Comprehensive Assessment of the Effectiveness of Interstate Electric Ties in Northeast Asia

L. S. Belyaev, H.-Y. Kim, T.-H. Lyu, S. V. Podkovalnikov, and J.-Y. Yoon

Abstract – **The paper indicates potential effectiveness of creating interstate electric ties and power pools (ISETs and ISPPs) in Northeast Asia (NEA). The methodology and a system of mathematical models for comprehensive assessment of ISET effectiveness are generated. The results of effectiveness assessment for the ISETs "Bratsk-Beijing" and "Vladivostok-Pyongyang-Seoul" are analyzed. The developed methodology is proposed for assessment of these ties. The paper emphasizes the topicality of assessing ISETs and ISPPs creation in NEA as a whole.**

Key words **– interstate electric ties and power pools, electric power systems, peak loads, energy and economic benefits, integrated assessment of effectiveness, mathematical models.**

I. INTRODUCTION

Creation of interstate electric ties and power pools is a global process taking place in different regions of the world. Numerous ISETs and bulk ISPPs have been created in North America, Europe, countries of the former USSR. In South America and some regions of Africa and Southeast Asia the ISETs and the ISPPs have been intensively formed and in South and Northeast Asia the possibilities of ISET and ISPP creation have been studied.

The driving forces of the process are the benefits achieved owing to creation of ISETs and ISPPs: a) decreasing demand for installed generating capacities due to diversity in peak loads (both daily and yearly) in different countries and regions; b) increasing reliability of electric power systems (EPSs) to be interconnected; c) involvement of large renewable energy (primarily hydropower) in the energy balances of different countries; d) acquisition of incomes from electricity trade; e) reduction of electricity prices, etc.

All the indicated benefits can be achieved in NEA. The capacity benefits can be rather high because of diversity in the annual peak loads in different NEA countries by season. Hence, creation of ISETs and ISPPs in this world region is very effective. The studies on assessment of the ISET effectiveness in this region that are carried out by Energy Systems Institute (ESI) of Siberian Branch of the Russian Academy of Sciences and Korea Electrotechnology Research Institute – KERI (NEAREAST project) confirm this fact [1-8].

II. METHODOLOGY OF COMPREHENSIVE ASSESSMENT OF ISET EFFECTIVENESS

Numerous studies on ISET effectiveness in NEA have led to development of the corresponding methodology and a system of mathematical models [7, 8]. The general scheme of comprehensive assessment of ISET effectiveness consists of several stages.

A. *Stage 1*

First of all, ISET (ISPP) variants are determined. In this case the rational transfer capability of the ISET, its technical implementation and the required costs (capital and operating) are determined preliminarily. The ISET variants may differ in:

- technical implementation (alternating or direct current, different voltage levels, cable or overhead transmission lines and also their combination, etc.);
- volumes of required costs and resources;
- impact on EPSs to be connected (in particular, energy security of individual countries participating in the project on interconnection);
- reliability (of both ISET and the whole ISPP);

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- socio-environmental effects/impacts and other factors.

It is possible to qualitatively analyze the variants generated and reject the least preferable ones beforehand. The remaining several variants or even one should be quantitatively evaluated at the next stages.

B. Stage 2

Further, the energy and economic benefits derived from implementing the ISET variants and possibly other benefits (environmental, social) are estimated. The latter should be expressed in money terms or taken into consideration somehow in addition to the energy and economic assessment (e.g. as constraints). These data underlie energy and economic assessment of ISET effectiveness by comparing costs and benefits.

The energy and economic effectiveness of the ISET is assessed by comparison of two scenarios of development and operation of EPSs to be interconnected: without ISET and with its construction. The scenarios are called “separate” and “joint” operation of EPSs. The costs for the ISET and the benefit from its construction will consist of the lump-sum investment and annual expenses. These quantities must be determined for the scenarios of separate and joint operation of EPSs. Then, the scenarios should be compared with each other by combination of the lump-sum and annual costs called annualized costs. In this case a positive value of the energy and economic benefit (annualized costs at separate operation of EPSs must be higher than those at their joint operation) will be a condition for the energy and economic effectiveness of the ISET project. The ISET variant guaranteeing the maximum energy and economic benefit will be the most effective and hence is taken for further consideration. If none of the ISET variants is economically effective, it is excluded from consideration.

When determining the benefit the created ISPP is assumed to be an integral whole. However, this statement has a degree of conditionality, since the ISET involves different countries with their own interests. And such conditionality is inevitable, as far as the cost effectiveness of the ISET can be assessed only by comparing variants without it and with it. A similar procedure for ISET effectiveness assessment is applied in, for example, [9]. Interests of individual countries (project participants) are taken into account when assessing financial effectiveness of the ISET.

Quantitative determination of the energy and economic benefit calls for rather complex calculations on development of EPSs to be interconnected, operating conditions of power plants and power flows over the ISET, environmental and social impacts, etc. For this purpose special mathematical models (in particular, ORIRES and its modifications [7]) should be applied to calculate energy benefits and their economic estimates. Environmental and social benefits (or impacts) are taken into consideration based on the appropriate methods and models [8,10].

C. Stage 3

Reliability of power supply to consumers is verified in the scenarios of separate and joint operation of EPSs based on the failure rate of power plant facilities, transmission lines and the ISET itself. The first scenario evaluates required generating capacities, providing the needed level of power supply reliability at every node (EPS). The second scenario aims to estimate required generating capacities, providing the needed reliability level of EPSs based on generating capacities of adjacent EPSs, which can be used for mutual redundancy via ISETs in case of emergency. Power supply reliability equal to 0.9996 was taken as a standard and is generally accepted in many countries. The indicated calculations require a special model to estimate EPS reliability [11].

D. Stage 4

The study on load flows and security of the ISPPs (and ISETs) is carried out at the stage. In doing so technical implementation of the chosen variant of the ISET and ISPP is tested by using advanced technologies of operation control and power transmission (such as FACTS and others). The indicated studies are performed on the special model ANARES [12].

It should be underlined that the variants for development of ISPP and ISET that satisfy requirements of power supply reliability and technical feasibility can be determined by iterative repetition of calculations at stages 2-4.

E. Stage 5

The ISET benefits and costs are distributed among the project participants at the stage. In this case both the costs for development and operation of EPSs to be interconnected and ISETs and incomes (expenses) from electricity export (import) of individual countries should be allowed for. The resulting benefit derived by some country consists of the differences (with the corresponding sign) in capital investment, operating costs, environmental and social consequences for the variants with separate and joint operation of EPSs and also incomes (expenses) from electricity sale (purchase).

Naturally the resulting benefit depends on the prices of exported (imported) electricity. The price rise will lead to increase in the benefit for an exporting country and vice versa, decrease for an importing one. Change in the export price will make it possible to change distribution of the overall benefit, achieved by the whole ISPP, among individual countries and provide that every country should benefit from it. Therefore, before distribution of the benefits an agreement (at least preliminary) should be concluded about prices of electricity transmitted in every direction and probably in different seasons of a year and hours of a day. The initial prices can be determined by the special model (the "market" ORIRES) [7]. The final agreement about prices can be reached only after assessment of the financial effectiveness of the project for every participant. But before it the prices may be iteratively adjusted.

Investment in the ISET should be distributed among the project participants after distribution of the benefits (and possibly in parallel with it). In principle, such distribution can be implemented in a variety of ways, in particular by negotiations. A rather reasonable (fair) way is to distribute costs for the ISET construction in proportion to the benefits derived by every country.

Financial effectiveness of the ISET for individual participants will depend on distribution of costs for the ISET. Assessment of financial effectiveness of the ISET, if it turns out to be insufficient for some project participants, may call for distribution adjustment and return to the considered stage of project assessment.

F. Stage 6

The financial (commercial) effectiveness for every project participant is assessed at the stage. It is a highly complicated process, especially for the competitive wholesale market at the ISET ends, when a lot of participants are involved in project assessment and implementation. The methodology of such assessment is presented in [13]. It aims to show that the incomes of every participant owing to the project implementation will exceed its costs. The calculations are made on the basis of investment, operating costs, all types of incomes, inflation, risks, etc. and besides, for a long time period. The latter covers the term of ISET construction and its service life. In so doing the incomes and expenses of the project participant are discounted and reduced to a certain point of time (e.g. to the year of project implementation start). The calculation results are used to determine indices of the project benefit and profitability (they are several) and every participant takes a positive or negative decision on participation in the project.

A net present value (NPV) is assumed to be the key index of financial effectiveness of the project for its participant [13]. The positive NPV in this case is the main criterion of project effectiveness for every participant. A special mathematical model for calculation of financial flows is also needed for assessment of financial effectiveness. Such models have been constructed and applied in particular to assess financial effectiveness of electric power projects [14].

At this stage a mix of sources for the ISET project investment is determined, the influence of reforms and liberalization of power industry on the project in the countries participating in it is estimated. The ways of electricity trade among the countries, political prospects, and other issues can be analyzed in addition [7,8].

It should be noted that the described methodology has been only partly applied so far to assess effectiveness of ISETs and ISPPs.

III. MATHEMATICAL MODELS FOR ASSESSMENT OF ISET EFFECTIVENESS

The key model for assessment of energy and economic effectiveness of ISET is the ORIRES [7]. It is a static linear programming model. It is a multi-nodal model in which nodes represent all EPSs to be interconnected. The model considers four seasons of a year with two types of days (working and non-working) that consist of 24 intervals (hours) each, for every season. The model is written for the final (studied) year of the considered period (for instance, the year 2030). The power plants and ties that exist at the beginning of this period (for instance, 2010) and continue to work until the end of the period are treated as operating ones, and commissioning new power plants and ties is considered for the whole period. Independent (optimized) variables of the model are operating and installed capacities of power plants, charge capacity of pumped storage power plant, transfer capability of and power flows via ISETs. Balance equations, capacity resources and operation constraints are considered in the model. The optimal solution in the model is determined with regard to the minimum annualized cost (as an objective function) for power system interconnection including ISETs. It should be noted that KERI has improved the model in terms of environmental factors. Additional equations for calculation of CO_2 emissions from thermal power plants (TPPs) of various types as well as constraints on these emissions (for each country) were introduced in the model. The updated model was used for calculations for the NEAREST project.

Along with this model it is also sensible to use the “nonlinear” ORIRES, in which fuel costs of TPPs and power transmission losses in ISETs are represented by quadratic functions [7]. The nonlinear modification of the model makes it possible to specify operating conditions of power plants in EPSs and ISPP and the flows through ISETs for the intervals equal to a day, a season and a year. Thus, the model can be used to solve simultaneously optimization problems of short-, mid- and long-term operation of power systems and pools which normally required the use of various models [15]. The installed capacities of power plants (by their type) and transfer capabilities of ISETs that have been calculated by the basic ORIRES model are not optimized in the nonlinear ORIRES and are assumed as input information.

Reliability of the created ISPPs and ISETs is estimated by the YANTAR software [11]. The software enables one to obtain an optimal reliability solution meeting the calculated standard indices of power supply reliability of the considered EPS development options in an interactive mode (2-5 iterations). It also allows one to determine:

- capacity reserves in EPSs (nodes of the ISPP);
- ISET reliability and transfer capability requirements;
- effective joint operation of every EPS at given transfer capabilities of ties and principles of mutual redundancy (power exchange between EPSs at emergencies).

Under the NEAREST project Korean experts developed a special mathematical model to estimate the reliability of ISPP and ISETs in Northeast Asia [16]. It is methodologically close to the YANTAR software.

The ANARES software [12] is intended for online calculations, analysis and scheduling of EPS operation. The software makes it possible to solve a variety of applied problems, including:

- calculation of steady states;
- operation optimization to decrease active power losses;
- calculation of voltages to meet feasible region constraints;
- calculation of marginal flows by the method of heavy load conditions;
- calculation of short-circuit currents;

- calculation of electromechanical transient processes;
- calculation of security indices;
- processing of control measurements (for a measurement day);
- state estimation.

All the applied problems are solved on the basis of one database and in a single graphical system providing representation of the calculation results and initial data. The use of this software will make it possible to estimate technical feasibility of a considered variant of ISETs and ISPPs.

The "market" modification of the ORIRES model [7] is aimed at calculating prices and volumes of electricity traded among countries. It takes into consideration the economic interests of every ISPP participant. This is achieved by replacing a single objective function of the basic ORIRES model by their set, where every participant is assigned to its objective function. The objective functions for all participants are of one type. They are the functions of annualized costs. Every market participant minimizes its function by decreasing the costs.

Objective functions are optimized by every market participants, taking into account balance and operation constraints. These constraints are included in the basic version of the ORIRES model and change little in the "market" modification of the model. In addition to the variables indicated for the basic ORIRES version this model includes variables of prices of electricity traded among the countries.

The model for financial analysis [14] makes it possible to estimate the basic financial indices of the investment project of ISET, first of all, NPV.

IV. CASE STUDIES

In the 1990s Russia, Japan, Republic of Korea (ROK) and China started the studies on prospects for development of ISPP and effectiveness of ISETs in NEA [17-20, et al]. The studies showed high potential effectiveness of some ISETs. Many research and design organizations of Russia have paid much attention to the prospects of extending electric ties among Eastern Russia and NEA countries. The studies performed in this field [1-3,5-7,etc.] allowed the potential directions of such ties to be determined and pre-feasibility studies of individual ISETs to be carried out. Also possible variants of technical performance of individual interstate electric ties were preliminarily outlined.

The studies focused on the ISETs from East Siberia to North and Northeastern China ("Bratsk-Beijing", "Bratsk – Shenyang"), from Primorie Territory to Democratic People's Republic of Korea (DPRK) and ROK ("Vladivostok-Pyongyang-Seoul", "Vladivostok-Chongjin"), from Southern Yakutia to Northeastern China and ROK, from Buryatia to Mongolia, from Southern Yakutia to Japan and others. Most of these lines are DC lines. They connect national EPSs operating at different frequency (50 and 60 Hz) and are rather long and costly. However, in the case when ISETs connect countries with different seasons of annual electric peak loads they can be quite effective. These are the ISETs "Bratsk-Beijing" and "Vladivostok-Pyongyang-Seoul".

The ISET «Bratsk-Bejing» was studied in [5]. Since 2000 the annual maximum load in the EPS of North China has shifted from winter to summer time, and the summer maximum continues to increase relative to the winter one. In Siberia EPS, on the contrary, electricity consumption declines in summer (and partially in spring and autumn) and peaks in winter. In the effectiveness assessment the ISET "Bratsk-Beijing" was supposed to provide a benefit to the interconnected EPSs with seasonally different peak loads. The mentioned benefit implies saving of installed capacities in the power systems to be interconnected and, therefore, more complete use of existing power plants (or those to be commissioned in order to cover the domestic load) due to construction of the ISET. Construction of special export power plants is not required, hence, this is the reason for the ISET high effectiveness.

The ISET "Bratsk-Beijing" transfer capability is estimated at 5-6 GW (depending on the flatness of annual load curve in the EPS of Siberia). Volumes of generating capacities saved in both countries by means of power flow exchange along the ISET, and its net economic benefit (saved investment in power plants minus investment in the ISET) make up 9–11 GW and nearly US$ 6–7 billion, respectively (depending on transfer capability). A more detailed study of the ISET by the above proposed methodology is needed.

The ISET "Vladivostok-Pyongyang-Seoul" was assessed by ESI [7]. It was also comprehensively studied in the framework of the NEAREST project [8]. The calculations made by the ESI, using the optimization model ORIRES, showed that the economic effectiveness of this ISET also substantially depends on the benefit gained from seasonally different annual peak loads in the EPS of the Russian Far East (RFE) and the EPS of ROK. Thus, with the transfer capability of transmission line equal to 4 GW a decrease in the required construction of new generation capacities in the ISPP can amount to 7.6 GW and the saving of investment – to US$12 billion.

Additional calculations on the model have shown that if there are no constraints on transfer capability of ISET and the within-year distribution of power output of the RFE Zeya and Bureya hydropower plants (HPPs), the generating capacities to be constructed in the ISPP can be decreased by 1 GW more under average water conditions in the rivers. And the saving of investment will rise by US$1.6 billion.

This result indicates that owing to seasonally different annual peak loads of ISPP considerable part of annual generation of the above HPPs will be utilized during spring-summer floods. In other words, the requirements to shift this generation to winter periods and correspondingly to regulate water storage of their reservoirs are not so exacting.

The KERI studies in the framework of the NEAREST project [8] were devoted to a thorough analysis of different variants of the ISET "Vladivostok-Pyongyang-Seoul" in terms of technology (reliability, security, feasibility), economy and environment. In fact they have proved the effectiveness of the ISET variant previously studied at the ESI. Additionally, possible worsening of the environmental situation due to increase in electricity production by TPPs in the RFE was shown. The study also determined the price of electricity to be transmitted from RFE to ROK, which is acceptable for the Korean side.

V. FUTURE WORKS FOR THE REALIZATION OF ISETS

The electricity cooperation between NEA countries has far been delayed due to socio-economic difference and political tensions. Shaping ISPP NEAREST is a long-term international project, which has a potential for economic benefits; but at the same time, it has many political and technical obstacles it should overcome. Energy security and transparency of electricity trade between concerned countries should be respected and maintained. In order to realize, participating countries must maintain close relations in terms of international politics and economical cooperation, and notably, electricity-related cooperation between the ROK and the DPRK. In addition to NEAREST scenarios, power exchange model, financing issue and power transaction price would be discussed. Finally, it is suggested the establishment of policy plan draft to realize this grand NEAREST project. This suggestion includes the agreements among participating countries on NEAREST and to build a new independent transmission company that is in charge of financing, construction, operation and maintenance of an interconnected power system based on its financial contribution ratio. It is recommended that this independent transmission company obtains the funding from international financial institutions and embarks on the power system interconnection.

VI. CONCLUSIONS

The methodology has been developed to comprehensively assess the ISET effectiveness. It includes the following stages:
1) development of ISET (and ISPP) variants;
2) assessment of energy-economic benefits to be gained depending on the ISET variant, and, possibly, some other benefits/impacts (environmental, social), and choice of the most effective variant;

3) reliability testing of power supply to EPS and ISPP, considering failure rate of equipment at power plants, transmission lines and ISET itself;
4) studies of load flows and security of ISET;
5) distribution of the ISET-related benefits and costs among the project participants;
6) estimation of financial (commercial) effectiveness for every project participant.

The use of developed methodology calls for employment of a system of models. This is the family of ORIRES models (basic, nonlinear and market ones) that have been developed specially for the problems of ISET effectiveness assessment. The system includes the software packages YANTAR and ANARES to solve a wide range of problems related to reliability estimation and study of load flows. The system also includes the model for assessment of financial effectiveness of ISET.

In order to more thoroughly estimate the top-priority ISETs in NEA, such as “Bratsk-Beijing” and “Vladivostok-Pyongyang-Seoul” it is necessary to apply the developed methodology and the system of models for assessment of the overall effectiveness. The study on the effectiveness of ISPP to be created in NEA as a whole is also topical. It will contribute to the improvement of estimation of individual ISETs in the ISPP to be created.

To realize the global project of ISETs and ISPP creation in NEA region it is needed to conclude agreements among participating countries and to build a new independent transmission company that is in charge of financing, construction, operation and maintenance of an interconnected power system based on financial contribution of each country.

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VIII. BIOGRAPHIES

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