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Assessment and Forecasting of Additional Costs of Oil-Production Companies to Reduce Risks from Permafrost Degradation

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Abstract—The article considers the methodology and results of the economic assessment of additional costs of the oil industry in the northern regions of Russia required for the construction of oil-production facilities under conditions of degradation of permafrost soils. On the basis of the analysis of three scenarios of oil extraction development, it is shown that depending on the situation the annual additional costs of the construction of oil-production facilities can vary from 53.4 bln rubles to 268.4 billion rubles. This makes up from 4.4 to 22% of the total value of investments in the extraction in the four largest oil-extracting regions of the country located in permafrost zone.

Keywords: permafrost soils, investments, oil production, infrastructure, foundations, fixed assets, degradation, climate change

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The intensity of global climate change is most pronounced in Northern Eurasia. The growth rate of the annual average air temperature in the North is twice as high as the global average [1], which, in turn, accelerates thawing of permafrost soils, reduces their bearing capacity, thus contributing to subsidence, deformation, and collapse of the facilities built on them [2, 3]. Even now in the permafrost zone, a significant number of accidents related to permafrost degradation are observed, of which the largest and most resonant was the accident at an oil storage facility in Norilsk, which resulted in a spill of more than 20000 tons of diesel fuel.

Special climatic conditions in the permafrost zone determine the need for special and strict requirements for the construction of foundations of buildings and structures [4] at the facilities of the fuel and energy complex. In particular, in order to enhance the reliability of structures, pile foundations embedded in permafrost and connected by load distribution structures, which serve as a support for the erected buildings, are widely used. When designing pile foundations, two basic parameters are taken into account: the thickness of the active layer and the maximum temperature of the permafrost that determine the length, number, and location of piles so that the pressure under the foundation footing corresponds to the bearing capacity of the soil. The piles should be several meters longer than the maximum thawing depth of the permafrost. The above principles are also true for the construction of oil production facilities, such as drilling and pumping units, buildings, and storage facilities.

In order to adapt oil production facilities and maintain their operability in changing climatic conditions, including accelerated permafrost thawing and degradation, a number of engineering measures are used. First of all, reinforcement of foundations, while the weight of the structures remains unchanged, by increasing the length and, if necessary, the number of piles installed in permafrost. This reduces the load on each pile and helps to maintain their stability if the permafrost thawing depth deepens. Another effective way is soil thermal stabilization using special technical means [5–7]. However, these and other technical measures of adaptation of structures and buildings require significant additional costs, the volume of which will increase in the future due to the intensification of permafrost degradation processes, which implies the need for the constant assessment of the possibility of emergency situations and the cost of reducing these risks.

Modern studies show a significant scale of uncertainties and risks associated with permafrost degradation. In a recent interdisciplinary work, its reputable authors estimated the total expected damage to the economy from permafrost degradation in the Arctic zone of the Russian Federation for the period up to 2050 to 5–7 trillion rubles [8]. In the work of S.V. Badina the cost of the infrastructure in the Arctic

Table 1. Some economic indicators of the oil industry in 2020

Region	Share of extractive industries in GRP, %	Oil production in 2020, million ton	Capital investments in oil industry, billion rub	Share of investments into fixed capital in the oil industry in the total volume of investments, %	Operating well stock, units	Annual commissioning of oil wells, units
Russian Federation	10.5	475.6	1795.4	8.8	178772	7535
Nenets AO	32.8	13.9	80.4	41.3	1759	111
Yamalo-Nenets AO	61.5	36.9	754.0	75.0	7367	624
Khanty-Mansi AO	66.5	209.4	270.9	27.3	83756	4340
Krasnoyarsk krai	16.2	19.4	112.3	23.4	1105	200

Source: Compiled by the authors according to Rosstat data.

zone of the Russian Federation built in the permafrost zone by the middle of the 21st century was estimated at $133.5 billion [9]. The authors of this article in a series of works published over the past few years proposed approaches to the aggregate assessment of permafrost degradation risks [10] and presented specific results of such an assessment as applied to individual sectors of the economy and economic complexes (road infrastructure, housing sector, and healthcare facilities) [11–13].

This article attempts to make a similar assessment in relation to the fuel and energy complex of Russia, more specifically, an assessment of the expected damage from permafrost degradation for enterprises in key oil-producing regions of Russia. According to statistical data, more than two-thirds of Russian oil production and 80% of natural gas production are concentrated in regions located in the permafrost zone. At the same time, in previously published reviews and analyses of our colleagues, with few exceptions [14], the focus was either on data on the share of fuel and energy resources production in the permafrost zone, without a specific quantitative assessment of the expected damage or additional costs [15], or on estimates of the costs of eliminating the consequences of specific accidents in the industry [16]. We have no specialized data at our disposal, or estimates of the number of fields located in the permafrost zone, their productivity, which seriously complicates an objective assessment of the aggregate risk for these industrial facilities. However, a detailed assessment of the expected costs in gas production was given by the authors earlier in relation to the Yamalo-Nenets Autonomous Okrug [17].

Economy of oil-producing regions of the north of Russia. According to Rosstat, four northern regions of Russia (Nenets, Yamalo-Nenets, and Khanty-Mansi Autonomous Okrug as well as Krasnoyarsk krai), whose territory is fully or partially located in the permafrost zone, account for 58.9% of Russia's total oil production. In the structure of their gross regional product, the share of the extractive industries, as well as the share of investments in the fixed assets of the oil sector, is appreciably (in most cases, several times) higher than the average Russian values (Table 1).

The basis of investments in the fixed capital of the oil industry is formed by the funds allocated for oil field development, including exploration, drilling, and operation of oil wells and building of the infrastructure. The share of capital facilities (buildings, oil wells, and oil infrastructure) in the structure of investments of the oil industry of the regions under consideration is about 65%.

The total operating well stock in the regions under consideration is 94000 units (Table 1). Every year more than 5000 new wells are put into operation. The average service life of an individual well is usually about 15–25 years; by the middle of the 21st century, most of the wells put into operation before 2020 will be gradually decommissioned, and the main production will be carried out at new wells. Taking this circumstance into account, the priority in this work is given to the assessment of additional costs for the construction of new wells and the accompanying oil infrastructure.

Methodology of the assessment of additional costs of oil field development and operation caused by permafrost degradation risks. The general approach to the mentioned cost assessment is based on the approved earlier methodology of assessment of gas fields of Yamalo-Nenets Autonomous Okrug [17], with minor modifications conditioned by the industry specifics. The first stage of modeling involves geo referencing of specific oil fields to permafrost zones based on the databases of the International Permafrost Association as well as determination of the permafrost typology in accordance with the classification adopted by the said association.

If each field is precisely georeferenced, there is no need for synthetic calculations of object-specific permafrost referencing, which were used in our previously published works. However, it should be taken into account that the presence of permafrost zones on the territory of the field does not mean that all facilities are located exactly in these zones. Therefore, the following formula is used for further calculations:

$$OF = 0.95OF_1 + 0.75OF_2 + 0.35OF_3, \quad (1)$$

where OF is the oil fields (number of wells and associated infrastructure facilities) located on continuous (OF_1), discontinuous (OF_2), and massive-island (OF_3) permafrost.

Next, it is planned to assess the cost of development and operation of oil fields located in the permafrost zone, which includes the assessment of the cost of production wells and accompanying infrastructure. In order to assess the cost of production well foundation, data on the cost of construction of a typical oil field in Russia are used. The calculations are performed according to the building regulations (SNiP) for the construction of foundations in oil production projects [18–21]. The Uralmash 5000/320 EK-BMCh unit designed for drilling of production and exploration wells up to 5000 m deep in various geophysical conditions with air temperature range from –45°C to +40°C was chosen as the drilling equipment. As a base model example for the calculations, data on the Romashkino field (the Republic of Tatarstan) are used.[1]

For facilities built in the permafrost zone, it is necessary to deepen the foundations to a depth of at least 2 m greater than the depth of seasonal ground thawing. According to the international Circumpolar Active Layer Monitoring (CALM) program, the seasonal thawing depth in Nenets AO averages 116 cm, in Yamalo-Nenets AO, 0–126 cm, in Khanty-Mansi AO, 87–126 cm, and in Krasnoyarsk krai, 79–97 cm [22]. At the current rate of climate change and permafrost degradation, the thawing depth can increase by 0.5–0.8 m in all the studied regions by the middle of the 21st century. Taking this into account, the pile length of 4–5 m was adopted for the period 2022–2035 and 5–6 m for 2036–2050, respectively, depending on the region. Soil thermal stabilization devices can also be used to strengthen the structures during the construction of foundations, which can increase the cost of foundation works by 29.2–56.6% depending on the specific technology. General technical and economic parameters of *well foundations* are presented in Table 2.

The cost of *oil infrastructure foundations* was assessed by the previously approved method of comparison of the total volume of investments in fixed capital by types of fixed assets; regional data on the volumes of investments in fixed capital are presented by the relevant economic activity (oil production) [23]. For the calculations we use the data on the immovable part of fixed assets (buildings and structures), which, when built in the permafrost zone, cannot be moved in case of accidents and, accordingly, are exposed to the risks of collapse. The cost of foundation work is 5–20% of the total construction cost, depending on various factors (this study assumes the maximum cost of foundation work, given the complexity of design and construction in the permafrost zone). In addition, due to the lack of information on facilities and infrastructure costs in a particular field, it is assumed that the amount of investment in fixed assets is proportional to the number of wells put into operation.

In general terms, the calculation formulas for the periods 2022–2035 (2) and 2036–2050 (3) are as follows:

$$I_{ob} = I_{ot} I_{fa} \times 0.2 - I_{bw1} No_1, \quad (2)$$

$$I_{ob} = I_{ot} I_{fa} \times 0.2 k_i k_c - I_{bw2} No_2, \quad (3)$$

where I_{ob} is the total investment in oil field infrastructure foundations; I_{ot} is the total investment in oil production (Rosstat data for 2020); I_{fa} is the share of investment in buildings and structures (according to Rosstat data for 2020); I_{bw1} and I_{bw2} are well foundation costs (data on costs are presented in Table 2) for the periods 2022–2035 (I_{bw1}) and 2036–2050 (I_{bw2}), respectively; No_1 and No_2 are annual well commissioning for the periods 2022–2035 (No_1) and 2036–2050 (No_2), respectively; k_i is the permafrost ice content (low, 1, medium, 1.1, and high, 1.2); and k_c is the factor for the increase in cost of infrastructure construction.

At the final stage three scenarios of oil production in the studied regions are considered (pessimistic (negative), moderate, and favorable), and the additional costs arising in the construction of oil infrastructure in conditions of permafrost degradation within the mentioned scenarios are assessed (Table 3).

The proposed model assessment of expected costs involves some assumptions related to the lack of some statistical data and a high degree of uncertainty and variability in the external environment, namely:

— The most likely baseline climate change scenario RCP8.5 is used, which provides for the worst-case climate forecast and, accordingly, takes into account the maximum climate risks.

[1] The foundation parameters are assumed in the calculation: for the fields outside the permafrost zone: the depth of 0.5 m, substrate consists of 2 × 1 × 0.6 3-ton blocks and 1.2 × 0.6 × 0.6 1.92-ton blocks (24 blocks × 2), the foundation area is 28.3 m × 14.9 m = 421.7 m^2 (in accordance with the building regulations); in 2018 prices, the cost of foundation works is 24 × (13102 + 4905) = 432200 rubles; for deposits in the permafrost zone in the climatic conditions of 2020–2035, the depth is 3–4 m, pile foundation: 4–5 m × 0.4 m, 1.65–2.05 tons, load distribution structures: 0.5 m × 1.2 m, 1.625 tons, foundation weight: 98 units × (1.65(2.05) + 1.625) = 320.95–360.15 tons; in 2018 prices, the cost of foundation works is 1365700–1577800 rubles taking into account the regional adjustment factor for the increase in cost of construction; for deposits in the permafrost zone in the conditions of 2036–2050, piles of 5–6 m × 0.4 m, 2.05–2.45 tons, will be used; if the other proportions are observed, the cost of foundation works will be 1532500–1749500 rubles.

Table 2. Technical and economic parameters of well bases in oil fields*

Region/municipality	Depth of average seasonal permafrost thawing for 2005–2020/2036–2050, cm	2022–2035			2036–2050			
		A	B	C	A	B	C	D
Nenets AO	116/186	500	360.15	1577.8	600	399.35	1749.5	990.2
Yamalo-Nenets AO								
Krasnoselkupsky district	89/165	400	320.95	1418.7	500	360.15	1591.9	901.0
Nadymsky district	126/202	500	360.15	1591.9	600	399.35	1765.2	999.1
Purovsky district	87/163	400	320.95	1418.7	500	360.15	1591.9	901.0
Tazovsky district	91/167	400	320.95	1418.7	500	360.15	1591.9	901.0
Yamalsky district	80/156	400	320.95	1418.7	500	360.15	1591.9	901.0
Khanty-Mansi AO								
Beloyarsky district	126/165	500	360.15	1573.2	500	360.15	1573.2	890.4
Nizhnevartovsk district	88/164	400	320.95	1402.0	500	360.15	1573.2	890.4
Surgutsky district	87/127	400	320.95	1402.0	500	360.15	1573.2	890.4
Krasnoyarsk krai								
Baikitsky district	80/150	400	320.95	1365.7	500	360.15	1532.5	867.4
Taimyrsky district	97/167	400	320.95	1365.7	500	360.15	1532.5	867.4
Turukhansk district	80/150	400	320.95	1365.7	500	360.15	1532.5	867.4
Ust-Yenisei district	79/149	400	320.95	1365.7	500	360.15	1532.5	867.4

* For climatic conditions of the corresponding periods: (A) minimum depth of the well foundations (cm); (B) minimum mass of the foundation (m); (C) cost of the foundation per one well (thousand rubles); (D) additional costs for the thermal stabilization system per one well (thousand rubles).

Sources: Thawing depth according to the CALM data (https://www2.gwu.edu/~calm/data/north.htm), foundation parameters are assessed based on the authors' calculations.

Table 3. Forecast of annual average oil production for the period up to 2050, million ton*

Region	Total (2020)	In the permafrost zone	Annual average oil production forecast for the period 2036–2050					
			A		B		C	
			total	perma-frost	total	perma-frost	total	perma-frost
Russian Federation	475.5		370.0		475.5		530. 0	
Nenets AO	13.9	13.9	12.2	12.2	13.9	13.9	16.9	16.9
Khanty-Mansi AO	209.4	78.2	165.0	61.6	209.4	78.2	259.9	97.1
Yamalo-Nenets AO	36.9	36.9	26.0	26.0	36.9	36.9	35.8	35.8
Krasnoyarsk krai	19.4	19.4	71.6	71.6	19.4	19.4	123.4	123.4

* (A) pessimistic (negative) scenario; (B) moderate scenario; (C) favorable scenario.

Source: Assessments of the Institute of Economic Forecasting of the Russian Academy of Sciences.

— The predicted permafrost thawing depth is based on observational data for the period 2006–2015. Data from 2016 onwards indicate that this process accelerated. The comparison of data from individual geocryolithological observation stations over the period 1997–2020 shows that in 1997–2006 the increase in thaw depth was about 10 cm per decade and in 2006–2015, 20 cm; in the last five years, the rate of processes doubled.

— Due to the lack of prediction estimates of the number of wells put into operation, the proposed scenarios assume the use of existing data on the construction of wells in 2020 with a proportional adjustment for the increase/decrease in oil production in the studied regions. The number of new wells and related infrastructure facilities is assumed to be proportional to the growth of production in each particular field.

Table 4. Costs of foundation works in 2020–2035

Region	Oil production in the permafrost zone in 2020, million ton	Number of wells commissioned in the permafrost zone	Total cost of foundation works for the period 2022–2035, million rub		
			wells	buildings	facilities
Nenets AO	13.9	105	197	195	12535
Yamalo-Nenets AO	28.2	505	867	697	42045
Khanty-Mansi AO	78.2	568	951	683	43648
Krasnoyarsk krai	20.2	185	301	272	17488
TOTAL	140.5	1363	2316	1847	115716

Source: authors' calculations.

— Given the fact that soil thermal stabilization systems are already used in the construction of certain oil production facilities, it is assumed that at present about 30% of foundation works are designed using this technology. Accordingly, for the forecast period 2022–2035, the costs of soil thermal stabilization are included in the costs of foundation works in the construction of new facilities. For the period 2036–2050, it is assumed that 30% of the foundation works are also designed using thermal stabilization, but the corresponding costs of thermal stabilization are given separately (Table 4).

— Assessments are made for price and production conditions of 2020.

Assessment of additional costs to ensure the sustainability of the oil infrastructure in the permafrost zone. According to the calculations, about 140 million ton of oil were produced in the permafrost zone in 2020. Production is carried out at 141 oil fields, the largest of which are concentrated in the Khanty-Mansi Autonomous Okrug. Among the most significant and largest fields in the regional section, the producing infrastructure of which is fully located in the permafrost are the Trebs and Titov oil fields in the Nenets AO, which account for 30% of the regional production; Yarudeyskoye, Vostochno-Messoyakhskoye, and Novoportovskoye fields in the Yamalo-Nenets AO with a total annual average production volume of 15.3 million ton or over 50% in the region; a group of ten fields located in Surgut municipal district of Khanty-Mansi AO, which produce about 50 million ton of oil; and also the Vankorskoye project (13.8 million ton) in Krasnoyarsk krai.

A specific feature of the Nenets and Yamal-Nenets Autonomous Okrugs is that their entire territory is in the permafrost zone, and, accordingly, all the structures associated with oil production are built taking into account this factor. The permafrost characteristics of the regions differ: the Nenets AO is in the continuous permafrost zone, the Yamal-Nenets AO is characterized by continuous permafrost in the north and discontinuous permafrost in the south, the Khanty-Mansi AO is completely in the island permafrost zone, oil producing municipalities of the Krasnoyarsk krai are in the continuous permafrost zone, excluding the fields of Baykitsky District. According to our estimates, 25 fields out of 141 (or nearly 18% of their total number) are located in the continuous permafrost zone, including 13 fields in the Nenets AO, seven fields in the Yamalo-Nenets AO, five fields in the Krasnoyarsk krai; in the discontinuous permafrost zone, there are 29 deposits (or 20% of the total number), including 28 deposits in the Yamalo-Nenets AO and one deposit in the Khanty-Mansi AO; 87 deposits (or 62% of the total number) are in the island permafrost zone, including eight deposits in the Yamalo-Nenets AO, 78 deposits in the Khanty-Mansi AO, and one deposit in the Krasnoyarsk krai.

At present, 1363 oil wells are operating in the permafrost zone. The assessment shows that in the case of the construction of wells and oil infrastructure facilities in the permafrost zone, the total cost of foundation works is 119.98 billion rubles, or about 10% of the total volume of regional investments in the oil industry (see Table 4).

According to the estimates given in [10], by the middle of 21st century the depth of permafrost thawing will deepen in all the studied regions by 0.5–0.8 m. Correspondingly, it will require change of the foundation depth and, in some cases, the use of soil thermal stabilization systems, which, in turn, will increase capital expenses for the development of new wells and construction of the accompanying oil infrastructure. At the same time, the volume of investments will be decisively affected by the dynamics of oil production (demand), which will change in the long term. According to the previously mentioned three scenarios of oil production development (see Table 3), the expected additional costs to minimize the consequences of permafrost degradation are calculated (Table 5).

Negative scenario (2036–2050) assumes that the annual average volume of oil production in Russia will decrease to 370 million ton, compared to 475.5 million ton in 2020. The biggest drop in production (about 44.4 million ton) is forecast for the Khanty-Mansi AO; in the Krasnoyarsk krai, production is expected to rise to 71.6 million ton. The total cost of foundation

Table 5. Assessment of costs to reduce risks of permafrost degradation during development and operation of oil fields, million rubles/year*

Total cost of foundation works for climatic conditions of 2036–2050														
Negative scenario					Moderate scenario					Favorable scenario				
a	*b*	*c*	*d*	Total	*a*	*b*	*c*	*d*	Total	*a*	*b*	*c*	*d*	Total
Nenets AO					Nenets AO					Nenets AO				
196	198	12747	4448	17590	224	226	14548	5077	20074	272	276	17738	6190	24476
Yamalo-Nenets AO					Yamalo-Nenets AO					Yamalo-Nenets AO				
753	529	37824	13218	52323	1068	838	53663	18782	74351	1038	815	52180	18263	72296
Khanty-Mansi AO					Khanty-Mansi AO					Khanty-Mansi AO				
950	710	45372	15886	62918	1207	902	57649	20185	79942	1498	1014	71535	25011	99058
Krasnoyarsk krai					Krasnoyarsk krai					Krasnoyarsk krai				
488	456	29308	10231	40483	365	342	21957	7665	30329	2319	2170	139338	48640	192466
TOTAL					TOTAL					TOTAL				
2386	1893	125251	43783	173313	2863	2308	147816	51708	204696	5127	4275	280790	98104	388296

* * (*a*) wells, (*b*) buildings, (*c*) facilities, and (*d*) soil thermal stabilization systems.

Source: Authors' calculations.

works (wells, buildings, and facilities) will be 129.5 billion rubles; if soil thermal stabilization systems are used everywhere, it will increase by one third: up to 173.3 billion rubles.

Under *moderate scenario* (taken as a base for 2036–2050), the volume of oil production both in Russia and in the studied regions will remain unchanged, and in general in these regions it will amount to 279.6 million ton per year. In this case, the total cost of well foundations, buildings, and facilities will be 153.0 billion rubles, and using soil thermal stabilization systems it will increase, like in the previous scenario, by a third: up to 204.7 billion rubles.

In the *favorable scenario,* the growth of all-Russian oil production reaches 530 million ton in annual average terms, including 436 million ton produced in the four northern regions under consideration. The main growth is expected in the Khanty-Mansi AO (up to 259.9 million ton, of which 97.1 million ton will be produced in the permafrost zone fields) and Krasnoyarsk krai (up to 123.4 million ton, which will be produced entirely in the permafrost zone fields). Expected costs of foundation works (wells, buildings, and facilities) will amount to 290.2 billion rubles, and when using soil thermal stabilization systems, it will also increase by a third (up to 388.3 billion rubles).

Let us consider the above assessments in the context of sectoral indicators. If in 2022–2035 the total expenditures on foundation works are 120 billion rubles (see Table 4) or 9.8% of the total volume of regional sectoral investments (2020 is the reference), then after 2036 in negative scenario expenses are to be 129.5 billion rubles, and if soil thermal stabilization systems are used, they will increase up to 173.3 billion rubles, while oil production volumes will decrease by 4.8 million ton. The main increase in costs in this scenario is associated with a significant reduction in oil production in the Khanty-Mansi AO with its simultaneous growth in the Krasnoyarsk krai, while at the same time the relative costs increase. In the moderate (baseline) scenario with the unchanged level of oil production, the total cost of foundation works will be 204.7 billion rubles. The favorable scenario assumes growth of these costs to 388.3 billion rubles with increase in oil production by 1.5 times in relation to the moderate scenario.

In any scenario of oil production in the permafrost zone, there are different variants of the development of oil fields, which depend on admissible risks and possible marginal costs of building the specific infrastructure. It is obvious that the choice of the optimal solution depends on many factors, among which the reliability and accident-free operation of the fields, cost-effectiveness, and availability of technological solutions in the territory are a priority.

* * *

The four northern regions, Nenets, Yamal-Nenets, Khanty-Mansi AOs, and Krasnoyarsk krai, are the key centers of oil production in Russia. At the same time, since these centers are in permafrost zones, they are most vulnerable to the effects of climate change, primarily related to permafrost degradation. It is necessary to plan and implement adaptation measures for oil field facilities in order to ensure their sustainable operation in the long term. Modern permafrost-specific field development technologies form the basis for these adaptation measures and make it possible, if not to eliminate, then to largely mitigate the risks of structural collapse in the permafrost zone. At the same time, such technologies significantly increase the construction cost.

The attempt of an enlarged assessment of the total costs of foundation works associated with the development of oil fields in the permafrost zone undertaken by the authors (the results of which are presented above) showed that the annual average value of these costs varies from 129.5 billion rubles to 290 billion rubles depending on the scenario (the level of oil production) without using thermal stabilization systems in 2036–2050. In the same period, the use of thermal stabilization systems in order to reduce the risks of permafrost degradation in order to provide sustainable operation of the oil fields increases the variation range of these costs depending on the level of oil production: from 173.3 billion rubles to 388.3 billion rubles. Additional costs of foundation works in 2036–2050 in comparison to 2022–2035 will be 9.7–170.3 billion rubles depending on the scenario, without the cost of thermal stabilization systems, and if they are used, costs will increase up to 53.4–268.4 billion rubles in prices of 2020.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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