Modeling the operating modes of solar power plants for powering reclamation plants for water treatment and wastewater reuse

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Abstract. The article proposes the author's approach to modeling in the SimInTech environment the operating modes of energy complexes based on solar power plants that power reclamation installations for water treatment and wastewater reuse. The proposed model makes it possible to calculate the technical potential of electricity generation and the power factor of solar power plants. And also explore various options for building an autonomous energy complex supplemented with electricity storage devices.

1 Introduction

The key problem of irrigation of agricultural lands in Kazakhstan is the lack of water resources. Kazakhstan is located mainly in the steppe zone, where precipitation is insufficient to ensure adequate irrigation. Historically, most of the country's irrigated agricultural area is in the north and west, where climatic conditions are not very favorable for agricultural production. The high degree of deterioration of the obsolete infrastructure of irrigation systems also has a negative impact. A significant part of the functioning irrigation systems were put into operation in the USSR and now require modernization and repair. The shortage problem is aggravated by an unbalanced water resource management system, irrational use of water resources, and a low proportion of reclamation and reuse of wastewater.

Excessive water consumption in agriculture and improper irrigation organization lead to negative consequences, such as contamination of soil and water resources with chemicals, soil salinity and the formation of saline areas. The development of irrigation systems is hampered by a lack of qualified personnel. The need to train and attract specialists who can

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effectively manage irrigation systems and develop new technologies and methods of irrigation is an urgent task.

2 Research methodology

To solve the problem of irrigation in Kazakhstan, it is necessary to educate and train specialists in the field of irrigation, implement work to modernize and repair irrigation systems, and attract investments in infrastructure development. It is especially important to create international scientific teams focused on the development and implementation of effective irrigation methods that will allow the use of water resources as efficiently as possible.

An effective solution to the problem of water scarcity is the widespread introduction of wastewater reuse. In world practice, the leaders are the countries of the Middle East and North Africa, in countries such as the UAE, Qatar, Kuwait. Wastewater reuse technologies are widely developed in the Russian Federation and Turkey.

In accordance with ESG criteria and criteria for sustainable environmental management, technologies used to solve problems of irrigation of agricultural areas should not lead to an intensification of anthropogenic load on the ecosystem. Carbon neutrality technologies are a priority. The peculiarity of existing water treatment technologies is the use of energy carriers in the production process. The key energy carrier is electricity.

Specific electricity consumption for wastewater treatment depends on various factors, such as:

1. Treatment Methods: Different wastewater treatment methods require different amounts of electricity. For example, biological treatment processes typically require more energy than physical or chemical treatment methods.
2. Size and Scope: Large wastewater treatment plants serving large numbers of people or businesses may consume more electricity due to the need to treat large volumes of wastewater.
3. Availability of additional equipment: Certain processes, such as aeration, mechanical mixing or chemical injection, may consume additional electricity.
4. Equipment Design and Condition: Old or inefficient equipment may use more electricity than new, modern equipment.
5. Energy Efficiency: Implementing energy efficient technologies and processes in wastewater treatment plants can significantly reduce energy consumption.

Therefore, the exact value of specific electricity consumption for wastewater treatment may vary depending on all these factors.

In general, the energy consumption of wastewater treatment technologies depends on several factors, including wastewater characteristics, contaminant volumes and concentrations, treatment requirements, and equipment and processes used.

Table 1. Specific energy consumption of various wastewater treatment technologies.

№	Wastewater treatment technology	Specific energy consumption, kWh/m³
1	Mechanical cleaning (coarse and fine cleaning)	0,1 – 0,5
2	Aeration systems (activated and passive sludge)	0,5 – 1,5
3	Biological treatment (activated and passive sludge)	1 – 3
4	Filtration (sand filters, membrane filters)	0,5 – 2,5
5	Chemical treatment (flocculation, sedimentation, coagulation)	0,5 – 3
6	Ultrafiltration and reverse osmosis	2 – 6

One of the most common wastewater treatment methods is mechanical treatment, which is used to remove solids and floating matter from wastewater. This process usually does not require significant energy consumption and can be carried out using filters, sieves, separators and other equipment.

Biological wastewater treatment, such as active and passive sludge ponds, relies on the use of microorganisms to degrade organic contaminants. This process may consume some energy to maintain optimal living conditions for microorganisms, for example to provide aeration or heat wastewater during cold periods.

Another wastewater treatment technology, reverse osmosis (RO), is used to remove dissolved salts and other unwanted substances by passing wastewater through a semi-permeable membrane. The reverse osmosis process requires significant energy consumption to generate a high enough pressure to overcome the osmotic pressure and force wastewater through the membrane.

Electrocoagulation and electroflotation are processes that use an electric field to remove various contaminants from wastewater. These technologies may require power consumption to operate the electrolytic cells and to maintain the electric field.

Membrane-based ultrafiltration and reverse osmosis processes also have some energy consumption for pumping wastewater through the membranes and for cleaning and regenerating the membranes. However, energy consumption may vary depending on the type of membrane, equipment used and operating conditions.

The above examples allow you to estimate energy needs when choosing a water treatment technology or designing a power supply system.

For example, the design capacity of the pumping stations of the wastewater disposal system in the city of Kyzylorda is 78.4 thousand cubic meters. m per day, which is equivalent to discharges of 28.6 million cubic meters. m per year. According to the recommendations of the Kazakh Scientific Research Institute of Water Management, when planning irrigation activities on fruit plantations in the southern regions of Kazakhstan, it is necessary to adhere to irrigation standards within the range of 4500 - 6000 cubic meters. m/ha. With an estimated garden area of 5 hectares, the total water requirement can be determined in a volume of up to 30 thousand cubic meters for one-time watering. When 20% of the nominal volume of wastewater is diverted for irrigation needs, the minimum period for irrigation of the site, taking into account 15% of losses, will be at least 2 days.

At the same time, electricity consumption for water purification and water treatment needs will be 45 thousand kW/h per day. Which in annual volume will be about 16.5 * 106 kW/h, and in value equivalent 471 million tenge or 97.3 million rubles. at the exchange rate for February 2024. Moreover, according to research by the International Renewable Energy Agency (IRENA), over 10 years, the average cost of constructing solar power plants has decreased by more than 5.6 times from 4,808 usd in 2010 to 857 usd in 2021 and continues to decline. The key factors that determined such a significant reduction in cost were:

- Reduced prices for photovoltaic modules. Between 2009 and 2021, the average price of silicon panels decreased by 88%-95%.
- Reducing the cost of equipment for the electrical part of the station (Solar PV Balance-of-System).

It should be noted that there are significant differences for different regions of the planet. Thus, the leaders in terms of unit costs are Russia and Japan. where there is almost a twofold (98%) increase in the average cost of constructing solar power plants, while in China and India similar projects will cost 27% and 31% less than the world average. As a result, a project implemented in Japan will require 2.87 times more investment than a similar project in China.

An analysis of regional markets made it possible to identify the prerequisites for such a significant difference in the cost of implementing solar energy projects in China and Japan:

- Industrial factor: China is actually the largest manufacturer of solar panels in the world, which reduces the cost of materials and technologies for the construction of solar power plants.
- Labor factor: Labor costs in China are lower than in Japan, which also reduces the overall cost of project implementation.
- Political factor: The leadership of the People's Republic of China actively supports the development of national energy, incl. solar energy through targeted subsidies for projects, benefits and preferences for companies, which makes the construction of solar power plants more attractive.
- Infrastructure factor: China has developed infrastructure for the installation and operation of solar panels, which also reduces the cost of the project.

In general, these factors have a stimulating effect and ensure the leadership of the People's Republic of China in the field of solar energy. Today in China, according to Rystad Energy's forecast, the total installed capacity of solar power plants already exceeds 500 GW, with 1 TW expected by the end of 2026.

It should be noted that solar energy support projects in China are scientifically based. Conducted in-depth theoretical research, modeling and feasibility studies made it possible to build the world's largest solar energy system, despite the presence of serious limitations.

Initially, the following factors hindered the development of solar energy in China:

- Heterogeneous distribution of population and industry across the territory of the PRC. The densely populated southeast of the country and low population density in the northwest.
- The potential of solar resources (number of cloudless days and free territories) for energy production in the southeast of the country is significantly lower than in the densely populated industrialized northwest.
- Infrastructure restrictions on the transport of electricity across the country.

In order to comprehensively study the possibilities of solar energy in China, a predictive multidimensional multimodel was built. With the help of the model, it became possible at the feasibility study stage to conduct a comprehensive analysis of most of the factors affecting the volume and efficiency of electricity production at solar power plants, as well as the impact of generation on the energy system and the demand for generated electricity by consumers. In addition to technical and technological factors, the predictive contour of the model builds a forecast in accordance with the expected changes in the energy system, technology development, and the Chinese economy on the horizon until 2060. Particular emphasis is placed on predicting solar productivity in different regions of the country. Data from meteorological satellites is taken into account in a retrospective of six years. In the course of the research, the "technical potential of the PRC territory" was calculated using the model. Thus, as of 2020, when all natural and urban sites are used for solar energy needs, the technical potential of solar energy is 13 times greater than China's electricity needs and amounts to about 100 petawatt hours. The introduction of new, highly efficient technologies by 2060 can provide an increase of up to 50%. This high energy intensity of the green energy sector is necessary to achieve net-zero carbon emissions by 2060. It is important to note that most of the territories have an average power factor of solar power plants (actual performance) - 17.6% of the rated power. In the USA, the capacity factor of solar power plants reaches 25%.

Therefore, it is especially important at the stage of planning and justification of the project to conduct a comprehensive study of the effectiveness of the SES. And one of the first parameters for modeling is the amount of solar radiation received, which means electricity generation.

In terms of the initial data for building an energy supply system for a wastewater treatment plant, using the example of the actual output of the SPP "Baikonyr Solar" located in the

Sulutobe district of the Shieli region, in order to fully cover the need for electricity, it is necessary to place about 40,000 photovoltaic panels on an area of 33 hectares. The implementation of the Project will reduce annual CO2 emissions into the atmosphere by 16.6 thousand tons.

For reference: 150,822 photovoltaic panels, 14 central inverter power plants, as well as a substation with an operating voltage of 220/20 kV are installed on the territory of the Baikonyr Solar SES. The area of the plots is 150 hectares. Electricity generation is 200 thousand kW per day, which is equivalent to 73 million kWh per year.

The scale of the project determines the relevance of modeling and optimization. One of the primary tasks is to conduct a comprehensive analysis of the effectiveness of investments in the project's energy supply system.

The effectiveness of the project depends on the following factors:

- technical potential of the territory,
- basic and forecast value of electricity generation volumes,
- power factor of solar power plants.

3 Research results

All the necessary data can be obtained as a result of constructing a multi-model SES, the basic element of which is the model of the arrival of solar radiation. The SimInTech environment developed by the Russian company 3V Service was chosen as the modeling environment. SimInTech is a comprehensive modeling and analysis environment used to create and test various types of models in various fields, such as industry, transport, energy, ecology, etc. It can be used to carry out complex modeling, analysis and optimization of processes and systems, as well as study their behavior under different conditions.

When constructing the model, the hypothesis was taken as a basis: the initial data (the amount of solar radiation and load parameters) are for the most part functions of many variables, some of which are stochastic in nature. The amount of solar radiation received in the general case can be described by the following equation 1:

$$R(t) = R_{\mathrm{pr}}(t) + R_{\mathrm{d}}(t) + R_{\mathrm{ot}}(t) \tag{1}$$

where: $R_{\mathrm{pr}}(t)$ – direct solar radiation; $R_{\mathrm{d}}(t)$ – diffuse solar radiation; $R_{\mathrm{ot}}(t)$ – part of the directed solar radiation reflected from the earth's surface (negligibly small).

$R_{\mathrm{d}}(t)$ is calculated according to expression 2:

$$R_{\mathrm{d}}(t) = 0.33\ [0.55 + 0.434 \cos(\theta) + 0.313\ (\cos(\theta))2] \bullet$$

$$\bullet (R_{\max} - R_{\max} \sin(\alpha) \bullet (\sin(\alpha)+c) - 1) \sin(\alpha) \tag{2}$$

Solar radiation on the earth's surface has the following characteristics:

1. Conditional inexhaustibility;
2. Availability of proven solutions for creating photoenergy systems;
3. The total arrival of solar radiation on the earth's surface is a function of random and calculated variables;
4. The given specific energy saturation of photovoltaic power plants is many times inferior to all types of traditional power plants.

The amount of direct solar radiation arriving at the earth's surface can be determined as a function of 3:

$$R_{\mathrm{pr}}(t) = R_{\max} \bullet K_{\mathrm{geogr}} \bullet C_{\mathrm{orb}} \tag{3}$$

where: K_{geogr} is the coefficient of the geographical position of the receiving surface, adjusted taking into account the optical properties of the atmosphere; K_{orb} is the coefficient of the orbital-spatial position of the earth in orbit and the relative position of the earth and the sun.

The works [1-5] outline the functional dependences of the arrival of solar radiation on the listed factors. When calculating direct solar radiation on the surface, the spatial diagram presented in Fig. 2 is used.

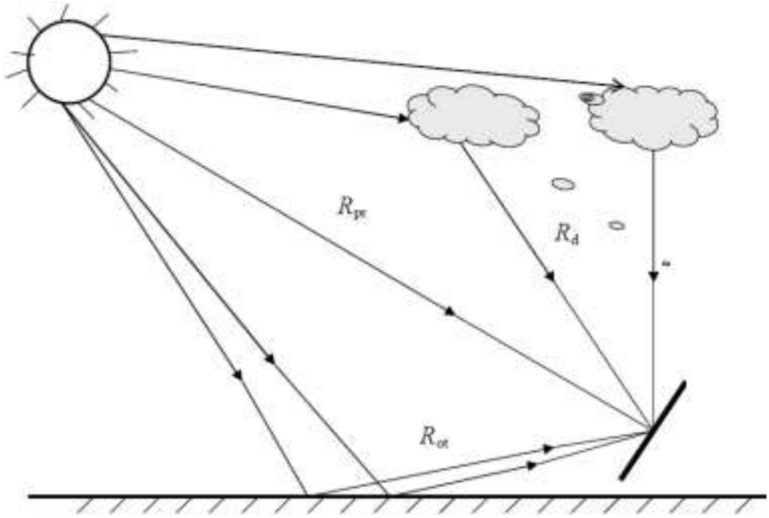

Fig. 1. Basic components of solar radiation on the Earth's surface.

The coefficients of solar radiation arrival are found according to relations 4, 5:

$$K_{geogr} = R_{max} \bullet \sin(\alpha) \bullet (\sin(\alpha)+c)-1 \tag{4}$$

$$K_{orb} = \cos(\theta) = \sin(\delta)\sin(\phi)\cos(s)-\sin(\delta)\cos(\phi)\sin(s)\cos(\gamma)+ +\cos(\delta)\cos(\phi)\cos(s)$$

$$\cos(\omega)+\cos(\delta)\sin(\phi)\sin(s)\cos(\gamma)\cos(\omega)+\cos(\delta)\sin(s)\sin(\gamma)\sin(\omega) \tag{5}$$

where: R_{max} – solar constant, 1370 W/m2; c is a dimensionless quantity characterizing the degree of transparency of the atmosphere (for average transparency c = 0.81); ϕ - geographical latitude of the place; δ – sun declination; s – angle of inclination of the plane under study to the horizon; α – height of the Sun; β – azimuth of the Sun; Ɣ – azimuthal angle of the study area; θ – angle of incidence of direct solar radiation; s – angle of inclination of the area under study.

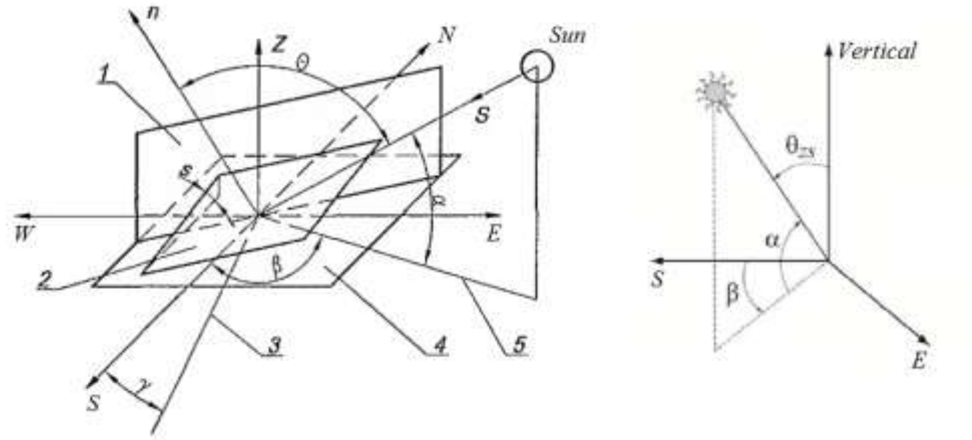

Fig. 2. Scheme of angular coordinates of the sun position relative to a geographically oriented system. where: 1 – vertical plane; 2 – inclined plane (site under study); 3 – horizontal projection of normal n; 4 – horizontal plane; 5 – horizontal projection of the sun's ray; Z – vertical position; n – normal to the inclined plane; S – direct solar radiation on the Earth's surface.

The resulting analytical dependencies make it possible to determine the total influx of solar radiation at any time, but are quite labor-intensive for direct calculation.

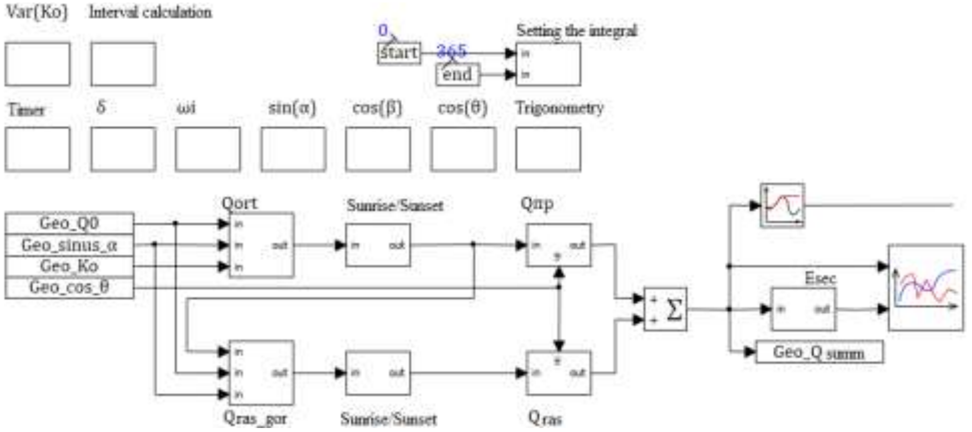

Fig. 3. Model of total solar radiation arrival on an inclined surface implemented in the environment dynamic simulation SimInTech.

The implementation of the above analytical dependencies in SimInTech is presented in Fig. 3.

4 The discussion of the results

As a result of testing the created model, it becomes possible to calculate the arrival of solar radiation on an inclined surface (Fig. 4) for an arbitrary time interval and use the obtained data for further calculations when drawing up energy balances and designing photovoltaic and hybrid power supply systems for projects.

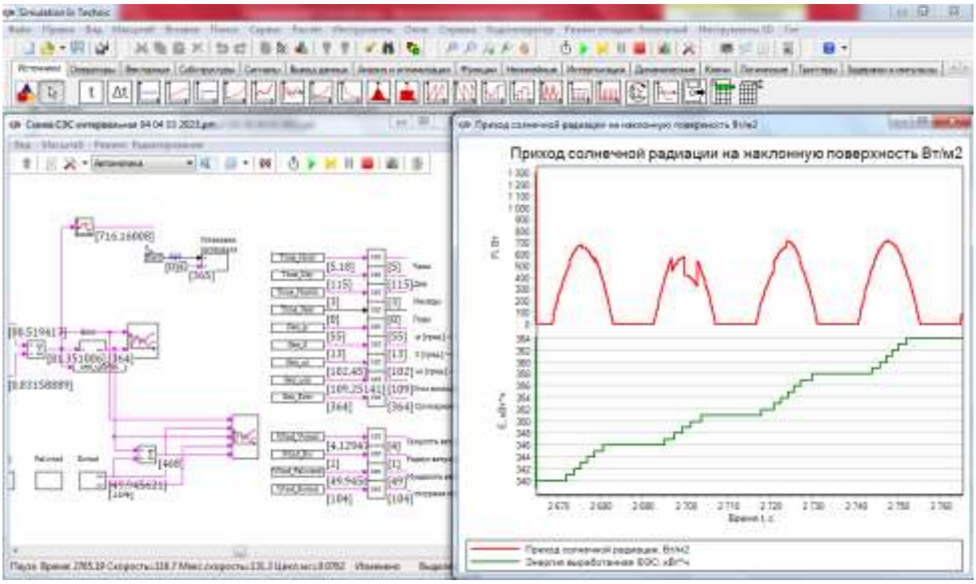

Fig. 4. Dynamic calculation of solar radiation arrival on an inclined surface implemented in the SimInTech environment.

The proposed model of the arrival of solar radiation is the basic link of a multi-model of solar power plants built in the dynamic modeling environment SimInTech and allows you to calculate the technical potential of the territory, the basic and forecast value of electricity generation volumes, and the power factor of solar power plants.

5 Conclusions

Using the model, at the stage of feasibility study of projects, it is possible to conduct a comprehensive analysis of most of the factors affecting the volume and efficiency of electricity production at solar power plants, as well as the impact of generation on the energy system and the demand for the generated electricity by consumers. In addition to technical and technological factors, the predictive contour of the model will make it possible to build a forecast in accordance with the expected changes in the energy system, technology development, and on the required planning horizon.

References

1. S. M. Voronin, S. M. Voronin, *Formation of autonomous power supply systems for agricultural facilities using renewable energy sources: monograph* (Azov-Black Sea State Agroengineering Academy Publishing House, 2010)
2. V. Bocharnikov, O. Kozinskaya, M. Denisova, O. Bocharnikova, T. Repenko, BIO Web of Conferences **67**, 02004 (2023)
3. A. Galeeva, N. Mingazova, I. Gilmanshin, BIO Web of Conferences **67**, 01018 (2023)
4. A. Bayanova, BIO Web of Conferences **67**, 02007 (2023)
5. V. I. Vissarionov, G. V. Deryugina, V. A. Kuznetsova, N. K. Malinin, *Solar energy: Textbook for universities* (MPEI Publishing House, 2008)
6. V. I. Velkin, *Methodology for calculating complex renewable energy systems for use in autonomous facilities: monograph* (UrFU Publishing House, 2015)

7. I. R. Gilmanshin, *Renewable energy sources. Part 1. Conversion and use of solar energy: textbook. manual for independent work of master's students* (Kazan Publishing House. University, 2018)
8. I. Botygin, N. Goncharova, A. Sherstneva, V. Sherstnev, BIO Web of Conferences **67**, 03014 (2023)
9. B. V. Lukutin, I. O. Muravlev, I. A. Plotnikov, *Power supply systems with wind and solar power plants: textbook* (Tomsk Polytechnic University Publishing House, 2015)
10. S. P. Khabarov, *Fundamentals of modeling technical systems. Simintech environment* (Lan Publishing House, 2019)
11. Z. Shamsutdinov, BIO Web of Conferences **43**, 01025 (2022)
12. B. A. Kartashov, E. A. Shabaev, O. S. Kozlov, A. M. Shchekaturov, *Environment for dynamic modeling of technical systems SimInTech: Workshop on modeling automatic control systems* (DMK Press. Electronic books, 2017)
13. V. B. Shleinikov, *Graphs of electrical loads: guidelines for laboratory* (Orenburg State university Publishing House, 2011)
14. N. I. Cherkasova, A. N. Tatarnikova, *Energy Economics: Textbook for students of specialty 140211 of all forms of study* (Rubtsovsky Industrial Institute Publishing House, 2011)
15. E. Yu. Fedorov, A. V. Ferenets, G. S. Khairullina, Bulletin of the Kazan State Technical University A.N. Tupolev, **79** (2023)
16. J. Kasper, M. Magdowski, R. Vick et al., *IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility, EMC/APEMC 2018,* **60** (2018)
17. E. Yu. Fedorov, G. S. Khairullina, N. Sh. Shakirzyanova, Bulletin of the Kazan State Technical University A.N. Tupolev **72(2)** (2016)
18. E. Fedorov, A. Ferenets, N. Dudka, A. Snegurenko, Journal of Physics Conference Series, **012001** (2021)
19. T. B. Putivskaya, BIO Web of Conferences **43**, 02030 (2022)
20. K. Murtazova, BIO Web of Conferences **43**, 02020 (2022)
21. S. A. Lizunov, Bulletin of the Kazan State Technical University A.N. Tupolev **79(2)** (2023)