Hydropower Development in Eastern Russia in the Context of Interstate Cooperation: Current State and Prospects

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***Abstract* — The paper describes the hydropower potential of Eastern Siberia and the Russian Far East. Currently, only 7.5% of the technical hydropower potential of Russia's East is used. Expansion of the hydropower sector in this region is a main goal of the national electric power development. Russia is also interested in the development of electric ties with Northeast Asian countries. The paper presents several potential projects for interstate electricity transmission to be implemented with the neighboring countries (China, Mongolia, Republic of Korea and Japan). Results of the international studies show evident advantages for interconnected countries. Continuation of a multilateral analysis and investigations of the hydropower development promotes the interstate power interconnection and cooperation.**

***Index Terms* — cross-border cooperation, Eastern Russia, hydropower potential, inter-state interconnection, investment attraction, potential utilization**

I. Introduction

Energy utilization has evolved over time from firewood to fossil fuels, and then to clean energy resources derived from hydropower, wind power, and solar power [1]. Fast industrialization caused rapid energy industry growth. At the same time, extensive utilization of fossil resources resulted in environmental pollution and climate change. Many of energy-scarce countries became dependent on resources and energy supply. Seeking a solution to energy scarcity and environmental problems most of the world's major nations followed the road of clean energy production. The world has abundant clean energy resources, far more than enough to meet global energy needs [1]. The massive development of hydropower, onshore wind energy, and solar power has become the world's dominant form of energy provision.

The efficiency of the power resources utilization and secure electricity supply increases with the large-scale interconnection of national electric power systems. The ultimate objective is the coordination of energy production and electricity exchange in line with progress in the political, economic and environmental fronts [1].

Hydropower is the most technologically and economically viable type of clean energy. Asia expects the development of large-scale hydropower potential in the future. Russia is among the top five countries in terms of hydropower reserves and developed capacities. World average water utilization is estimated at 41% of the global theoretical reserves [1]. Utilization rate in Russia is low and is estimated at 10.9 %. Development of the Russian hydropower potential, particularly in the Eastern part of the country, provides new prospects for interstate energy cooperation.

II. Hydropower potential and its current utilization

Russia has significant hydropower resources in different parts of the country.

The country has more than 3 million big and small rivers, and more than 2.8 million lakes. About 250 rivers are longer than 500 km, 58 of which are over 1,000 km long. Forty of these super long rivers are in Siberia and the Far East [2]. The major rivers in Siberia are the Ob River, the Yenisei River, and the Lena River. The Yenisei River is No. 1 in Russia because it provides the best water resources. In the Far East, the main river is the Amur River which is approximately 4,400 km long, flowing into the Pacific Ocean. Its upper and middle reaches are located along the Chinese-Russian border; while its lower reach

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http://dx.doi.org/10.25729/esr.2019.01.0006
Received April 24, 2019. Revised May 27, 2019.
Accepted June 06, 2019. Available online June 25, 2019.

Table 1 Hydropower Resources Of Rivers In Eastern Siberia And Russia's Far East.

Country, region	Total, 2013		Average electric energy output at operating HPPs, 2013, billion kWh	Use of energy potential, %
Potential	Billion kWh	%		
1. Theoretical (gross)				
- Russia, total	2396	100	1023,5	42,7
- Eastern Siberia	993	41,4		
- Far East	1009	42,1		
2. Technical				
- Russia, total	1670	100	174,74	10,46
- Eastern Siberia	757	45,3	94,72	12,5
- Far East	684	41	13,44	1,96
3. Economic				
- Russia, total	852	100	174,74	20,5
- East Siberia	396	46,5	94,72	23,9
- Far East	294	34,5	13,44	4,57

lies within the Russian territory.

The hydropower resources in Eastern Siberia and the Far East play and will play an important role in the implementation of Russia's energy policy. The gross hydropower potentials of the rivers in the Eastern Siberia and the Far East regions are respectively 993 and 1009 billion kWh /year, or 41.4 and 42.1% of the national hydropower potential (Table 1). Allocation of hydropower potential across the territory of the country is shown in Figure 1 [3].

Russia has 102 hydropower plants with the capacities of over 100 MW each, making it the world's fifth hydropower producer. The hydropower capacity installed in the country reached 49.7 GW in 2016 [4]. In terms of installed capacity, three of the world's top 10 hydropower plants are located in Russia.

Small hydropower plants with a capacity of less than 30 MW are an alternative to the fossil fuel which is used for electricity production in the remote regions in Russia. Replacement of traditional fuel plants in such regions by small hydropower plants will make it possible to increase the local energy security and to decrease fuel delivery costs.

Russia's hydropower generation represents 4.88 % of the world's electricity generated using this type of energy source. Within Eurasia, the electricity generation from hydropower plants represents 66.79 % of the total [4].

Hydropower generation in Russia was 174.7 TWh in 2013 and accounted for about 17% of the total electricity generated (1023,5 TWh). The amount of 174.7 TWh represented 20.5 % of the economic and only 10.46 % of the country's technical potential. The technical potential of

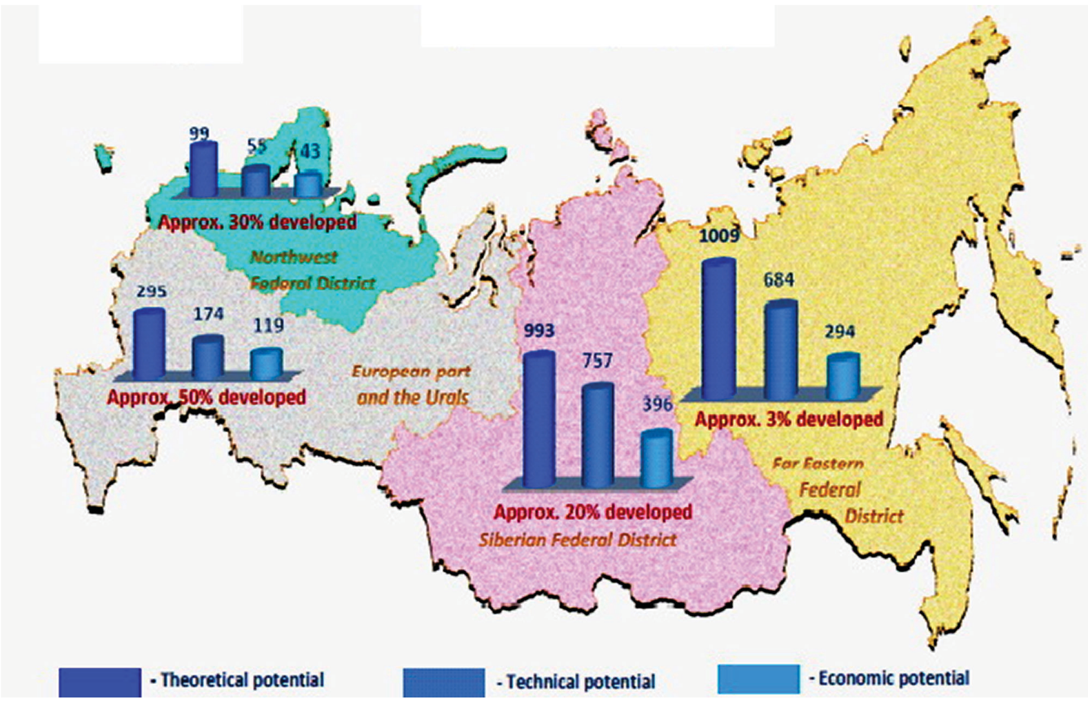

Fig 1. Allocation of hydropower potential in Russia.

the Eastern regions is used by less than 7.5 % .

Hydropower plants with the total installed capacity of 7 million kW are under construction and more than 12 million kW are planned for construction [2]. Technical conditions for the development of hydropower resources in the east of Russia, especially in Eastern Siberia, are more favorable than in the rest of the country.

III. Hydropower development in eastern russia: current state and prospects

Hydropower is the pillar of Eastern Russia's power industry. Growing utilization of hydropower provides [3]: high capacity flexibility, no fuel component in the production cost, renewable and environmentally clean power generation, the synergistic effect for the territory development due to new emerging energy-intensive enterprises.

Water use for electricity production in the Eastern territories of the country started in the 1950s. Several powerful hydroelectric plants have been built since then on the Yenisei, Angara, Zeya and Vilyui rivers. The power plants provided regional economy and industries with reliable energy supply. Aggregate installed capacity of those plants was around 23,5 GW [4].

Several new hydropower projects were designed in the 1960 -70s. However, for various reasons, not all of the plans developed 40-50 years ago turned out to be feasible under modern socio-economic conditions. In particular, in the new contexts, for economic, environmental and water management reasons, it was necessary to abandon the construction of previously designed powerful hydroelectric plants on the main channels of large rivers (the Yenisei, the Lena, and the Amur) in the east of the country. Thus, the prospected technical potential of the hydropower resources of Eastern Siberia and the Far East was noticeably reduced.

The new contexts include changed schemes for attracting investments, revision of plans for the development of industrial production in the regions, the introduction of additional environmental and technological restrictions, new technologies in the construction industry and the emergence of new ways of generating electricity. The new contexts are reflected in the Energy Strategy of Russia for the period until 2030 developed by the Ministry of Energy of the Russian Federation. Individual sections of the Strategy indicate the targets for the use of the hydropower resources of Siberia and the Far East.

At the end of 2017, the total installed capacity of hydropower plants in the eastern regions of Russia was 28946.4 MW [4], including 25286.4 MW in Eastern Siberia, and 3660.0 MW in the Far East. In the coming years, the hydropower potential of the eastern territories will be increased due to the construction of Bureya hydropower plant (2000 MW) in the Far East, Svetlinskaya hydropower plant (360 MW) in Eastern Yakutia and Ust-Srednekanskaya (570 MW) hydropower plant in the Northeast. The Bureya and Svetlinskaya HPPs are in the final stages of construction. Location of the existing and new HPPs is shown in Figure 2 [6]. Difficulties in the development of hydropower potential are associated with extremely high capital intensity and long construction periods of hydropower plants. These are the main barriers to the development of hydropower generation under tough global competition, even in the countries with a large hydropower potential. The construction of a large hydropower plant costs billions of dollars (several thousand dollars per 1 kW of installed capacity) and lasts 5-8 years. Given the site selection, design and preparatory work, it may take 15-20 years to construct a hydropower plant.

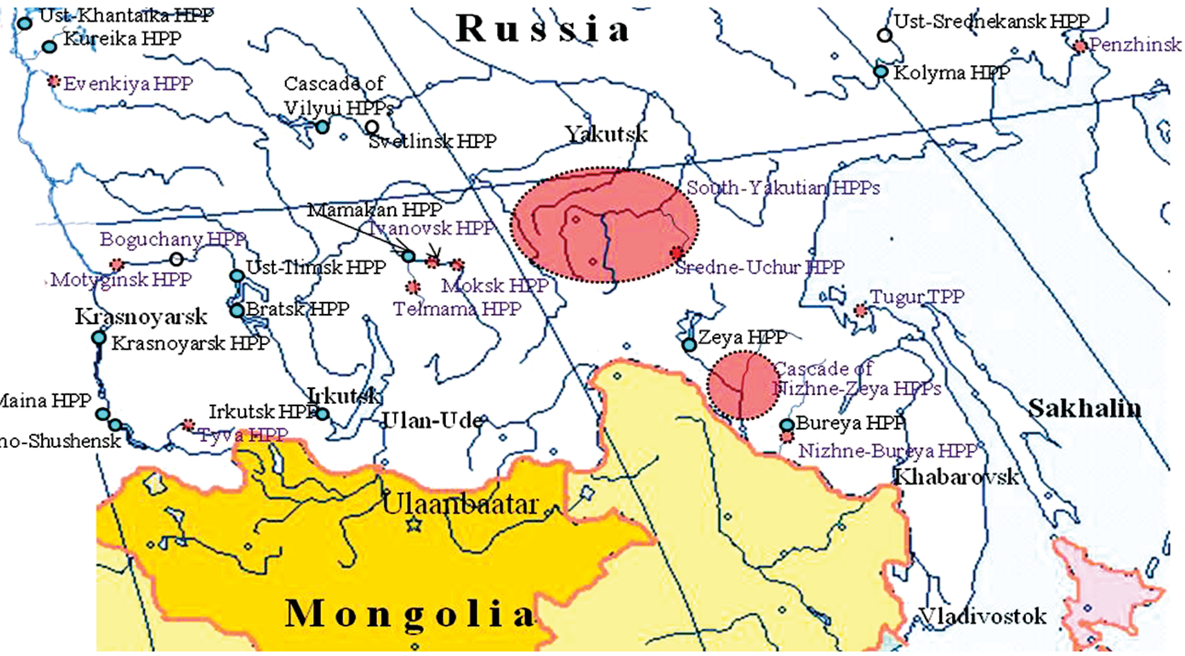

Fig. 2. A map of hydro and tidal resources development in Eastern Russia.

Further hydropower development in Eastern Russia depends essentially on how the economy of the eastern regions will grow and how the cross-border electric ties will be built.

Currently, there are no tidal power plants (TPPs) in Eastern Russia. Sites for construction of two TPPs are available in the Far East region, but the construction has not been started yet.

IV. Attraction of investment in the hydropower development

Russia encourages domestic and foreign investment in its power industry. The Russian power sector needs around \$600-\$800 billion until 2030, including \$55-\$125 billion for hydropower development [7], which has been complicated by the chronic lack of funding over the past 15 years. Currently, policymakers continuously try to find the right balance between investments and reasonable end-user power prices.

There are different forms of investment attraction from domestic financial sources, including financial funds of the power companies, emission of additional shares (stocks) and bonds, bank loans, budget funds, and leasing schemes. Practically all main Russian banks take part in financial support of the projects for construction of new power facilities and modernization of existing ones.

In spite of the existing international financial pressure, there is a favorable climate for investment in Russia's power industry. Since 2007-2008, Fortum (Finland) E.On (Germany), Enel (Italy) have become the main foreign investors. These companies own more than 25 GW or almost 10% of available generation capacity [2].

The Commission for Power Production Enterprises established in April 2008 mainly comprises Russia's domestic and foreign power enterprises, covering 40% of Russia's total installed capacity and over half of the independent power producers in Russia. Its members include Russian private stock companies IES Holding, EuroSibEnergo, SUEK, Nornikel, and Lukoil.

The Russian hydropower industry stagnated during the industry reforms in the 1990s but it has been reviving with the establishment of State-controlled RusHydro Holding in 2004. RusHydro currently includes 15 federal hydropower plants, including Sayano-Shushenskaya (6000 MW) and Zeiya (1330 MW), the first large hydropower plant in the Far East region. The goals of the Holding are to ensure reliable and safe operation of existing hydropower facilities, to complete projects in progress, and to design and build new plants. RusHydro is investing massively in upgrading its aging infrastructure.

Those initiatives are now beginning to bear fruit. The Holding has completed construction of 3 GW Boguchanskaya hydropower plant in Siberia, in collaboration with Russian aluminum producer RUSAL. Another project of the RusHydro Holding is Bureya (2 GW) hydropower plant located at the Amur River in the Far Eastern region. The plant has six 335 MW turbines and is designed to reduce regional fossil fuel consumption and local flooding on the Bureya and Amur rivers.

Several concluded contracts have paved the ways for various opportunities across the country, including the upgrade of EuroSibEnergo's existing assets and construction of new hydro plants, specifically in Siberia. New generation facilities will not only meet growing domestic demand but will also create additional capacity for electricity export to Northeast Asian countries.

New sources of finance and investment have appeared in the past few years. One of the sources is 'New Development Bank' founded by the BRICS countries including Brazil, Russia, India, China, and South Africa in July 2014. Several key countries have established the China-led Asian Infrastructure Investment Bank, which intends to include hydropower in its investment portfolio.

In the private sector, new financial sources such as the IFC's InfraVentures (IFC Global Infrastructure Project Development Fund) have emerged offering innovative solutions for hydropower development.

V. Cross-border and inter-state power cooperation

Eastern Russia possesses enormous unused hydro resources. Expansion of hydropower construction in

this part of the country is considered to be a main goal of the national electric power development. There are plans to construct HPPs not only to cover the increasing domestic demand but also to export electricity to the neighboring countries in Northeast Asia (NEA): China, Republic of Korea (RoK), Democratic People's Republic of Korea (DPRK), Mongolia and Japan. The electricity export will foster the development of interstate electric ties and the formation of NEA-wide interstate electric ties (ISETs). This will allow the connected countries to gain system benefits which will enhance the effectiveness of power plants and transmission system themselves.

Construction of hydropower plants plays an important role in the development of interstate power pool (ISPP) in many parts of the world. Changes in the political situation in NEA have made it possible to establish such kind of a grid in Northeast Asia. Interstate pools create the conditions for utilization of electricity generated by different types of power plants (fuel-burning, small hydro and tidal, renewable and others).

The development of hydropower and the development of interstate ties are mutually interrelated processes. On the one hand, both of them enlarge the utilization of renewable resources and enhance involvement of environmentally friendly generation. On the other hand, the development of ISETs and ISPPs makes it possible to increase the capacities of some HPPs. This increases their cost-effectiveness, decreases prices in the electricity markets and improves the reliability of electricity supply. The high load-following capability of HPPs with reservoirs allows decreasing the

Table 2. Potential interstate electric ties in northeast asia. [8]

The direction ofinterstate electric ties	Length, km	Voltage, kV	Transfer capability, GW	Power transmission, TWh per year
		Russia–China		
Bratsk–Ulaanbaatar–Beijing	2250	±600	5–6	18
DC system Ust'–Ilimsk–Khabarovsk	5000	±750	10.0	40
		Russia–Korean Peninsula		
Vladivostok–Pyongyang–Seoul	1150	±500	4.0	7
		Russia– Japan		
Sakhalin–Hokkaido–Honshu	1850/ 1400**	*±600*	4/3	24
		Asian Asian SuperGrid		
Gobitec– Mongolia, Russia, China, Korea, Japan	7300	±800	100*	200*

required generation capacities and fossil fuel consumption in interconnected electric power systems. Hydropower plants with regulated reservoirs have certain advantages as backup plants.

Seasonally variable annual load maximums in different national electric power systems (EPSs) ensure the difference in electricity consumption structure which is caused by the difference in climate and the level of socio-economic conditions in various countries. In the countries with the hot climate, this leads to a shift of the annual load maximum in the EPS from winter to summer. In NEA, such a situation is observed in Japan, RoK, and northern EPS of China.

In Eastern Russia, however, the winter load maximum exceeds essentially the summer one and this is expected to remain in the foreseeable future.

Due to the seasonal differences in the annual load maximums, the same generation capacities (including HPPs in different countries) can be employed to meet annual load maximums coming in different seasons. This will considerably reduce the demand for new generation capacities.

The efficient cross-border exchange requires the construction of reliable and productive transmission networks. There are several projects for the NEA interstate ties, Table 2, Figure 2. The projects are distinct in purposes of cooperation, electric energy sources on supplying (sending) end, directions, and technical performance of power transmission lines between cooperating countries.

The first project of Bratsk–Beijing interstate power transmission is focused on the organization of surplus electricity export from power plants in the electric power system of the East Siberia and its interconnection with the electric power system of North China to implement the integrated effects. The main goal of the project is to decrease the commissioning of new generating capacities in both electric power systems thanks to the non-coincident annual load peaks. According to the studies, the capacity effects amount to 9–11 GW and investment savings upon the project implementation are estimated at 6–7 billion USD.

A number of proposals for electric energy transmission from Siberia to China are largely oriented to the utilization of excessive seasonal hydropower output of the Angara–Yenisei cascade and Bureya HPP. The DC link Ust-Ilimsk HPP–Khabarovsk can become the backbone for this transmission in the future. It will transport over 70 TWh of environmentally clean and relatively cheap electric energy to provide Siberian and Far Eastern consumers with electricity and to export electricity to the East Asian countries.

The study findings indicate that electric tie between the EPS of the Russian East and the electric power system of the Republic of Korea, i.e., Vladivostok–Pyongyang–Seoul interstate electric ties, is the most effective. Compared with other potential projects (Table 2), this project is the most developed one. The estimated economic effect of the project will reach 14 billion USD in investments and nearly 2 billion USD in annual expenditures. Furthermore, the yearly economic benefit for Russia can reach 450 million USD. High efficiency of this project can be explained by the possible saving of generating capacities (8 GW) due to the variation in annual load peaks. However, the implementation of the project and safe ISET operation requires solving the political issues on the Korean Peninsula and the creation of conditions for strong economic and technical partnership between all counties participating in the project.

Nowadays, a pressing issue is electricity export from Russia to Japan. The idea of the project Sakhalin–Hokkaido–Honshu interstate transmission tie appeared in the 1990s. It was supposed to build two export-oriented TPPs in the Russian Far East in the first stage, and the Sakhalin–Sapporo–Tokyo DC transmission line - in the second stage. Supposed technical parameters of the line were: a voltage of ±400 kV, line length of 1600 km with two (50 and 40 km) underwater cable ducts.

As an alternative to this project, the project of an energy bridge between Russia and Japan was proposed later. It supposed the construction of a combined cycle power plant on Sakhalin Island with a capacity of 4 GW, cable DC transmission line with a length of 1800 km (1400 km of underwater cable) from Sakhalin to Honshu, and converting substations in Sakhalin, Hokkaido, and Honshu. The extension of this interstate transmission line to Khabarovsk could connect the EPS of the Russian East to the EPS of Japan. According to the studies, the expected potential power effect will make up 1.6 GW and investment savings will be 1 billion USD [9].

Now the initial project is revived, but with certain changes. It involves the construction of export-oriented power plants in Sakhalin (two coal-fired plants with a capacity of 1050–1200 MW and a combined cycle plant with a capacity of 800 MW), AC power transmission line in the territory of Sakhalin, and DC power transmission line through La Perouse Strait with a converter substation in the northern part of Hokkaido Island. This project is actively supported by the authorities of neighboring regions of Russia and Japan.

An alternative direction of electric tie lines between Russia and Japan is the construction of an interstate tie through China and countries of the Korean Peninsula. However, the implementation of this project is hindered by the problems in the Korean Peninsula.

Another possible area of interstate electric connections in NEA is electricity transportation from the Gobi energy complex. This project includes the creation of GobiTec complex with a total capacity of 100 GW based on wind and solar power plants (in equal proportion) and DC interstate links for electricity transmission to China, the Republic of Korea, Japan, and Russia. The creation of these links will lead to the formation of the Asian Super Grid.

It is clear that this is a long-term and very expensive project.

VI. Studies for the Northeast Asian Interstate Electricity Interconnections

Since the early 1990s, there have been studies on the efficiency and prospects of the interstate transmission system construction, and formation of the interstate power pool in Northeast Asia [10–12]. Research institutes of Russia, Republic of Korea, the People's Republic of China, Japan, Mongolia, and other countries, as well as Asia Pacific Energy Research Centre (APERC) in Tokyo (Japan) take part in these studies. The studies are financed by state budgets of the Russian Federation and the Republic of Korea, as well as the World Bank, and Russian holding companies (Evrosibenergo, InterRAO EES, and RusHydro).

The prospects for international cooperation in the electric power industry are conditioned by different causes. These include the differences in available domestic natural energy resources and in the level of their use, different demand for energy resources, as well as the acuteness of environmental problems in the individual countries. This is why the country-specific interests in integration and cooperation have been thoroughly investigated.

The People's Republic of China plays a leading role in the electric power industry in NEA. With regard to the electricity consumption growth rates and the degree of development of the power sector, China overtakes many countries and, in electric energy production, it has been a world leader since 2011.

The prevalence of coal in the structure of natural energy resources has determined the coal domination in the energy generation. Nowadays, the coal-fired thermal power plants (TPP) provide 80% of the total electric output in the country. A serious consequence of this situation is significant environmental pollution. In order to cope with this issue, China is planning to develop wind and solar energy complexes in the northern territories. This causes the necessity to transport capacities of these complexes to other areas and adjust the intermittent energy generation from wind and solar power plants.

The connection of China's national electric network to the eastern regions of Russia and other countries may play a certain role in solving domestic energy problems.

The Russian Federation is also highly interested in the development of interstate electric ties with the NEA countries. Moreover, the export of electricity from Eastern Russia to neighboring countries is considered as a factor that could stimulate the acceleration of economy, transport infrastructure, utilization of natural resources in undeveloped territories, and the development of these territories in general.

Electricity export from Russian hydropower plants is usually effective when surplus electricity is sold from operating power plants that do not require investment in capacity expansion. However, in the presence of interstate electric ties, it would be possible to sell surplus electric energy from the newly commissioned HPPs.

Integrated effects in the case of the interconnection of electric power systems of Russia and other NEA countries will significantly increase the efficiency of the cross-border transmission. The greatest effect can be achieved by decreasing the demand for generating capacities due to different seasons and time of the annual peak loads.

The consequences of the Fukushima nuclear power plant accident in Japan in 2011 have seriously impacted on the development of interstate electric ties in NEA. This accident has fundamentally changed the situation in the Japanese electric power industry. Since 2012, several nuclear power plants have been shut down. The termination of this part of electricity production had to be compensated for by an additional load of thermal power plants and a significant growth of gas and oil import. Due to the lack of possibilities for a wide development of renewable energy in the short term the country's electric power industry faces dependence on imported energy resources and the negative environmental effects of the thermal electric production.

In this context, it could be possible to significantly improve the environmental situation with the development of interstate electrical connections with neighboring countries and with the import of environmentally clean electric energy from Russia and China.

The Republic of Korea (RoK) has a very high level of electric power industry development. The structure of generating capacities in RoK is analogous to that in Japan. Besides, it has the same problems with energy resources endowment, like Japan. The Republic of Korea shows interest in developing electrical connections with Russia at the state level [10]. Furthermore, as evidenced by the studies conducted by the Russian (ISEM) and Korean (KERI) Institutes, the interconnection of Russian East EPS and RoK's EPS is technically feasible and very effective, especially for the Korean part. However, the unstable political situation on the Korean Peninsula is a serious obstacle to it. This cause is also an obstacle to the cross-border power transmissions to Northeast China.

The role of Mongolia in the development of the interstate electrical connections in NEA is significant, despite the relatively weak development of its electric power industry. Joint studies with Russia in the field of electric power supply have been carried out for a long time. Nowadays, the Mongolian Power sector is actively developing its electrical connections with China. A transit power transmission line between Russia and China could run through its territory. In the case of the creation of the Asian Super Grid, this country can play a decisive role in the formation of an interstate power pool in northeast Asia.

Summarizing the results of the international studies, we can state that in the event that the electric power interconnection is established in NEA, the countries involved will gain evident advantages. The formation and development of a regional interstate interconnection consist of several stages, whose succession and duration will depend on various conditions. However, in the first stage, the crucial role belongs, not to economic and technical factors, but rather to the political situation and the readiness of the countries and their electric power systems to cooperate in the field of statutory regulation in order to support their power security.

Another avenue for the studies to be conducted is the development of procedures for the medium-term hydropower generation scheduling in the interconnected electric power systems considering the participation of hydropower plants in the internal electricity markets.

Electricity generation scheduling is essential in the power system operation and management. Traditional problem statements aimed at reducing the total production cost hardly correspond to the market environment. In a new commercial framework, generation companies tend to maximize their profit. The problem statement should take into account the strategic behavior of electricity producers, locational marginal prices and the consumer response to the price levels.

The hydrothermal power systems require consideration of the objective function and water balance constraints embracing the whole medium-term scheduling period. Conducted studies have considered specific features of the problem statement for a wholesale market environment. The proposed approach is based on a bi-level optimization technique [13, 14]. The problem formulation allows for possible distortions of economic and technical parameters of generating units. The proposed technique obtains equilibrium of the generation companies' interests and simulates the competitive behavior under oligopoly electricity market. The developed algorithm is based on the stochastic dynamic programming method [15]. The applicability of the proposed method and algorithm is demonstrated on the example of the Siberian electric power system.

VII. Conclusion

Eastern regions of Russia possess enormous hydropower resources. The technical hydro potential of Eastern Russia is used by less than 7.5%. Expansion of hydropower construction in this part of the country is considered to be a main goal of the national electric power development.

Russia is highly interested in developing interstate electrical connections with Northeast Asian countries. Moreover, the electricity export from Eastern Russia to neighboring countries is considered as a factor that could stimulate the growth of the economy, transport infrastructure, utilization of natural resources in undeveloped territories, and the development of these territories in general. However, the possibilities of interstate cooperation in the short term are limited due to formidable political and economic obstacles.

In the event of their electrical interconnection, the NEA countries neighboring Russia gain evident advantages. Should the existing obstacles be eliminated, the electric power systems to be connected should be poised to cooperate in the field of statutory regulation for the provision of their power security.

Conducted multilateral analysis and investigation of the hydropower development in Northeast Asia promotes the interstate power interconnections and cooperation.

Acknowledgment

The research was carried out under State Assignment, Project 17.1.4 (reg. no. AAAA-A17-117030310449-7) of the Fundamental Research of Siberian Branch of the Russian Academy of Sciences.

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