E3S Web of Conferences **384**, 01025 (2023) https://doi.org/10.1051/e3sconf/202338401025
RSES 2022

Methodology for ranking critical energy facilities on the example of some emergencies in the gas industry

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Abstract. The paper presents the main components of a methodical approach to assessing the level of significance of critical energy facilities on the example of individual outages of the most important facilities of the Russian gas transmission network. Approaches to modelling the fuel and energy complex of the country and its constituent energy systems: gas, electricity and heat supply are presented. Algorithms for identifying critical energy facilities of the industry, regional and federal levels, as well as examples of their ranking depending on the level of expected consequences for consumers of electrical and heat energy in case of loss of performance of these critical facilities are given.

1 Introduction

In the context of the possible implementation of large-scale emergencies in the energy sector, accompanied by a decrease in the productivity of some energy facilities and related energy systems (ES), it is not always possible to ensure a deficit-free energy supply to consumers. In these cases, it is necessary to talk about minimizing the volume of possible shortages of final types of energy among consumers. Among the causes of large-scale emergencies in the energy sector, we can single out the causes caused by intentional impacts. It is logical to assume that intentional impacts can be aimed primarily at those facilities, the decrease in the efficiency of which can significantly reduce the production capabilities of some ES and the energy sector as a whole and can lead to significant shortages of the corresponding types of fuel and energy resources (FER).

It is logical to identify such critically important facilities (CF) of the ES and of the energy sector as a whole. Not all CFs of ES are CFs of the energy sector, i.e. the loss of productivity of not each of them can lead to shortages of final types of energy among consumers. The task of the study is to form an algorithm for identifying the CFs of ES and to form a methodological approach to determining the level of these CFs.

2 Algorithms for identifying CFs of ES and of the energy sector

2.1 CFs of ES

CFs of ES of the federal level can be recognized as objects, the termination of which may cause significant undersupply of the relevant fuel and energy resources throughout the country as a whole. At the same time, the shortage of supplies can be in relative terms δ_{sum} or more of the country's total need for this type of FER. As such δ_{sum} for the gas industry, earlier in [1, 2] a value of 5% was taken. Objects that are not included in the list of federal CFs of the considered ES can be defined as the CFs of the ES of the regional level, but the termination of their operation may cause undersupply of the corresponding FER to at least one of the regions in the relative value of δ_{reg} and more. As such δ_{reg} for the gas industry in [1, 2], a value of 40% was taken. The algorithm for the formation of lists of CFs at the regional and federal levels of any ES is shown in Fig. 1.

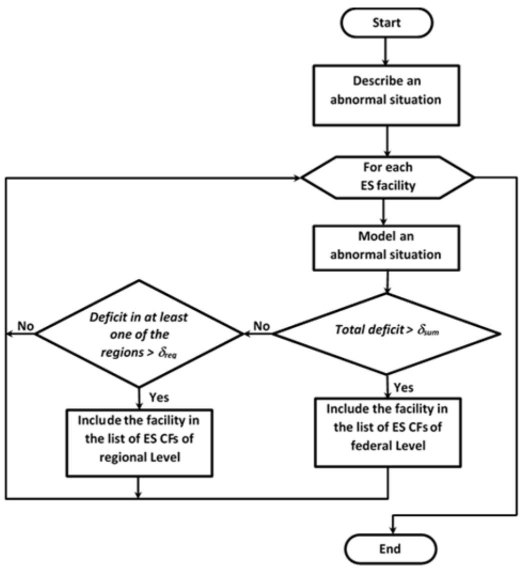

Fig. 1. Algorithm for the formation of lists of ES CFs.

Research is carried out by enumeration of various emergencies. The result of modeling studies is the

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magnitude of deficits of the corresponding FER for its consumers. Comparison of the relative value of the total deficit of this type of fuel and energy resources with the agreed value of the conditionally permissible relative deficit δ_{sum} allows us to single out some CFs of ES in their federal list. CFs of ES which were not included in this list should be checked for the formation (when they are turned off) of the deficit of this type of FER in the regions. If the relative deficit of this type of FER in any of the regions exceeds the conditionally permissible value δ_{reg}, then this CF falls into the regional list of CFs of this ES.

2.2 CFs of energy sector

The algorithm for the formation of the list of CFs at the level of the energy sector is shown in fig. 2. This algorithm begins with the analysis of the set of CFs ES of the federal level, which is formed during the operation of the algorithm presented above, in Fig. 1.

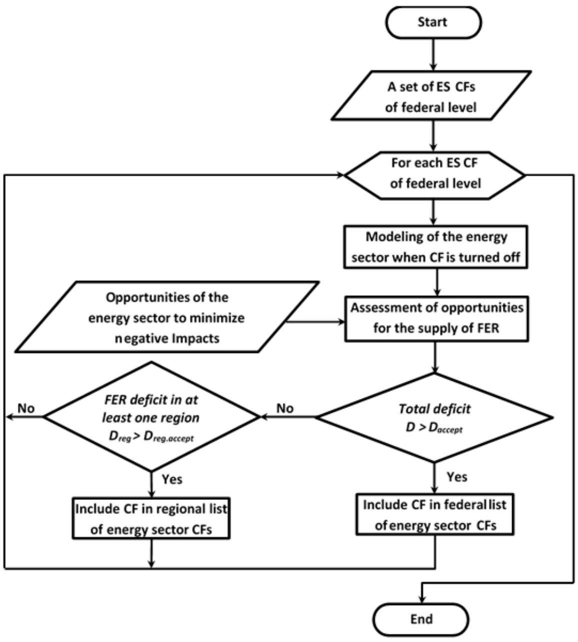

Fig. 2. Algorithm for the formation of lists of energy sector CFs.

Research is carried out using the economic-mathematical model of the energy sector [3, 4], while taking into account it's possibilities to minimize the deficit of FER. Comparison of the relative value of the total energy deficit among consumers with the value of the conditionally acceptable relative deficit (D_{accept}) makes it possible to form a federal list of energy sector CFs from some of the ES CFs of the federal level. The loss of operability of some ES CFs, which, according to the accepted rule, did not fall into the federal list of energy sector CFs, can lead to significant energy shortages among consumers in one or more regions. Facilities that are not included in the federal list of energy sector CFs, but capable of causing a shortage of energy resources greater than the conditionally acceptable ($D_{reg.accept}$) should form a regional list of energy sector CFs.

Let us dwell in more detail on the aspects of the functioning of the unified electric power system (UES) and the unified gas supply system (UGSS) of Russia that are closest to the task of research.

3 Modeling of emergency modes in the energy systems of Russia and of energy sector as a whole

3.1 Unified gas supply system

The gas industry of Russia, in the technological part, is represented by the UGSS and local gas supply systems in the east of the country. The UGSS, through a multi-line gas transmission network (GTS), connects gas fields in the European part of the country with natural gas consumers in the same European part and in the regions of Western Siberia.

The existing territorial structure of the UGSS of Russia has a number of significant drawbacks. Today, more than 85% of all Russian gas is produced in the northern regions of the Tyumen region. The main consumers of gas within the country - its European regions and gas export points - are located at a distance of 2-2.5 thousand km from the places of its production. All this gas is transported over long distances using multi-line gas transmission corridors, often with a significant concentration of gas flows in one corridor. These corridors have a large number of mutual intersections and bridges. Currently, GTS of Russia has several intersections of main gas pipelines (MG) that are potentially dangerous for the operation of the UGSS. Failure of some of them can lead to significant restrictions on gas supplies to consumers. A significant part of such intersections is UGSS CFs from the standpoint of ensuring GTS operability.

The ESI SB RAS has developed software "Oil and Gas of Russia" [1, 2]. This software includes a streaming simulation model of the UGSS of Russia. the research scheme of the model contains 382 nodes, including 22 underground gas storage facilities (UGS), 28 gas sources, 64 gas consumers (regions and points of gas export delivery), 268 nodal compressor stations (CS), 628 arcs (MG corridors and individual MG). When solving the problem of estimating the state of the system after a disturbance, the criterion for the optimal distribution of flows is the minimum gas deficit at the consumer at the minimum cost of its delivery.

Shutdown of objects leads to the solution of the problem of distribution of flows in the system in order to maximize the supply of gas to consumers. The model is formalized as a maximum flow problem [5, 6]. The calculation graph is supplemented with two fictitious nodes: O - total source, S - total sink, while additional sections are introduced that connect node O with all sources and all consumers with node S. The mathematical notation of the task has the following form:

$$\max f \tag{1}$$

under the conditions that

$$\sum_{i\in N_j^+} x_{ij} - \sum_{i\in N_j^-} x_{ji} = \begin{cases} -f, j=O \\ 0, j\neq O, S \\ f, j=S \end{cases} \quad (2)$$

$$0 \le x_{ij} \le d_{ij} \text{, for all (i, j)} \quad (3)$$

Here: N_j^+ a subset of arcs “incoming” to node j; N_j^- - a subset of "outgoing" arcs from node j; f - the value of the total flow through the network; x_{ij} - flow along the arc (i, j); d_{ij} - restrictions on the flow along the arc (i, j).

Problem (1)-(3) about the maximum flow has not a unique solution. The next step is to solve the problem of the maximum flow of minimum cost, i.e. the cost functional is minimized:

$$\sum_{(i,j)} C_{ij} x_{ij} \to \min \quad (4)$$

where C_{ij} is the price or unit costs for gas transporting.

The result of solving the problem is to determine the possibilities of satisfying consumers with gas, identifying the volumes of possible undersupplies of gas in one or another emergency situation. Based on these results, objects are identified, the cessation of which will lead to a potential shortage of gas in the network. By cutting off facilities, the shutdown of which will lead to a potential shortage of gas in the network less than the threshold value of 5%, a list of UGSS CFs is formed.

For example, let's choose the most indicative situations with the loss of productivity of some UGSS CFs. Using specialized models to minimize the shortage of electric power and information on the expected undersupply of gas to gas-consuming power generating facilities for the relevant unified electric power systems (UPS), we calculate the possible volumes of undersupply of electricity to consumers.

3.2 Unified electric power system

The purpose of UES modeling in this case is to determine the undersupply of electricity to consumers as a result of accidents at fuel and energy facilities. Problem to be solved: for the known structure, parameters of the elements and the schedule of power consumption of the UES, it is necessary to determine the non-admission of electricity for the period from the beginning of the emergency and the reduction of gas supply to gas-consuming power generating facilities until it is completely eliminated. The UES calculation model is a graph whose nodes are energy zones, and the arcs are interzone connections. The energy zone includes a part of the power system, as a rule, it is a regional power system, which contains a set of generating units and is characterized by power consumption in each hour of the billing period. Interzone communication includes power lines that connect energy zones. Thus, for each hour of the billing period, it is necessary to solve the following problem [7]:

need to find:

$$\sum_{i=1}^{I} (\overline{N}_{cons,i} - N_{cons,i}) \to min, \quad (5)$$

considering balance constraints

$$N_{gen,i} - N_{cons,i} + \sum_{j=1}^{J} (1 - z_{ji}\, a_{ji}) z_{ji} - \sum_{j=1}^{J} z_{ij} = 0, i = 1, \dots, I,\ i \neq j, \quad (6)$$

and linear inequality constraints on variables:

$$0 \le N_{cons,i} \le \overline{N}_{cons,i}, i = 1, \dots, I, \quad (7)$$

$$0 \le N_{gen,i} \le \overline{N}_{gen,i}, i = 1, \dots, I, \quad (8)$$

$$0 \le z_{ji} \le \overline{z}_{ji}, 0 \le z_{ij} \le \overline{z}_{ij}, j = 1, \dots, J, i = 1, \dots, I, i \neq j, \quad (9)$$

where: $\overline{N}_{cons,i}$ is the value of power consumption in energy zone i, MW; $N_{cons,i}$ – secured power consumption in energy zone i, MW; $\overline{N}_{gen,i}$ – available generating capacity in energy zone i, MW; $N_{gen,i}$ - used generating capacity in the reliability zone i, MW; $\overline{z}_{ji}$ – interzone communication capacity, MW; z_{ji}, z_{ij} – actual load of interzone communication, MW; I=J is the number of energy zones.

3.3 Energy sector as a whole

The problem of modeling the energy sector as a whole is described in detail in [8] and mathematically represents a classical problem of linear programming. The statement and restrictions of this problem are written as follows:

$$AX - \sum_{t=1}^{T} Y^t = 0 \quad (10)$$

$$0 \le X \le D \quad (11)$$

$$0 \le Y^t \le R^t \quad (12)$$

where t - categories of consumers; A – matrix of technological coefficients of production (extraction, processing, transformation) and transport of certain types of fuel and energy; X - the desired vector, the components of which characterize the intensity of the use of technological methods of functioning of energy facilities (extraction, processing, transformation and transport of energy resources, fuel reserves); Y^t – the desired vector, the components of which characterize the volumes of consumption of certain types of fuel and energy by certain categories of consumers (t); D - a vector that determines the technically possible intensity of the use of individual technological and production methods; R^t is a vector with components equal to the volumes of the given consumption of certain types of fuel and energy by certain categories of consumers.

The objective function then has the following form:

$$(C, X) + \sum_{t=1}^{T} (r^t, g^t) \to \min \quad (13)$$

where, the first component reflects the costs associated with the functioning of the ESs. Here C is the vector of unit costs for individual technological methods of functioning of energy facilities; the second component is the damage from the shortage for each type of fuel and energy for each of the selected categories of consumers. The magnitude of the deficit of energy resources among consumers g^t is determined by the expression. The vector r^t

conditionally denotes "specific damage" at the consumer.

This study uses only a part of the capabilities of the presented model, implemented within the framework of the "Correctiva+" [9], concerning the production of thermal energy. As a result of the calculations, the following are determined: possible volumes of undersupply of thermal energy in the regions of the country in case of shutdown of the corresponding UGSS CFs, taking into account the interconnected work of all branches of the energy sector, reserves of energy resources, the possibility of interchangeability of various types of energy resources and their diversification.

4 Assessing the possibility of supplying energy resources in the event of the shutdown of some gas industry CFs

4.1 Natural gas

The studies were carried out on the model of the Russian gas industry described above. Baseline for calculations: average day of maximum gas consumption in the network (January 2021). On such days, the work of the network can be considered the most intense. The total gas flow through the network on that day, including exports, amounted to approximately 2,180 million m^3, while gas consumption within the country was about 1,550 million m^3/day. Studies have shown that a potential shortage of gas among consumers can be observed when the operation (one by one) of 449 UGSS facilities (242 nodes, 199 arcs and 8 intersections of the gas pipelines of the settlement graph) is stopped. Of this number of objects earlier [1; 2, 10, 11], 61 facilities were singled out, single shutdowns of which can lead to a relative gas deficit of 5% or more of the total gas demand for the UGSS. These facilities include 22 main line arcs between nodal CSs, 36 nodes (30 nodal CSs, 5 head CSs at field exits, 1 CS at UGS outlets) and 3 MG intersections between CSs. These objects represent a modern list of UGSS CFs.

Let us consider an illustrative example to assess the possibilities of reliable supply of electrical and thermal energy to end consumers and, thereby, to classify certain UGSS CFs as CFs of the energy sector. To do this, we will single out several UGSS CFs located at different points of the gas transmission network. The selected CFs include three intersections of MG corridors between CSs and five nodal CSs at MG intersections.

Based on the solution of problem (1)-(4), the possibilities of gas supply to consumers were assessed with the help of the software "Oil and Gas of Russia" in the event of shutdown of the selected UGSS CFs. Each study dealt with the failure of one CF. For example, Table 1 below provides information on the estimated possibilities of gas supply to the regions of the Russia in the event of the loss of operability of one of the UGSS CF. The real names of the UGSS CFs have been replaced with conditional ones. Table 2 provides information on the total possibilities of satisfying gas consumers in the event of a loss of operability of the UGSS CFs. These CFs in Table 2 are ranked by the value of the total gas deficit.

Table 1. Loss of operability of the UGSS CF "Intersection No. 1".

Region	Consumption	Supply	Deficit
	million m^3/day		%
Perm region	66	0,7	99
Kirov region	13,3	0	100
Rep. of Udmurtia	13,2	5,6	58
Rep. of Bashkortostan	62,4	10	84
Rep. of Tatarstan	69	50	28
Rep. of Mari El	5	0	100
Rep. of Chuvashia	7,7	0	100
Rep. of Mordovia	10	0	100
Nizhny Novgorod region	29,3	5,5	81
Kostroma region	18,2	0	100
Arkhangelsk region	14	0	100
Vologda region	33,8	0	100
Rep. of Kareliaя	3,7	0	100
Leningrad region	77,5	67,7	13
Novgorod region	15,4	12,7	18
Smolensk region	9,6	0	100
Kaluga region	6,9	4,1	41
Moscow region	140,7	98,4	30
Tula region	29,4	0	100
Bryansk region	8	0	100
Oryol region	5,5	0	100
Lipetsk region	17,5	0	100
Voronezh region	21,1	0	100
Kursk region	8	0	100
Belgorod region	28,6	0	100
Total for UGSS	**1550**	**1091**	**30**

Table 2. Total possibilities of gas supply in the event of a loss of operability of the UGSS CFs.

CF	Consumption	Deficit
	million m^3/day	%
Intersection No. 2	1217	21
CS 1	1220	21
CS 2	1351	13
CS 3	1357	12
CS 4	1389	10
CS 5	1442	7
Intersection No. 3	1454	6

The values of the calculated undersupply of gas, noted in tables 1, 2, will affect the process of fuel supply to the corresponding gas-consuming power generating sources. Due to the fact that different types of electricity generating sources operate in the UES of Russia, adequate modeling allows us to answer the question: how problems with shutting down CFS in the gas industry can affect the supply of electricity to consumers.

4.2 Electricity

The assessment of the undersupply of electricity was carried out for the conditions of the functioning of the UES of Russia in 2022, [12]. Undersupply of electricity was estimated for the period of the first two weeks of January. When assessing the undersupply of electricity, an accounting of scheduled repairs of generating equipment was carried out [7]. Table 3 shows the ratio of undersupply of electricity in the conditions of shutdown of the UGSS CF to the values of the required level of electricity consumption in the UES of Russia and in the United Power Systems (UPS) of Russia for the period under review.

Table 3. Expected relative undersupply of electricity in the UES of Russia in the event of a loss of operability of the UGSS CF.

United Power System	Required level of electricity consumption, billion kWh/day	Scenario of the UGSS CF shutdown, undersupply* (%)							
		Inter-section No. 1	Inter-section No. 2	CS 1	CS 2	CS 3	CS 4	CS 5	Inter-section No. 3
UES of Russia (without the UPS of the East)	45260	0,3	-	0,6	-	0,7	1,6	0,3	0,2
UPS of Northwest	4599	2,4	-	-	-	-	-	2,8	-
UPS of Center	9549	-	-	-	-	-	-	-	-
UPS of Middle Volga	4668	-	-	-	-	-	-	-	-
UPS of South	4722	-	-	-	-	-	-	-	-
UPS of Ural	11821	-	0,1	2,1	-	2,6	6,2	-	0,8
UPS of Siberia	9901	-	-	-	-	-	-	-	-

* - "-" means less than 0.1

Taking into account the magnitude of possible undersupply of electricity by the UPSs, it is clear that the shutdown of "Intersection No. 2", "Intersection No. 3" and "CS 2" can be largely compensated by the capabilities of the UES of Russia itself. From the standpoint of possible undersupply of electricity, these UGSS CFs cannot be attributed to the energy sector CFs. All the rest of the selected UGSS CFs, i.e. "Intersection No. 1", "CS 1", "CS 3", "CS 4", "CS 5" can be attributed to the energy sector's CFs of regional level.

4.3 Thermal energy

Undersupply of gas will also affect the generation of thermal energy in some regions. In general, in Russia, the share of thermal energy generated from natural gas in 2021 amounted to almost 76%, in the European part of the country this value exceeded 89% (calculations based on [13]). Estimated values of possible undersupply of thermal energy by regions within the UGSS coverage area in case of shutdown of the UGSS CHP are presented in Table 4.

Table 4. Relative undersupply of thermal energy in the regions in the event of a shutdown of the UGSS CFs, %.

Federal district (FD), region	Share of heating power on gas	Scenario for shutdown of the UGSS CFs							
		Intersection No. 1	Intersection No. 2	CS 1	CS 2	CS 3	CS 4	CS 5	Intersection No. 3
Russia (without Far Eastern FD	**76**	**10**	**7**	**5**	**4**	**1**	**3**	**2**	**2**
Central FD		*14*	*10*	*7*	*10*	*5*			
Belgorod region	98	62							
Bryansk region	99	63							
Voronezh region	96	61	61	61	61	11			
Kostroma region	79	50							
Kursk region	95	60	60	60	60	60			
Lipetsk region	80	51	51		51				
Oryol Region	99	63	63	63	63	63			
Smolensk region	93	59							
Tula region	87	56	56	56	56	56			
Northwestern FD		*11*	*5*	*5*	*5*			*16*	
Republic of Karelia	60	38						38	
Arkhangelsk region	52	33							
Vologda Region	77	49	49	49	49			49	
Leningrad region	52							23	
Privolzhsky FD		*18*	*15*	*8*	*2*				*8*
Republic of Bashkortostan	98	25	25	18					
Mari El Republic	91	58	58	58	58				
Republic of Mordovia	99	63	63	63	63				
Chuvash Republic	99	63	63	63					
Perm region	90	54	54						54
Kirov region	78	50	50	50					50
Nizhny Novgorod Region	96	29							
Ural FD							*21*		
Tyumen region	71						45		
Chelyabinsk region	84						23		
Siberian FD							*3*		
Altai region	13						8		
Omsk region	58						24		

It can be seen from the Table 4 data that in most cases consumers of the Central, Northwestern and Privolzhsky federal districts will suffer the most. First of all, this is due to the high share of gas in the production of thermal energy in these regions. According to the relative values of the possible undersupply of thermal energy, it can be seen that the shutdown of the first 3 UGSS CFs (one by one) can lead to restrictions in the production of thermal energy in Russia in the UGSS coverage area equal to or more than 5%. These CFs should be included in the federal list of energy sector's CFs. The shutdown of the remaining 5 UGSS CFs can lead to restrictions on thermal energy in some regions. These objects should be attributed to the regional level of energy sector CFs.

4.4 Energy sector as a whole

In Table 5, the results of the analysis on the attribution of the UGSS CFs to various lists of the energy sector CFs are brought together.

Table 5. Results of classifying UGSS CFs as the energy sector CFs.

UGSS CF	Energy systems CFs				Energy sector CFs	
	Power industry		Heat power industry			
	Fed.	Reg.	Fed.	Reg.	Fed.	Reg.
Intersection No. 1		+	+		+	
Intersection No. 2			+		+	
CS 1		+	+		+	
CS 2				+		+
CS 3		+		+		+
CS 4		+		+		+
CS 5		+		+		+
Intersection No. 3				+		+

Thus, the studies have shown that all analyzed UGSS CFs in terms of the degree of consequences (in case of their shutdown) can be considered as CFs of the energy sector. The first three of those CFs listed in Table 5 refer to the federal level, while the rest CFs refer to the regional level of the energy sector CFs.

5 Conclusion

The paper presents the main provisions of the methodological approach to determining the level of CF in the energy sector. Using the analysis of the interconnected operation of the UGSS, UES of Russia and regional heat supply systems as an example, it is shown that not all critical objects of one energy system can significantly affect the reliability of energy supply to consumers from another energy system directly related to the first one. An analysis of the results of model studies showed that all of the UGSS CFs selected for the example are CFs of the energy sector, but some of them should be included in the federal list, while others should be included in the regional list.

The developed approach allows us to formulate the procedure for identifying energy facilities, which are the CF of the federal and regional levels of the energy sector. First of all, attention should be paid to such facilities from the standpoint of ensuring reliable fuel and energy supply to consumers and, in general, from the standpoint of ensuring the requirements of the country's energy security at the federal and regional levels. The corresponding strategic task in the development of the energy sector should be the task of forming directions and specific ways to reduce the critical importance of such critical facilities for the potential operability of the corresponding ESs and the energy sector as a whole.

The research was funded by the Russian Science Foundation, grant no. 23-29-00460, 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).

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