significantly every year, thanks to the growth of coal shipments to countries of the Asia-Pacific region (APAC).

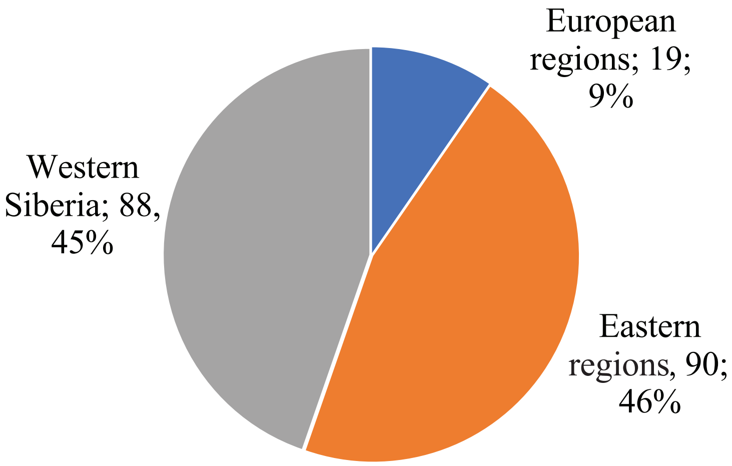
The Energy Strategy of the Russian Federation to 2035 and the Program for Development of the Coal Industry of Russia to 2035 consider the growth of coal production mostly in the eastern regions of Russia and mainly for the development of coal export. Coal mining companies and some power plants using coal as fuel are mainstay companies for monotowns in some regions. Most monotowns are situated in the eastern regions of Russia and Western Siberia. The coal industry is of considerable social importance, primarily because of the high demand for labor and the concomitant need for social services and infrastructure in the coal mining region.

The study of trends and prospects for coal movements from the eastern regions of Russia and the factors influencing the coal supplies is relevant because of the great social and economic significance of coal mining enterprises in the region.

II. Coal Industry of the Eastern Regions of Russia

The eastern regions of Russia have significant coal reserves suitable for various uses, including coal export.

The balance reserves of coal of categories A+B+C1 in the eastern regions are 88 billion tons [1] and account for 45% of those registered in the State Balance Sheet of Mineral Reserves of the Russian Federation (Fig. 1). The assets of the enterprises currently operating in the eastern regions amount to 8.35 billion tons or only 9.5% of the balance reserves of the region, which indicates a considerable potential for their involvement in the economic turnover.



Source: Calculated according to the data presented in the «State Balance Sheet of Mineral Reserves of the Russian Federation as of January 1, 2019» [1].

Fig. 1. Distribution of coal balance reserves of categories A + B + C1 (billion tons; percentage) by region of Russia.

Table 1. Indicators of the coal industry development in Russia and its eastern regions, million tons.

Indicator	Year 2010	2015	2016	2017	2018	2019	2020	2020–2010
Production total, incl.	323.4	374	386.9	414.1	441.6	442.7	401.6	78.2
- Eastern regions	111.3	131.2	136.9	142.8	155.2	162	153.6	42.3
Processing, total, incl.	117.6	178.3	186.6	190.3	199.0	210.9	207.2	89.7
- Eastern regions	20.4	39.7	41.6	47.4	47.4	49.0	50.1	29.7
Deliveries to the domestic market, total, incl.	199.8	174.6	167.0	169.9	180.5	180.2	164.0	-35.8
- Eastern regions	92.75	89.07	87.08	90.41	95.88	94.41	85.13	-7.62
Exports, total, incl.	96.3	151.4	162.3	186.3	193.2	193.4	195.5	99.2
- Eastern regions	16.3	30.8	34.2	38.4	42	47.2	53.4	37.1
Share of eastern regions								
- Production	34%	35%	35%	34%	35%	37%	38%	4%
- Processing,	17%	22%	22%	25%	24%	23%	24%	7%
- Domestic market	46%	51%	52%	53%	53%	52%	52%	6%
- Export	17%	20%	21%	21%	22%	24%	27%	10%

Source: The figures for the eastern regions were estimated based on official statistics [3].

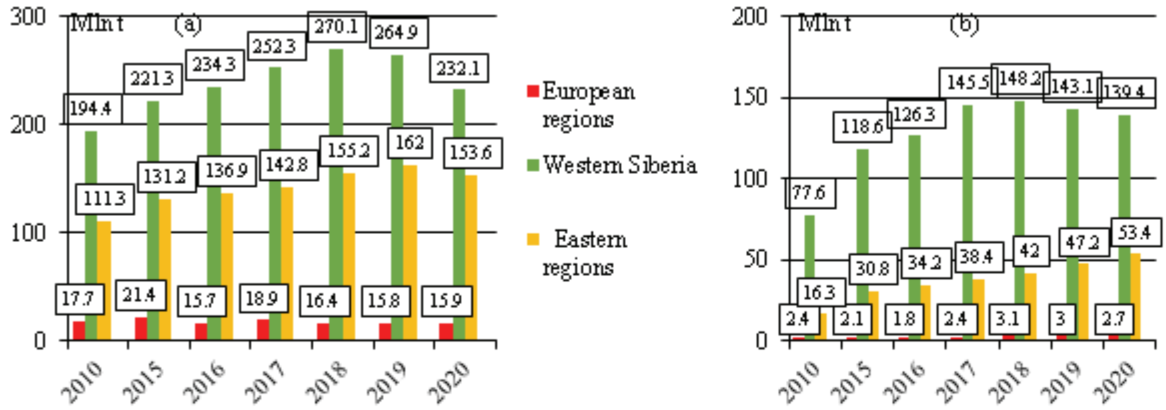
A retrospective analysis of the coal industry development in Russia from 2010 to 2020 shows an increase in the volume of mining, processing, and supply of coal in Russia, and especially that of the eastern regions (Table 1). During the period under review, the proportion of coal originating from the eastern regions in Russia's overall production increased from 34% to 38%. The shares of other regions, including Western Siberia, where the main coal mining facilities are located, decreased. Coal is mined mainly by the open-pit method, which is deemed most economically feasible [2].

The volume of coal production in the eastern regions increased by 42.3 million tons over the period in question (Fig. 2(a)), and in Western Siberia by 37.7 million tons, while in European Russia, it decreased by 1.8 million tons.

The growth in coal production in Russia's eastern regions is mainly due to an increase in exports (Fig. 2(b)) to eastern destinations. The exports of Russian coal in recent years have tended to grow and have exceeded deliveries to the domestic market since 2016 [3]. The main source of growth in exports was the eastern direction [3] due to the strengthening of positions in the markets of countries of the Asia-Pacific region (APAC).

The share of eastern regions in the mix of exports increased from 17% in 2010 to 21% in 2020, although the main growth in supplies was provided by the regions of Western Siberia. Coal export shipments from Western and Eastern Siberia increased approximately twofold, and from the Russian Far East almost fourfold. The growth in coal exports from the eastern regions was also facilitated by the increase in coal processing (Table 1). Exports are mainly high-quality products of coal processing.

Analysis of trends in the production, processing and supply of Russian coal shows the ever-increasing role of the eastern regions.



Source: Calculated based on official statistics [3].

Fig. 2. Dynamics of coal mining and export by region of Russia: (a) – mining; (b) – export.

Table 2. Coal supplies to the domestic market to major consumers, million tons.

Indicator	Year							2020-2010
	2010	2015	2016	2017	2018	2019	2020	
Russia, total, incl.	199.8	174.6	167.0	169.9	180.5	181.3	164.0	-35.8
- Coking needs	38.5	35.2	34.2	31.8	31.6	31.5	34.7	-3.8
- Power plants	95.9	92.1	85.2	87.5	85.8	84.1	73.6	-22.3
- Others	65.4	47.3	47.6	50.6	63.1	65.7	55.7	-9.7
Eastern regions, total, incl.	92.8	89.1	87.1	90.4	95.9	94.4	85.1	-7.6
- Coking needs	0.1	2.1	2.2	2.6	2.7	2.1	1.0	0.9
- Power plants	64.3	64.3	60.5	63.1	67.5	68.3	59.4	-5.0
- Others	28.3	22.7	24.4	24.7	25.7	24.5	24.7	-3.6
Share of eastern regions								
Coking	0%	6%	6%	8%	9%	7%	3%	
Power plants	67%	70%	71%	72%	79%	81%	81%	
Others	43%	48%	51%	49%	41%	37%	44%	

Source: The figures for eastern regions were estimated based on official statistics [3].

III. Coal Supply Trends

A. Domestic coal market.

Analysis of the dynamics of supplies to the domestic market shows a steady downward trend in the coal deliveries in the country as a whole (Table 2). The decrease in coal deliveries across the country as a whole was 35.8 million tons, including 7.62 million tons from the eastern regions, due to the conversion of some consumers, mainly power plants, to gas. Coal deliveries decreased in all areas of its use.

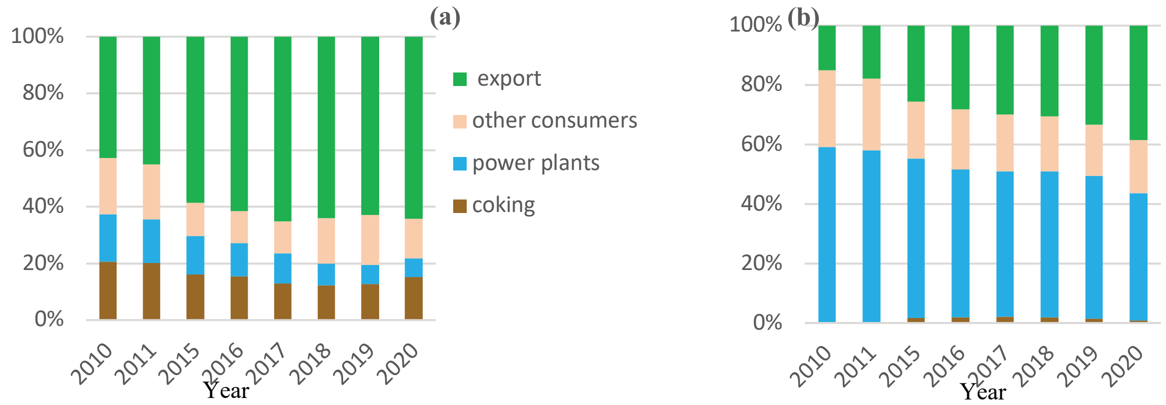
While coal deliveries to the domestic market in Russia as a whole decreased, the share of domestic supplies from the eastern regions increased, almost in all areas of coal use. The main coal consumers in Russia's domestic market are power plants and boilers. In the statistical data [3], boilers are classified as other consumers. Coal supplies to power plants decreased by 22.3 million tons (23% compared to 2010), including nearly 5 million tons or 8% from the eastern regions. At the same time, the coal from the eastern regions supplied to power plants still prevails in the country's supplies, unlike that from the European regions and Western Siberia (Fig. 3). Coal supplies to coke manufacturing and coke by-product recovery plants fell by 7 million tons nationwide, while supplies from the eastern regions increased by almost 2 million tons by 2019. The share of coal from the eastern regions in supplies serving the needs of coke manufacturing and coke by-product recovery in recent years has amounted to 7–9% of total supplies.

The 2020 supply volumes are not representative because of the downturn in the economy associated with the pandemic.

Most consumers of coal from the eastern regions are located in the regions of coal mining and those closest to them. Only coal from Krasnoyarsk Territory (Kansk–Achinsk) and Khakassia are supplied to the European regions and the Ural.

B. Export.

Internationally, Russia is one of the leading countries in terms of available reserves of coal, its production, consumption, and exports. The eastern regions of Russia play an important role in this. Data from Russian [3] and international [4] statistics on coal production in Russia and other indicators differ, but this has no effect on Russia's position in the international coal market. Only the United States is ahead of Russia in terms of coal reserves. Russia



Source: Calculated according to international statistics [4, 8].

Fig. 3. Deliveries of Russian coal: (a) from European regions and Western Siberia; (b) from the eastern regions.

Table 3. Export destinations of Russian coal, million tons.

Indicator	Year							2020 - 2010
	2010	2015	2016	2017	2018	2019	2020	
Exports, including	96.3	151.4	162.3	186.3	193.2	192.3	195.4	99.1
Eastern direction	7.1	45.4	51.2	60.4	60.4	63.1	73.5	66.4
incl. export from the eastern regions	0.9	29.2	32.4	36.2	36.3	44.6	48.7	47.8
Western and southern directions	89.2	106.0	111.0	125.9	132.8	129.2	122.0	8.7
Share of exports to the eastern directions	7.4%	30.0%	31.6%	32.4%	31.3%	32.8%	37.6%	
Share of eastern regions in export volumes to the eastern destinations	13%	64%	63%	60%	60%	71%	66%	

Source: Calculated according to official statistics [3].

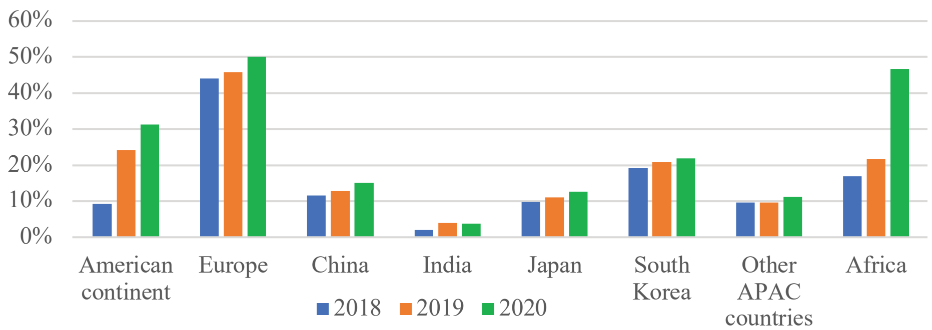


Fig. 4. The share of Russian coal in total imports of the importing countries.

is second in exports only to Australia and Indonesia, and ranks 6th after China, India, Indonesia, the United States, and Australia in terms of production volumes. Russia's share in global coal exports grew from 9.9% in 2010 to 17.8% in 2020 [4].

In the period from 2010 to 2020, exports from Russia more than doubled (Table 3) [3]. Deliveries to eastern destinations increased more than tenfold from 7.1 million tons to 73.47 million tons, including those of coking coal from 2.3 million tons to 10.97 million tons. Russian coal exports to western and southern destinations increased by about 40% from 89.2 million tons to 122 million tons. Growth in exports to eastern destinations was provided by coal mining enterprises in Western Siberia and the eastern regions. Enterprises based in the eastern regions accounted for more than 70% of the increase in exports eastward. Russia delivers coal to the world's largest coal importers, including China and Japan, South Korea, Taiwan, India, Malaysia, and Vietnam [5].

According to international statistics [4-8], the share of the eastern direction in export deliveries increased from 46% in 2018 to 56% in 2020. There is an upward trend in the share of coal imports from Russia in the imports of the world's main coal importers, including China, Japan and South Korea (Fig. 4).

The competitors of Russian coal in the APAC coal market are Indonesia, Australia, USA, South Africa, and Mongolia. If one takes into account the coal reserves-to-production ratio in these countries [4], then there may be fewer competitors in the future (Table 4). Coal reserves-to-production ratio is calculated by dividing proven reserves by annual production [4] and stands for the number of

Table 4. The share of the main coal exporters in the coal import by the main importers of Russian coal at the Asia-Pacific market in 2020.

Country, indicator	Russia	Australia	Indonesia	Mongolia	South Africa	Others
China	12.8%	32.3%	34.2%	16.0%		4.8%
India	3.9%	14.6%	45.8%		21.1%	14.6%
Japan	11.0%	58.7%	14.4%			15.9%
South Korea	20.9%	36.3%	21.3%			21.5%
Other Asia-Pacific countries	9.7%	28.8%	46.7%			14.8%
Country's share in world imports	16.6%	27.5%	26.0%			29.9%
Coal reserves-to-production ratio, years	407	315	62	58	40	

Source: Calculated according to international statistics [4].

years that natural resources will last if consumption rates remain the same.

Most regions export products of hard coal processing, i.e., steam and coking coal concentrates. Low-grade coal processing products are supplied to the domestic market. Run-of-mine coal is exported in insignificant quantities.

Growth in coal production in the eastern regions is associated with the growth of exports [3]. The clear leader is the Sakhalin region, where with an increase in production by 10 million tons in the period under review, exports rose by 12.36 million tons, which is partly due the proximity to target APAC markets. Export shipments from the Republic of Khakassia, Transbaikal Territory, and the Republic of Sakha (Yakutia) increased significantly. Khabarovsk Territory, the Tyva Republic, and Chukotka Autonomous District, which had not exported coal before 2010, became coal exporters as well.

An analysis of coal supply trends shows that the coal industry in Russia and especially in its eastern regions is becoming more and more export-oriented.

IV. Prospects for Coal Supplies from the Eastern Regions

A. Domestic coal market.

Supply of coal from the eastern regions to the domestic market depends on its use mainly for the needs of the energy sector (mostly at power plants). Other uses (coke manufacturing and coke by-product recovery, coal chemical industry) and other consumers (boilers, households, industrial sector, and transport) have a less significant impact on supply volumes. The tendency to reduce supplies to consumers will continue due to the activities aimed at converting certain categories of consumers to gas.

Projects to build coal-fired power plants in Eastern Siberia and the Russian Far East have been considered in various state federal and regional strategies and programs (Program for the Development of the Russian Coal Industry to 2035; Energy Strategy of the Russian Federation to 2035; Scenarios for the Development of the Russian Electric Power Industry to 2030; Federal Target Program «Economic and Social Development of the Russian Far East and the Baikal Region to 2025»). The above documents envisioned the construction of coal-fired thermal power plants using low-grade products of coking and steam coal processing, and run-of-mine coal. Projects to build coal-fired thermal power plants from time to time appeared in and disappeared from policy documents over the years. The revision of the Coal Industry Development Program approved in 2014 considered the construction of several coal-fired power plants at different coal deposits of large (2 400–4 800 MW) and smaller (900–1 500 MW) capacity. The construction of coal-fired power plants was considered for the Irkutsk and Amur Regions, Transbaikal and Khabarovsk Territories, and some other eastern regions.

Most of them were focused on electricity export. In the latest revision of the program, the number of coal-fired power plant projects has been reduced and the construction of power plants for electricity export is not currently being considered. The coal deliveries from the eastern regions to the domestic market can be increased mainly by constructing power plants, However, their decrease is possible due to the conversion of coal consumers to gas. In the short term, the conversion of some power plants in some Russia's eastern regions to gas cannot have a significant impact on the volume of coal supplied to power plants. The conversion of power plants in the Russian Far East (Vladivostok CHPP-2, Khabarovsk CHPP-2, and Anadyr CHPP) to gas, leads to a reduction in coal supplies by about 0.5 million tons, which is much less than the annual fluctuations of coal deliveries to the region's power plants due to climatic conditions.

The program documents do not provide for significant expansion of coke manufacturing and coke by-product recovery and it is most likely that the volumes of supplies targeting this area of coal use will stabilize.

According to the Strategy for Long-Term Development of the Russian Federation with Low Greenhouse Gas Emissions to 2050 and the conversion of consumers to gas, it is projected that the coal consumption by boilers, the industrial sector, transport, and households will go down.

Almost all brown coal and low-grade hard coal are suitable for the needs of the coal chemical industry. Their greatest resources for the development of coal chemical industry are the coal of the Kansk-Achinsk coal basin, the Amur Region's lignite deposits Svobodnoe, Sergievskoe,

Table 5. Possible range of increase in coal production and export, million tons/year.

Indicator	Year		
	2020	2030	2035
	Actual	Possible range	
Production	153.6	182–227	195–275
Export	53.38	64–94	75–130

and Tygdinskoe. Existing projects for the development of coal chemical manufacturing, differ in their degrees of completion, from a preliminary assessment to the specific implementation steps. The most mature project is presented in the Program for Development of Innovative Territorial Cluster «Integrated processing of coal and man-made waste» in the Kemerovo region. In the short term, the supplies of coal for the needs of the coal chemical industry cannot have a significant impact on the volume of supplies for other purposes.

Integrated use of coal is possible when creating a deposit-based cluster comprising the facilities of coal production, power generation, coal chemical industry, and others for processing waste from major enterprises, including recovery of valuable elements and production of construction materials. The mix of enterprises of such clusters is deposit-specific because each deposit has unique mining, geological, and hydrological conditions of development; chemical composition of coal and its quality characteristics; and the state of transport and energy infrastructure. [9–11].

B. Export.

The decarbonization policy in most countries leads to adjustments in projections of demand for coal. At the same time, according to experts, the demand for coal in APAC countries continues to grow. According to the projection by the British oil and gas company BP, by 2040 global coal consumption will increase slightly (0.8%) compared to 2016, with reduced consumption in most countries of the world and increased consumption in APAC countries [12]. China (25% of global coal consumption, despite the decline in overall consumption) and India (14% of global coal consumption) will remain the leaders. According to the projection made by the International Energy Agency [6, 12], demand for coal is also expected to grow in Asian countries, with relatively stable volumes of consumption in other regions of the world. East Asian countries are importers of Russian coal, and coal mining enterprises in the Russian Far East are geographically advantageous for selling coal to Asian markets. The main competitors of Russian coal in this market are the largest coal exporters: Australia and Indonesia.

If the state of the coal market is favorable, the prospects for the development of Russian exports, especially those of coal from the eastern regions, are quite bright.

Analysis of existing investment projects, disregarding the demand for coal in the future, indicated the possible ranges of increasing the coal production and exports (Table 5). Growth in coal production is possible in almost all eastern regions of Russia, which is to be achieved through the utilization of production capacities to a fuller extent and the reconstruction of existing facilities and construction of new ones. First of all, this will affect regions with sufficient reserves of high-quality coal, which is in demand in the world market. Coal exports from the Republics of Khakassia and Sakha (Yakutia); Sakhalin Region; Krasnoyarsk, Khabarovsk, and Primorsky Territories could grow by one and a half times or more as compared to 2020. There may be a significant increase in coal exports from regions that previously exported coal in small volumes (the Tyva Republic, Magadan Region, and Chukotka Autonomous District), as well as from the Kamchatka Territory and Amur Region, which previously did not export coal.

V. Factors Influencing the Development of Coal Supplies

The main factors influencing the development of coal supplies are the demand for coal, the balance coal reserves, and the condition and capabilities of the transport infrastructure. With the growing demand for coal, mainly in the international coal market, there are also factors both favorable for coal supplies and limiting them. The most important of these are geopolitical conditions, the policy of the Ministry of Transport of the Russian Federation on prioritizing freight carried by rail transport, the availability of balance reserves and production capacity of facilities, and the decarbonization policy of the world's economies. Other factors such as coal prices, geographic, climatic, geopolitical, and other conditions can both facilitate and constrain coal supplies.

A. Demand for coal in the world market.

Projections of coal consumption in the world made by international organizations in different years are characterized by great uncertainty and ambiguity [6, 12–14]. The growth in demand for imported coal is predicted for APAC countries. Developing APAC countries are building coal-fired power plants and are planning to build new facilities using coal as fuel [15].

Volumes of coal imports are influenced by changes in the economic growth rates in the importing countries and unpredictable conditions of economic development caused by political decisions, such as sanctions, and others. The greatest growth in demand is possible in India, with a drop in demand in China and its stabilization in South Korea, Japan, and Taiwan. The decline in demand for imported

Table 6. Balance reserves of coal in the eastern regions, billion tons.

Coal type, mining method	Balance reserves by category			Off-balance reserves
	A+B+C1	C2	A+B+C1+C2	
Total, incl	88.0	39.9	127.8	29.2
- Brown	61.2	25.4	86.6	12.0
- Hard	26.7	14.4	41.2	17.1
Including coking, of which	8.9	4.5	13.4	1.4
- High-value coals	4.3	2.7	7.1	0.1
- Anthracite	0.03	0.03	0.07	0.07
Open-pit mining, total, incl.	71.7	28.5	100.1	16.0
- Brown	57.8	22.5	80.3	10.4
- Hard	13.9	6.0	19.8	5.6

Source: Calculated based on the data presented in the «State Balance Sheet of Mineral Reserves of the Russian Federation as of January 1, 2019» [1].

coal in China is also due to plans to increase domestic coal production [16].

In May 2021, the independent international pricing agency Argus held the conference «Russian Coal 2021 – CIS and Global Markets» [17]. The global market review at the conference noted the prospects for coal demand recovery after the Covid-19 pandemic, changes in trade flows and the strengthening of Russian coal's position in premium and growing markets such as China, Japan, South Korea, and Taiwan. It was also noted that there were prospects for an increase in the share of Russian coal in imports of APAC countries.

The reduction in demand for coal in coal-importing countries is due to the following: domestic policies regarding energy sources, the achievements in energy conservation, the shift from energy-intensive industries, and the development of new, more efficient energy sources.

B. Geopolitical conditions.

Currently, geopolitical conditions have become one of the most important factors influencing the volume and destinations of coal exports [18]. In the eastern regions, restrictions due to sanctions related to Russia's special operation in the Ukraine affected only Khakassia, which supplied coal to Poland and Great Britain. According to 2020 data, 1.9 million tons of 12.7 million tons were supplied from Khakassia to the above countries [3].

The largest importers of coal from APAC countries (China, Japan, and the Republic of Korea) have not joined the direct sanctions, which is why there is a theoretical possibility of redirecting exports to APAC countries. The main obstacle to coal exports to eastern destinations is the low throughput capacity of the railroads.

Changing geopolitical conditions can not only fundamentally alter the volume of supplies but also redraw the map of coal transport destinations.

C. Policy of the Ministry of Transport of the Russian Federation on prioritization of freight carried by rail transport.

In the current geopolitical context, the policy of the Russian Ministry of Transport has become the most important factor affecting the volume of coal supplies. The greatest damage from the sanctions for coal shipments from the eastern regions is related to restrictions on the transport of coal eastward since the policy of the Ministry of Transport of the Russian Federation on prioritizing freight carried by rail transport has changed.

Freight carried by Russian Railways is divided according to tariff classes. There are three tariff classes [19]. The first class, which includes coal, was a top priority, and freight of this class was transported at lower rates. Freight of the second class is transported at cost price. Relegation of coal from the first to the second tariff class is being discussed [20], which can render coal exports uneconomical.

Due to the insufficient throughput and carrying capacity of the railroads of the Eastern Polygon, the Government of the Russian Federation adopted Resolution No. 304 of March 6, 2022 «On Suspension of the Decree of the Government of the Russian Federation No. 710 of November 25, 2003 [21].

According to the rules of non-discriminatory access to the railway infrastructure, «transport of export coal from Kuzbass, Buryatia, and Khakassia in an eastward direction falls into the category of transport formed by the decision of Vladimir Putin,» subject to quotas. The total volume of quotas is 76 million tons, of which 18 million tons are for the eastern regions of Russia, which is less than 40% of the coal exported in 2020. Export-quality coal from other regions is not considered. Such a situation could lead to «the breakdown of contracts, failure to fulfill obligations, shutdown of enterprises, job cuts in the regions, a reduction in tax revenues and foreign exchange earnings [21], and a significant increase in social tension. This is especially true of monotowns, where the existing conditions will increase unemployment.

D. Balance coal reserves.

The availability of significant balance coal reserves is a favorable factor for the development of production and increase in coal supplies. A wide range of qualitative characteristics of coal from the eastern regions of Russia determines their suitability for different uses: exports, power generation, coke manufacturing and coke by-product recovery, coal chemical industry.

The balance reserves of coal of categories A+B+C1 in the eastern regions amount to 88 billion tons (Table 6). These reserves are promising in terms of their development with the state-of-the-art technology. Significant volumes of C2 reserves (39.9 billion tons of balance reserves and 29.2 billion tons of off-balance ones) create prospects for their further commercial development.

The ratio of balance reserves of categories A+B+C1 to inferred resources or the degree of exploration is low and averages only 10%. The degree of exploration differs greatly for different entities of the Federation and different areas of the region - from 0% to 50% or more. The appropriate exploration work will make it possible to book the inferred coal resources in the State Balance Sheet of reserves, which will increase the balance coal reserves.

The share of coal suitable for export in the balance reserves of categories A+B+C1 (hard coal: steaming and coking) is 30%. Steaming coal is represented by hard coal (including that suitable for export) and brown coal, their share in the balance reserves is 79%, with the predominance of brown coal. The main possible use of low-rank brown coal is for power generation. Hard coal from most of the deposits in the eastern regions can also serve as fuel for power plants. Other resources for the energy sector include low-grade products of coking and steaming coal processing. The coal reserves-to-production ratio for export from the eastern regions (at the 2020 level of volumes supplied) is about 500 years. Excluding resources for export, the lignite reserves-to-production ratio of the eastern regions alone exceeds 700 years for the needs of domestic consumption. Such a calculation is approximate; nevertheless, it allows estimating the possible horizons of coal deliveries, irrespective of the addition of promising deposits to the balance sheet of reserves.

Coal is a powerful sorbent. Coal from deposits located in the eastern regions contains rare-earth and other components such as germanium, vanadium, chromium, gold, platinum, silver, titanium, and others, and in the case of some deposits the above are available in commercially significant concentrations [22–24]. Development of new technologies for the recovery of rare and rare-earth elements from coal and coal combustion products are subjects of numerous studies in many countries [25–29].

The significant balance coal reserves available in the eastern regions and favorable mining conditions for most of the deposits create opportunities for the expansion of coal production.

E. Current state of the transport infrastructure.

Most of the coal supplies (88% of the production volume in 2020) are transported by rail to the domestic coal market and to shipping ports and border crossings for export [30]. About 90% of Russian coal is exported by sea, in particular, through the ports in the Russian Far East. A serious issue is the remoteness of coal mines from export ports and the limited capacity of port facilities.

Growth in coal exports to eastern destinations caused an increase in rail traffic along the key routes of the Eastern Polygon, which includes the Far Eastern, Trans-Baikal, Krasnoyarsk, and East Siberian rail lines. The carrying and throughput capacity of the railroads, as well as that of coal terminals impose constraints on the transport of demanded coal volumes. Although the Russian Railways has been implementing the program to modernize the Eastern Polygon since 2013, the measures taken to date fail to meet the growing need to increase the volume of transported cargo, including coal.

Infrastructure constraints are the main obstacle to the increase in coal supplies from the eastern regions to APAC countries. According to analysts from the journal Mining Industry [31], about 6% of exports to APAC countries has to be transported via a «bypass» route running through the ports of the Baltic, Arctic, Black, and Azov Seas. Because of the poor throughput capacity of the Eastern Polygon, Elgaugol LLC (owned by A-Property) decided to put on hold mining at the Ogodzhinskoye deposit in the Amur Region in 2021 to ensure the shipment of the produced output from the top-priority Elga open pit [32]. The growth of coal supplies to eastern destinations has greatly exacerbated the problem of high utilization of the Eastern Polygon. Technologies are also developed and used to increase the weight of freight in railcars. SUEK–Kuzbass Joint-Stock Company's Transport Department together with JSC Russian Railways have developed and implemented a technology to increase the weight of freight to be carried by standard railcars up to 65–71 tons, and in the latest generation of railcars – up to 77 tons. The use of advanced technology allows a more intensive use of the eastern railway route, which has infrastructure limitations in terms of throughput and carrying capacity.

Coal deposits deemed promising for development are often located in regions with underdeveloped or non-existent transport infrastructure, which significantly increases the time of development of such deposits, for example, coal deposits in the Republics of Tyva and Sakha (Yakutia).

F. Coal prices.

Two types of coal (steaming and coking) are sold in the world market. Their prices differ significantly. The average monthly price of coking coal can be higher than that of steaming coal by 1.5 to 2.8 times [32]. Coking coal accounted for only 12% of total coal exports from Russia's eastern regions in 2020 [3].

The price of steaming coal is also influenced by the prices of other energy carriers largely by gas and to a lesser extent by oil. As gas prices rise, coal, being a cheaper resource, becomes more economically feasible, which can push coal suppliers to raise coal prices.

Coal prices depend on the type of contract. It is customary to distinguish between long-term contract prices and short-term (spot) ones. Spot prices are more sensitive to market conditions and are subject to greater fluctuations than long-term prices. For example, over the past five years, the average monthly price fluctuations for Russian steaming coal in contracts ranged from \$51 to \$92/t, and spot prices over the same period ranged from \$47 to \$170/t [33, 34]. Amid rising gas prices and declining coal exports from Australia, international coal prices continued to fluctuate with a pronounced upward trend in 2021, reaching record highs in April 2022 for coking coal at \$444.8/ton and steaming coal at \$325.3–333.8/ton in the Asian market [35].

The most significant price fluctuations are associated with a slowdown and then an increase in the rate of economic development related to the pandemic and geopolitical conditions. Analysis of the dynamics of coal prices in the APAC market [4] and the volume of coal exports from the eastern regions [2, 3] shows an increase in exports regardless of price fluctuations [3, 7]. This indicates the presence of sufficiently favorable price conditions for coal export from the eastern regions in the medium term.

Final coal prices depend on the relationship between supply and demand in the coal market. In the domestic market, the main consumers of coal are power plants. Each power plant is designed to burn coal from a specific deposit and supply volumes, accordingly, depend little on the price of the coal supplied. Analysis of the dynamics of average coal prices in the international market compared to the volume of Russian coal supplies shows that supply volumes depend less on price and more on demand and geopolitical conditions.

G. Geographical and climatic conditions.

Climate of most of the eastern regions of Russia is strongly continental. Temperatures can drop to –40° C to –50° C during certain periods at some deposits of the Far North regions and equivalent areas. This imposes restrictions on certain types of work as compared to other regions where earthworks can be carried out all year round.

Climatic conditions have a significant effect on the demand for coal for electricity and heat generation by cogeneration power plants. The eastern regions are home to Russia’s most powerful hydroelectric power plants, whose share in power generation dominates the region and whose power generation depends on the water content of the rivers. The power shortage is covered by coal-fired power plants. The fluctuation of coal supplies from the eastern regions to power plants ranges from –8% to +11% compared to the previous year. The fluctuations are mainly due to climatic conditions (cold and warm winters, the water content of rivers) and the available coal reserves in the warehouses of companies, which were unused in the previous year.

H. Decarbonization of the world economies.

The decarbonization trend followed by many economies of the world has become highly relevant in recent years [36]. Among the countries planning to reduce coal-fired power generation are the APAC countries importing Russian coal. In the long term (2040–2050), coal consumption may reach a plateau with a further decline in demand for coal. The decline in demand for coal due to the decarbonization policy pursued in the countries of the world had a greater impact on coal export to European countries. Russian coal export to APAC countries will remain lucrative for quite a long time, primarily because of the inertia of the energy sector development and the large investment outlays needed to replace equipment and energy carriers for power and heat generation. Unpredictable weather conditions (cold winters) and fluctuations in the cost of gas do not foster the desired reduction in coal consumption in European countries either, given that coal is still the cheapest source of energy. This is especially true for the countries with scarce energy resources, which include most of the APAC countries. The share of renewable energy sources (with the exception of hydropower), which is the focus of the transition to green energy is quite small [33], the rate of increase in this share is still limited by the high cost of energy from renewable sources.

The Strategy for Long-Term Development of the Russian Federation with Low Greenhouse Gas Emissions to 2050 suggests measures to improve the energy efficiency of the Russian economy. However, the process of switching the production processes to the best available technology takes much time and requires significant investment. In addition, there are no legal and methodological framework for the system of carbon regulation in the Russian Federation. The economy is currently being decarbonized through the conversion of energy facilities to gas. In European Russia, most power plants have been converted to gas. The eastern regions are dominated by coal power. According to the Federal Target Program «Economic and Social Development of the Russian Far East and the Baikal Region to 2025,» both individual boilers and the entire cogeneration plants are gradually being converted to natural gas.

According to the Ministry of Energy of Russia, the share of renewable energy sources (wind and solar) in the mix of installed capacity of power plants in Russia in 2020 was 1.1%. By 2027, it can reach 2.2% [35]. The main obstacle to increasing the capacity of renewable energy sources is their poor economic competitiveness compared to other power generation technologies.

I. Other factors.

Other factors affecting coal production and supply include:

- State support for the development of coal mining and supply;
- High dependence on imported mining equipment and spare parts;
- A lack of highly qualified personnel, not only at coal mining companies, but also for carrying out exploration

and other work;
- The high capital expenditures required over a long time;
- The need for infrastructure investment and a long payback period of investment;
- Unpredictable world events, such as the fires in Australia, the coronavirus pandemic, the sanctions imposed by individual states, and similar phenomena on a global scale.

Large-scale forest fires in Australia, which is the world's main producer of coking coal, may, to some extent, affect the global market conditions. The coronavirus pandemic has caused the introduction of temporary transportation restrictions, which affects the volume and speed of shipments.

State support to the development of coal mining and increase in coal deliveries, planned by the Program for the Development of the Coal Industry and other documents, has faded into the background against the backdrop of geopolitical events.

Foreign companies are interested in developing some of the coal deposits in the eastern regions. The development of coal mining at these deposits depends not only on the degree of participation of these companies in the implementation of projects, but also on the persistence of the interest manifested.

VI. Conclusion

The eastern regions of Russia have coal reserves suitable for different uses. The most likely increase in coal supplies is related to export, but it can be limited due to the current geopolitical conditions. The coal of some deposits has valuable elements: rare-earth metals and other substances that are in demand in the industrial sector and knowledge-intensive industries. Integrated use of coal from such deposits with the output of high value-added products is very promising.

Projections of demand for coal made by international organizations for the countries that are potential coal importers are favorable for the intensive development of coal export from the eastern regions of Russia. The main competitor of Russian coal is the coal from Australia, Indonesia, and Mongolia.

The prospects for export of coal depend on the potential for development of domestic and international coal markets; the tariff policy and freight priorities set by Russian Railways; restrictions on coal consumption, depending on the success of the decarbonization of the economies worldwide; domestic and foreign policies of coal-importing countries, and the prevailing geopolitical conditions.

The state of the global market with respect to energy prices has little effect on the volume of Russian coal exports.

Coal reserves in the eastern regions of Russia are poorly studied. Additional exploration work will not only increase the existing balance reserves but may also identify new deposits or areas promising for development.

The main limitations of an increase in coal export supplies are related to the capabilities of transport infrastructure, geopolitical conditions, the lack of demand for low-grade coal products in the domestic coal market, and the need for large investment outlays.

The significant coal resources available in the eastern regions, including high-rank coal, which is much in demand in the world market; the existing mining capacities, and high coal reserves-to-production ratio allow considering the coal of the eastern regions as a reliable resource to be supplied for export and domestically consumed for the long term.

The key risk for the coal industry in Russia's eastern regions is a potential decline in export volumes due to the geopolitical situation and the resulting changes in regulations of freight transport by rail. This can lead to increased economic instability and social tension in coal-mining regions.

The research was carried out within the scientific project XI.174.2 of the program of fundamental research SB RAS, reg. AAAA-A21-121012090010-7.

References

[1] *The state balance of reserves of mineral resources of the Russia Federation as of January 1, 2019. Issue 91, Coal, I, Summary data*. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Agency on Mineral Management, the Russian Federal Geological Foundation, 2019, 302 p. (in Russian)

[2] I. E. Petrenko, "The results of the work of the coal industry in Russia for 2021," *Coal*, no. 3, pp. 9–23, 2022, DOI: 10.18796/0041-5790-2022-3-9-23. (in Russian)

[3] Statistical and analytical information materials on the main indicators of production activities of Russian coal industry organizations. Available at: http://www.cdu.ru/catalog/statistic/?arrFilter_46_4252452532=Y&set_filter=%D0%9F%D0%BE%D0%BA%D0%B0%D0%B7%D0%B0%D1%82%D1%8C&set_filter=Y. (in Russian) (accessed April 23, 2022)

[4] Statistical Review of World Energy 2021. 70th edition. 72 p. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf (2021) (accessed April 23, 2022)

[5] BP Energy Outlook. 2019 edition. 73 p. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf (accessed December 23, 2021)

[6] "International Energy Outlook – 2017," *U.S. Energy Information Administration*, 2017. Available at: www.eia.gov/ieo (accessed April 23, 2022).

[7] Statistical Review of World Energy 2018. 70th edition.

56 p. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf (accessed April 23, 2022)

[8] Statistical Review of World Energy 2020. 69th edition. 68 p. Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf (accessed April 23, 2022)

[9] M. V. Golitsyn, V. I. Vyalov, A. Kh. Bogomolov, N. V. Pronina, E. Yu. Makarova, D. V. Mitronov, E. V. Kuzevanova, D. V. Makarov, "Prospects for the development of the technological use of coal in Russia," *Georesources*, no. 2(61). pp. 41–53, 2015. Available at: https://geors.ru/media/pdf/04_Golicyn_ris.pdf. (in Russian) (accessed April 23, 2022)

[10] Yu. A. Fridman, E. Yu. Loginova, G. N. Rechko, "Kuzbass in Search of a New Development Paradigm: Industrial Clusters," *Bulletin of the Kuzbass State Technical University,* no. 2 (114), pp. 135–145, 2016. Available at: https://cyberleninka.ru/article/n/kuzbass-v-poiskah-novoy-paradigmy-razvitiya-promyshlenennye-klastery/pdf. (in Russian) (accessed April 23, 2022)

[11] N. A. Lavrik, "Some prerequisites for the integrated development of coal deposits in the south of the Far East," *Mining Information and Analytical Bulletin. Separate issue: «Far East»*, pp. 420–430, 2005. (in Russian)

[12] "International Energy Outlook 2021," *U.S. Energy Information Administration*, 2021, 42 p. Available at: https://www.eia.gov/outlooks/ieo/pdf/IEO2021_Narrative.pdf (accessed April 23, 2022)

[13] BP Energy Outlook. 2020 edition. 81 p. Available at: https://www.connaissancedesenergies.org/sites/default/files/pdf-actualites/bp-energy-outlook-2020.pdf. (accessed April 23, 2022)

[14] Net Zero by 2050 A Roadmap for the Global Energy Sector. International Energy Agency. 224 p. Available at: https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf. (accessed April 23, 2022)

[15] United Nations ESCAP. Coal phase out and energy transition pathways for Asia and Pacific. 82 p. Available at: https://www.unescap.org/sites/default/d8files/knowledge-products/Coal-Phase-Out-and-Energy-Transition-Pathways-25-Feb-2021.pdf. (accessed April 23, 2022)

[16] O. A. Timofeev, F. F. Sharipov, B. V. Petrenko, "Impact of the COVID-19 epidemic on the coal market in China," *Coal,* no 1, pp. 63–67, 2021, DOI: 10.18796/0041-5790-2021-1-63-67. (in Russian)

[17] Argus Russian Coal 2021, CIS and Global Markets. 2021. [Online]. Available: URL: https://www.argusmedia.com/ru/conferences-events-listing/russian-coal-2021. (in Russian) (accessed April 23, 2022)

[18] A. Golyashev, A. Kurdin, A. Kolomiets, A. Nekrash, D. Fedorenko, S. Fedorov, "Russian fuel and energy complex under sanctions restrictions," *Energy Bulletin,* no. 106, 2022, 20 p. Available at: https://ac.gov.ru/uploads/2-Publications/energo106.pdf. (in Russian) (accessed May 30, 2022)

[19] F. Khusainov, "System of railway freight rates: history of formation and current state," Russian Open Academy of Transport, 101 p. Moscow, August 26, 2020. Available at: https://protariff.ru/uploads/bYxut2ZTkjnU27gl.pdf. (in Russian) (accessed May 30, 2022)

[20] "Railways load new tariffs," *Kommersant Newspaper*, no. 57, dated April 4, 2022. Available at: https://www.kommersant.ru/doc/5292874 (in Russian) (accessed May 30, 2022)

[21] On the suspension of the Decree of the Government of the Russian Federation of November 25, 2003 no. 710, Decree of the Government of the Russian Federation of March 6, 2022 no. 304, Moscow: Available at: http://pravo.gov.ru/proxy/ips//?docbody=&prevDoc=102084227&backlink=1&&nd=602901002 (in Russian) (accessed May 30, 2022)

[22] V. S. Bykadorov, V. F.Cherepovsky, *Coal base of Russia*, *Vol. III. Coal basins and deposits of Eastern Siberia Southern part (Krasnoyarsk Territory, Kansk-Achinsk basin; Republic of Khakassia, Minusinsk basin; Republic of Tyva, Ulugkhem basin; Irkutsk region, Irkutsk basin and coal deposits of Cisbaikalia)*. Moscow, Russia: CJSC «Geoinformmark», 2002, 488 p. Available at: https://www.geokniga.org/books/15173 (in Russian) (accessed April 23, 2022)

[23] G. P. Sidorova, A. A. Yakimov, N. V. Ovcharenko, T. O. Gushchina, "Rare and trace elements in the coals of Transbaikalia," *Vestn. Transbaikal. State University*, vol. 25, no 2, pp. 26–33, 2019. (in Russian)

[24] Yu. P. Trutnev., V. G. Vologin, "Information on the state and prospects for the use of the mineral resource base of the Far Eastern Federal District as of March 5, 2021," St. Petersburg: FGBU «VSEGEI», 2021. 12 p. Available at: https://www.rosnedra.gov.ru/data/Fast/Files/202104/c7b093284dc7ede9f597dbe834e37688.pdf (in Russian) (accessed May 30, 2022)

[25] A. P. Sorokin, I. F. Savchenko, L. P. Noskova, V. M. Kuzminykh, A. A. Konyushok, V. S. Rimkevich, and V. V. Krapiventseva, "Comprehensive use of caustobiolites from coals of the Far East based on innovative technologies in the field of coal chemistry," *Physical and technical problems of mineral development*, vol. 54, no. 1, pp. 147–157, 2018, DOI: 10.15372/FTPRPI20180119.

[26] H. Passos, B. Cruz, N. Schaeffer, C. Patinha, E. Ferreira da Silva, J.A.P. Coutinho, "Selective Sequential Recovery of Zinc and Copper from Acid Mine Drainage," *ACS Sustainable Chemistry & Engineering*, vol. 9 (10), pp. 3647–3657, 2021, https://doi.org/10.1021/acssuschemeng.0c07549.

[27] S. E. Crawford, J. E. Ellis, P. R. Ohodnicki, J. P. Baltrus, "Influence of the Anionic Zinc-Adeninate

Metal–Organic Framework Structure on the Luminescent Detection of Rare Earth Ions in Aqueous Streams," *ACS Applied Materials & Interfaces*, vol. 13 (6), pp. 7268–7277, 2021, https://doi.org/10.1021/acsami.0c20990.

[28] M. Alipanah, D. M. Park, A. Middleton, Z. Dong, H. Hsu-Kim, Y. Jiao, H. Jin, "Techno-Economic and Life Cycle Assessments for Sustainable Rare Earth Recovery from Coal Byproducts using Biosorption," *ACS Sustainable Chemistry &Engineering*, vol. 8 (49), pp. 17914–17922, 2020, https://doi.org/10.1021/acssuschemeng.0c04415.

[29] H. Schobert, "Introduction to low-rank coals: Types, resources, and current utilization," in *Low-Rank Coals for Power Generation, Fuel and Chemical Production,* pp. 3–21, 2017. URL: https://doi.org/10.1016/B978-0-08-100895-9.00001-2.

[30] O. Arkhangelskaya, S. Trofimov, P. Galova, V. Makhachev, *Review of the cargo transportation industry in Russia 2020*. Moscow, Russia: LLC «Ernst & Young – assessment and consulting services», 2021, 51 p. Available at: https://ru.investinrussia.com/data/file/ey-russia-transportation-services-2020.pdf. (in Russian) (accessed May 30, 2022)

[31] K. Istratova, "Coal industry 2021. What are the prospects?" *Mining industry*, no. 5, pp. 20–24, 2021. Available at: https://dprom.online/chindustry/ugolnaya-promyshlennost-2021-kakie-perspektivy/ (in Russian) (accessed May 30, 2022)

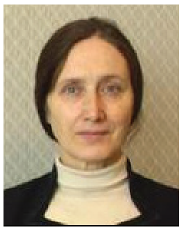
[32] "Elgaugol froze Ogoja for Elga". Available at: https://dprom.online/labels/vostochnyj-poligon/ (in Russian) (accessed May 30, 2022).

[33] A. Golyashev, A. Kurdin, A. Kolomiets, V. Skryabina, D. Fedorenko, S. Fedorov, "Fuel prices: between the market and regulation," *Energy Bulletin*, no. 103, 18 p, 2022. Available at: https://ac.gov.ru/uploads/2-Publications/energo/2022/energo_103.pdf. (in Russian) (accessed May 30, 2022)

[34] A. Honoré, "Decarbonization and industrial demand for gas in Europe," Oxford Institute for Energy Studies, 2019, 45 p. Available at: https://a9w7k6q9.stackpathcdn.com/wpcms/wp-content/uploads/2019/05/Decarbonization-and-industrial-demand-for-gas-in-Europe-NG-146.pdf. (accessed April 23, 2022)

[35] A. Golyashev, A. Kurdin, A. Kolomiets, A. Nekrash, D. Fedorenko, S. Fedorov, "Russian Fuel and Energy Complex under Sanctions Restrictions," *Energy Bulletin*, no. 107, 16 p, 2022. Available at: https://ac.gov.ru/uploads/2-Publications/energo/2022/Energo_107.pdf. (in Russian) (accessed April 23, 2022)

[36] "The share of wind and solar energy in electricity generation. World energy and climate data". *Yearbook 2021. Enerdata*, 2021. Available at: https://yearbook.enerdata.ru/renewables/wind-solar-share-electricity-production.html (in Russian) (accessed April 23, 2022)



Liudmila Takaishvili received a Ph.D. in engineering from the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences in 1991. Currently, she is a senior researcher at the Melentiev Energy Systems Institute SB RAS. Her research areas include the studies on the coal industry development prospects and the development of software and information support for these studies.

Alexander Sokolov received a D. Sc. degree in engineering from the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences in 2006. Currently, he is a chief researcher and the head of the Laboratory of the Energy Sector of Siberia and the Far East at the Melentiev Energy Systems Institute SB RAS. His research interests include the studies and modeling of the development prospects for the energy sector industries.

AGleb Agafonov received a Ph.D. in engineering from the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences in 1984. Currently, he is a researcher at the Melentiev Energy Systems Institute SB RAS. His research interests include studying the prospects for the development of the coal industry and modeling the prospects for the development of regional energy industries.