A comprehensive assessment of comparative effectiveness of projects for power export from East Siberia to China: A methodological approach and results of its application

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Abstract. The paper is concerned with a methodological approach to the assessment of comparative effectiveness of projects for the construction of export-oriented power plants and transmission lines under uncertainty of the power industry development in the region. The recommendations are given to select the most preferable project for the construction of an export-oriented power plant and transmission line for power export from East Siberia to China.

1 Introduction

Interstate integration and cooperation between Russia and NEA countries in the field of power industry is an indispensable part of the eastern energy policy of our country [1]. This cooperation suggests the development of interstate electric ties between the eastern regions of Russia and Chinese People's Republic, the Republic of Korea, Japan, Mongolia, and the Democratic People's Republic of Korea.

The transboundary transmission lines to be constructed for these purposes can be used both to export power from Russia, and to integrate power systems of the indicated countries for joint operation and formation of common electricity and capacity markets [2, 3].

In the future, the development of these ties is first of all planned through the projects of large-scale power export from Russia's eastern regions to the People's Republic of China [1,4,5].

An analysis of the export projects proposed in the eastern regions shows that their implementation (from design to completion of construction) is rather long (15-20 years), and is related to a considerable uncertainty of future conditions for the development of the power industry in the regions where these projects can be implemented (fuel prices, level of electricity consumption, etc.). In this situation, making decisions is subject to risk. Therefore, minimization of risks and study of various factors that affect the stability of decisions to be made under the considered conditions are essential for making decisions on export projects [6-11].

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2 Description of a methodological approach

A methodological approach proposed in the paper to comprehensively assess comparative effectiveness of projects for the construction of export-oriented power plants and power transmission lines under uncertainty of the electric power system expansion in the region includes four stages (Fig.1):

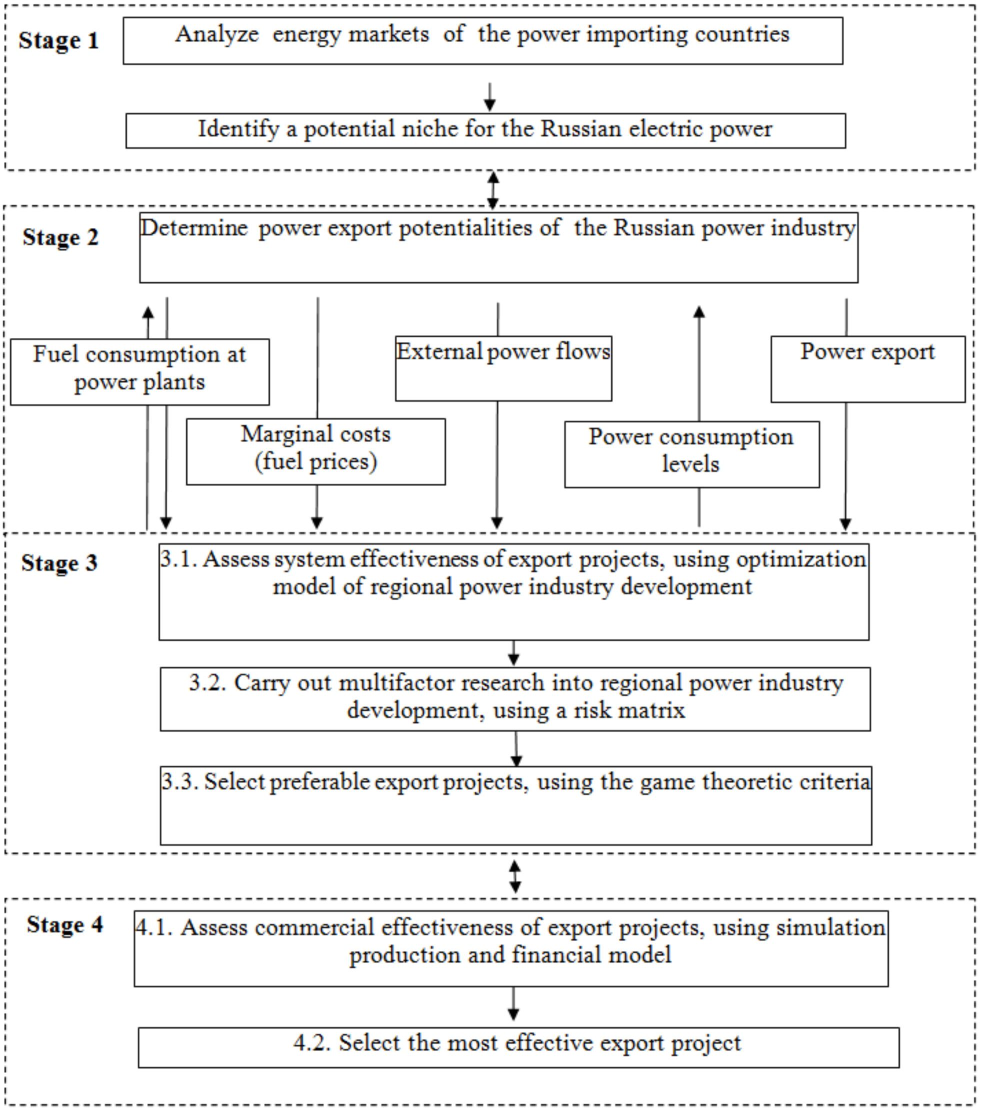

Fig.1. A block diagram of the methodological approach to comprehensively assess comparative effectiveness of power export projects under uncertainty of regional power industry development

1. Analysis of energy markets of the countries importing power, and determination of a potential niche for the Russian electric power.

2. Investigation of power export potentialities in terms of the national energy sector: fuel consumption at power plants of the region, fuel prices, external power flows between regions, volumes of power export from the region.
3. Assessment of the system effectiveness of export projects. To this end we:

- construct an optimization model of power system expansion in the region, and include alternately each considered project for the construction of export-oriented power plants and transmission lines in the region in this model.

- conduct a multifactor research into the regional power industry development, by using a payoff matrix and a risk matrix, which includes:

a) simulation of external conditions C^n of power system expansion (levels of power consumption, fuel prices, etc.);

b) determination of an optimal mix of energy facilities required for the expansion of regional power system for each of the considered export project, which is necessary to adjust the power system to the external conditions and planned power export deliveries;

c) construction of a payoff matrix $\| F_r^n \|$ (Table 1). In a general form, the coefficients of the payoff matrix F_r^n are defined as the total discounted costs of the regional power system expansion under the considered external conditions C^n of its expansion, and projects for construction of export-oriented power plants and transmission lines X_r. The obtained payoff matrix makes it possible to switch to the matrix of economic risks.

Table 1. A payoff matrix of regional power system expansion costs

Variants of power system expansion. Projects	**Conditions for the power system expansion**					
	C^1	C^2	C^3	C^n	…..	C^N
X_1	F_1^1	F_1^2	F_1^3	F_1^n	…..	F_1^N
X_2	F_2^1	F_2^2	F_2^3	F_2^n	…..	F_2^N
X_r	F_r^1	F_r^2	F_r^3	F_r^n	…..	F_r^N
…..	…..	…..	…..	…..	…..	…..
X_R	F_R^1	F_R^2	F_R^3	F_R^n	…..	F_R^N

d) construction of a risk matrix $\| \lambda_r^n \|$, whose coefficients are determined by subtracting the index of discounted costs F_{min}^n for the variant which under the conditions C^n has the minimum value of costs from the index of discounted costs F_r^n of the considered variant r of the payoff matrix, i.e.

$$\lambda_r^n = F_r^n - F_{min}^n$$

Coefficient of the matrix of economic risks λ_r^n is a characteristic of extra costs of the considered variant of regional power system expansion under certain conditions compared to the variant with the minimum costs under these conditions.

In a general case, the matrix of economic risks represents a generalized characteristic of possible economic consequences of the ignorance of real conditions for the regional power system expansion, and is a basis for the comparison of power system expansion variants and export projects under uncertainty;

e) selection (using the risk matrix and game theoretic criteria) of the most effective export projects in the region. The conditions of such a selection depend on the form of the applied criterion (Laplace, Bayes, Savage, Hurwitz). In this paper, we consider the applicability of two criteria:

- Laplace criterion (average risk)

$$\overline{\lambda_r} = \min_i \frac{1}{N} \sum_{n=1}^{N} \lambda_i^n, \quad \text{at} \quad i = 1,2,\ldots,R \; .$$

- Savage criterion (minimax risk)

$$\overline{\overline{\lambda_r}} = \min_i \max_n \lambda_i^n, \text{ at } i = 1,2,\ldots,R \text{ ; } n = 1,2,\ldots,N \text{ .}$$

Joint application of formal game theoretic criteria in a general case does not ensure the choice of a single result, but reveals several projects virtually identical in terms of the applied criteria. Such projects are considered equally cost-effective. The existence of equally cost-effective projects causes principal impossibility of complete formalization of the decision making process under uncertainty and requires some other criteria to make the final decision.

4. A production and financial model is used to assess the commercial effectiveness of the export projects chosen at the previous stage, and the most preferable of them is selected (according to the assumed criterion of commercial effectiveness).

3 Results of the research

According to the proposed methodological approach, the paper presents the assessment of comparative effectiveness of four projects for the construction of export-oriented power plants and transmission lines from East Siberia to China:

Project 1 – Thermal power plant (TPP) on Kovykta gas in the south of the Irkutsk Region;

Project 2 – TPP on Kansk-Achinsk coal in the Krasnoyarsk Territory;

Project 3 –TPPs on coal in the Republic of Buryatia (Olon-Shibirskaya TPP) and Trans-baikal Territory (Novaya-Kharanorskaya TPP);

Project 4 – TPP on Mugunsky coal in the Irkutsk Region.

The main technical – economic indices of the export-oriented power plants and transmission lines are presented in Table 2.

The optimization linear model defining the electric power industry of East Siberia was applied to assess the system effectiveness of the considered projects. The electric power industry is represented by 6 regional power systems (Khakass, Tyva, Krasnoyarsk, Irkutsk, Buryatia and Transbaikal regional power systems). The implemented version of the model covers a period from 2014 to 2030.

The calculations were carried out for four variants of combinations of external conditions for the power industry development in East Siberia: low and high projected levels of power consumption in the region (195-245 billion kWh), low and high fuel prices for power plants: gas - 115-150 $/tce, coal 40-75 $/tce.

Calculations on the optimization model of electric power system expansion in East Siberia made it possible to determine an optimal mix of energy facilities necessary for the development of electric power industry in the region and related costs for each export project and for each of the four variants of combinations of external conditions.

The research shows that depending on the external conditions, the construction of export-oriented power plants and transmission lines can lead to a noticeable change in the structure of power generation and costs of power industry development in the region. Thus, either regional power system will export its surplus power, or export-oriented power plants will deliver their surplus power to the system.

Further, according to the proposed methodological approach, the payoff matrix of costs is constructed, and then it is used to construct the matrix of economic risks (Table 3).

The obtained matrix of risks is used to select export projects that are most preferable in terms of the game theoretic criteria assumed in the paper (Laplace, Savage).

The studies demonstrate that the joint application of formal game theoretic criteria makes it possible to identify two export projects that are effective in terms of the applied criteria.

Table 2. Technical and economic indices of export projects

Index	Projects

	1	2	3		4
	TPP on Kovykta gas	**TPP on Kansk-Achinsk coal**	**Olon-Shibirskaya TPP**	**Novaya-Kharanorskaya TPP**	**TPP on Mugun-sky coal**
Power plants					
Installed capacity, million kW	3.2	3.2	2.4	0.8	3.2
Type of equipment	CCP*	USCPP **	USCPP	USCPP	USCPP
Efficiency, %	55	45	45	45	45
Electricity generation, billion kWh	20.8	20.8	14.4	4.8	20.8
Specific fuel consumption, gce/kWh	222	276	276	276	276
Type of fuel	Gas	Brown coal	Hard coal	Brown coal	Brown coal
Specific capital investment***, $/kV	1000	1600	1500	1600	1600
DC transmission line					
Length , km	1100	1860	380		1100
Voltage, kV	500				
Specific capital investment:					
- linear part, thousand $/km	600				
- substations, million $/pcs	100				

Note: * - CCPP (a combined cycle power plant consisting of a 300MW steam turbine and two 279MW gas turbines); ** - USCPP (a power plant operating at ultra-super-critical steam parameters); *** - from here on in 2010 prices.

Table 3. Matrix of economic risks of the electric power system expansion in East Siberia, million $

Projects	**Conditions for electric power system expansion**				**Criteria***	
	Variant 1	**Variant 2**	**Variant 3**	**Variant 4**	**Laplace** $\overline{\lambda}_r$	**Savage** $\overline{\overline{\lambda}}_r$
X_1	0	0	25.7	27.9	**13.4**	27.9
X_2	157	141	77	68	111	157
X_3	221	234	132	164	188	234
X_4	27.6	26.9	0	0	13.6	**27.6**

* in each column, the best variant is highlighted according to the respective criterion

In this case, the most preferable export projects are: *project 1,* that suggests the construction of a TPP on Kovykta gas as an export power plant, according to Laplace criterion (an average risk); and *project 4*, i.e. the construction of a TPP on Mugunsky coal, according to Savage criterion (a minimax risk).

Further, the simulation production and financial model is used to assess the commercial effectiveness of the chosen export projects, and the project to be implemented is selected. The preference is given to the project ensuring the minimum tariff of exported power at the sites where export transmission lines cross the border. The tariff is determined as a minimum power price acceptable for an exporter (disregarding excises and duties), which will compensate for operating costs (including payment for CO_2 emissions), investment costs, and ensure acceptable return on the invested capital.

The tariffs were calculated based on the following assumptions:

–design lifetime of power plant is 30 years for TPP on Kovykta gas, and 35 years for TPP on Mugunsky coal;

– design lifetime of an export ±500 kV transmission line is 25 years;

– internal rate of return is 15%;

– sources of funding are authorized capital;

Tax rates are assumed according to the current taxation system in the Russian Federation: tax on profit is 20 %;

– payback period for thermal power plants is 18 years;

– payback period for power transmission lines is 15 years;

– the projected price of Kovykta gas is 130-175 $/1000 m^3$, of Mugunsky coal - 25-30 $/t

Table 4 shows the export power tariffs (on the border with China) calculated using the simulation model for the assumptions made.

Table 4. Electricity tariff on the border with China

Index	**Measurement unit**	**TPP**	
		on Kovykta gas	**on Mugunsky coal**
Tariff at the receiving end, total	cent/kWh	7.9-8.8	10.1-10.6
Including for:			
generation	cent/kWh	6.5-7.4	8.7-9.2
transmission	cent/kWh	1.4	1.4

According to Table 4, the project for construction of the export-oriented TPP on Kovykta gas (in the south of the Irkutsk Region) with power transmission by DC line to the border with China is more effective (according to the assumed criterion) compared to the project for construction of the TPP on Mugunsky coal in the Irkutsk Region. The export tariff on the border in the case of TPP on Kovykta gas is estimated at 8-9 cent/kWh, whereas for the TPP on Mugunsky coal - it is 10-11 cent/kWh.

4 Conclusion

1. A methodological approach is proposed to comprehensively assess the comparative effectiveness of power export projects under uncertainty of the power system expansion in the region.
2. The comparative effectiveness of the projects for construction of export-oriented power plants and transmission lines to supply power from East Siberia to China is assessed according to the developed methodological approach.
3. Consideration is given to four potential projects for large-scale power export from East Siberia to China, that suggest the construction of export-oriented power plants and DC transmission lines to the area of the town of Zabaikalsk (border with China): TPP on

Kovykta gas in the south of the Irkutsk Region; TPP on Kansk-Achinsk coal in the Krasnoyarsk Territory; TPPs on coal in the Republic of Buryatia and Transbaikal Territory (Olon-Shibirskaya TPP and Novaya Kharanorskaya TPP); and TPP on Mugunsky coal in the Irkutsk Region.

4. The studies show that the project for construction of export-oriented TPP on Kovykta gas with a DC power transmission line to the border with China (the town of Zabaikalsk) is most preferable compared to the other considered projects for construction of export power plants and transmission lines in East Siberia.
5. The proposed methodological approach and findings of the research provide additional information for the promotion of cooperation between Russia and neighboring countries (China, in particular) in the field of power export.

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