# A New Economic Benefit Evaluation Model and its Application for Optimizing Transmission Capacity of Multinational Interconnections

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Abstract-Multinational power grid interconnections play an important role in supporting the vision of the Global Energy Internet. During the early stages of the Global Energy Internet, the value proposition of multinational interconnections should be carefully investigated in order to stimulate the activities for associated countries in such potential interconnections. This paper proposes a new economic benefit evaluation model which is quantified by using a chronological production cost simulation approach. The economic benefit model comprehensively considered investment costs and the benefits of the decrease of load payments and the increase of net generation revenue due to a transmission project interconnected with different countries. This economic benefit model can assist to quantitatively determine the optimal transmission capacity for multinational interconnections to achieve maximum economic benefits as a whole. In the case study, the economic benefit of an interconnected system of western China and the Gulf States is assessed by using the method proposed in this paper. And the optimal interconnection capacity with maximum benefit is achieved. The case study shows that the proposed method can be used for economic benefit assessment and is of great significance to the multinational and inter-continental transmission interconnections.

*Index Terms*—Economic benefit, global energy internet, production cost simulation, transmission planning.

#### I. INTRODUCTION

MULTINATIONAL power grid interconnections become the objective trend of regional and national power industry development around the world facing geographically unbalanced distribution of energy resources and electric demand. Global power grid interconnection play an important role in supporting the vision of a Global Energy Internet. In the context of the Global Energy Internet, State Grid Cooperation of China proposes the theoretical concept of a global energy internet and puts forward research on the transmission interconnection of multinational power grids according to the distribution characteristics of a global large-scale clean energy bases [1-2]. Multinational interconnections are complex with diverse issues including technical, economic and financial, legal, political, social, and environmental aspects. Besides technical aspects, multinational grid interconnection requires careful and precise evaluation of costs and benefits for transmission project during the early stages of planning, which is an important part in the global energy internet. Also critical, economic benefits reflects the long-term value of the transmission project for two even more interconnected countries, who need the mutual benefits for resources and electricity. Moreover, investors of such transmission projects need to clearly understand the revenue return over the life cycle of the project.

The multinational interconnections have been highlighted for rapid development, driven by various factors such as the environment, economy, society, technology and policy [3]. A quantitative analysis of opportunities and challenges of grid interconnections was conducted in [4]. In the multinational interconnection planning, how to choose a transmission interconnection project to get the optimal benefit is the key problem to be studied as part of the future large power grid expansion planning. In the context of the Global Energy Internet, various researches have been conducted on the interconnection projects. In [5], it employed linear programming techniques to investigate the environmental and economic benefits of multilateral power grid interconnections. And the proposed model minimized single-year overall system costs of multilateral power grid interconnection in Northeast Asia under energy resource and system operational constraints. A minimum cost model which can be used to account for economical energy exchange between utilities and evaluate production cost savings in multiple interconnected systems was proposed in [6]. Reference [7] proposed a comprehensive method that minimizes the total costs including various factors such as fuel cost, environmental cost, maintenance cost, start-up and shut-down costs to find the optimal operating point of a micro grid. In these studies, multiple stakeholders may not be taken into consideration, and usually they only aim at minimum cost. In addition, many studies have been performed on investigating the potential of Asia-Europe interconnections [8]-[10]. In [11], it proposed to establish a Northeast Asia Grid

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Interconnection in an effort to facilitate optimized resource allocation. Generally, in traditional least cost transmission interconnection planning methods, the optimal transmission project is selected based on its minimum cost [12]-[15]. This only provides the economic criterion of a transmission project, and the project still might not be able to provide a satisfactory profit.

However, there is a lack of economic benefit assessment research considering multiple stakeholders of multinational transmission interconnections. Without a reasonable economic benefit assessment, the interconnection project may face tremendous investment risk. In addition, the assessment of the transmission capacity during the planning stage and forecast of its utilization of long-distance and high-capacity transmission lines are generally lacking.

Therefore, with consideration of the benefits of multiple stakeholders, this paper innovatively presents an economic benefit evaluation model that comprehensively reflects the relationship of costs and benefits. The proposed economic model is used to determine optimal transmission capacity of multinational interconnections. This paper is organized as follows: Section II discusses the proposed method and its application. Section III introduces the background of the study system, and then presents the case results and its analysis. Finally, conclusions are presented in Section IV.

### II. ECONOMIC BENEFIT EVALUATION MODEL AND ITS APPLICATION

### *A.* Economic Benefit Evaluation Model for Multinational Interconnections

Economic benefit evaluation is the critical task during the planning stage of multinational transmission interconnections [16]. Interconnections allow the usage of the least cost generating resources shared among the interconnected areas and provide an overall cost savings. Alternatively, it allows cheaper energy from a country with surplus supply to be delivered to another country with capacity deficiency or more expensive energy. In general, the economic benefit of a transmission interconnection project for the purpose of energy trading primarily reflects two aspects: On the one hand, generation companies from electricity sending countries with rich primary fuel and surplus of generation capacity may obtain more generation revenue by selling more electricity; on the other hand, for electricity receiving countries that generally have the problems of either resource and generation scarcity or high electricity prices, electricity users may gain benefits by purchasing cheaper electricity.

In this paper, an economic benefit model is proposed which contributes to quantitatively evaluating the benefits of multinational interconnections. Based on previous analysis, the economic benefits of interconnected countries include the decrease of load payment and increase of generation revenue. Such benefit for an individual country should be aggregated as a whole for all interconnected countries. When two or more countries are interconnected, the electricity from the lower cost generation units in one country can be sent to another country with high cost generation units, which results in lowering load payments and providing better generation revenue. Meanwhile, the investment in the transmission line is the cost portion of such interconnections in the cost-benefit analysis. Therefore, net benefit of a transmission project should consider both economic benefits and the costs of investment.

Without a transmission project, total load payment and total net generation revenue in the interconnected system are  $LP^{B}$ and  $NGR^{B}$ , respectively. And with a transmission project, they are  $LP^{A}$  and  $NGR^{A}$ ; the cost of the transmission project is CT. The benefit calculation is based on the statistics for one year. The total net benefit model is shown as follows:

$$NB_i = (LP^B - LP^A) + (NGR^A - NGR^B) - CT$$
(1)

where *i* denotes different multinational transmission schemes. *1) Load Payment* 

Load payment is the product of the load and marginal cost on the load side. Marginal price is defined as the cost for serving the next unit of the load with minimum production cost [17], [18].

$$LP = \sum_{t=1}^{8760} (\sum_{m=1}^{N_{LD}} (p_{t,m}^{LD} * l_{t,m}^{LD}))$$
(2)

where LP (\$) is total load payment of the system.  $p_{t,m}^{LD}$  (MWh) is the marginal cost of load *m* at hour *t*.  $l_{t,m}^{LD}$  (\$/MWh) is the load MW amount of load *m* at hour *t*.  $N_{LD}$  is the number of all loads in the interconnected countries. 2) Net Generation Revenue

$$NGR = \sum_{t=1}^{8760} \sum_{i=1}^{N_G} [g_{i,t} \times p_{i,t} - f_i(g_{i,t})]$$
(3)

where  $N_G$  is the amount of generators across the area.  $g_{i,t}$  is the generation of generator *i* at hour *t*.  $p_{i,t}$  is the marginal cost at the location of generator *i* at hour *t*.

The generation cost function can be expressed as a rising quadratic curve, which is shown in (4).

$$f_i(g) = a_i(g)^2 + b_i(g) + c_i$$
(4)

where  $a_i$ ,  $b_i$ ,  $c_i$  are coefficients of the unit *i*.

3) The Investment Cost of an Interconnection Project

For a transmission interconnection project, the initial investment cost accounts for a large proportion which primarily contains the cost of the transmission lines and substation facilities. The cost estimation model is shown as (5).

$$CT_{total} = (C_T + C_S) \times (1 + overhead) / m$$
(5)

Among them, the transmission lines and substation costs are calculated as follows:

$$C_T = C_{baseline} \times L \tag{6}$$

$$C_{S} = C_{\text{basesub}} + C_{XFMR} \times Q_{capacity}$$

$$\tag{7}$$

where  $C_T$  is the total cost of the transmission lines, and  $C_S$  is the total cost of the main substations. *m* is the service life of the transmission lines.  $C_{baseline}$ (\$/km) is the baseline transmission costs, and *L* (km) is the length of the lines.  $C_{basesub}$  (\$/MVA) is the substation base costs including land costs, substation fencing, and the control building, etc.  $C_{XFMR}$  is the capital costs associated with each voltage class of transformer in a cost per

mega - volt ampere (MVA) unit.  $Q_{capacity}$  is the capacity of the transformers. In addition, *overhead* is the indirect cost. According to the experience value of western countries, it is 10% [19].

#### B. The Chronological Production Cost Simulation Model

On the basis of the future multinational interconnected countries' power development goals and electricity demand forecast, the multinational power grid interconnected system in the future years is established, and then a production cost simulation model considering transmission constraints is constructed.

Production cost simulation mimics power system operations based on the actual system physical and economic characteristics and is widely used in renewable energy consumption, reliability assessment, transmission network expansion planning and multi-area interconnection analysis [20]-[22]. Sequential production cost simulation simulates the operation of each generating unit on an hourly basis under a given chronological load profile, generation characteristics and fuel cost [23].

The chronological simulation method can better describe power system activities and accurately achieve different kinds of physical and economic performances of transmission, generation and load for the whole study period. In this method, electric load, transmission systems and generation systems are precisely modeled in detail. The main structure is shown in Fig.1.



Fig. 1. Production cost simulation framework.

The chronological production cost model performs simulations on an hourly basis. The study time interval is usually one year. The simulation performs a security constrained day unit commitment and real time economic dispatch ahead for each hour during the whole study time interval based on load, power generation, power grids and fuel conditions. At the end of the simulation, various statistical performance indicators are calculated. The basic simulation process is shown in Fig. 2.



Fig. 2. Production cost simulation process.

The core function of the production simulation is the transmission security constrained unit commitment and economic dispatch. The algorithm minimizes system production cost with consideration of constraints of energy balance, transmission system and generation characteristics. The unit commitment model can be found in [24]-[26].

The objective function of the economic dispatch at hour *t* is:

$$\min F_{t} = \sum_{n=1}^{NG} C_{n}(g_{n,t})$$
(8)

where NG is the total number of units;  $g_{n,t}$  is the active power of unit *n* at hour *t*;  $C_n(g_{n,t})$  is the cost function of unit *n*.

The generation cost of the units  $C_n[g_n(t)]$  is generally expressed as a quadratic function as follows:

$$C_{n}[g_{n}] = a_{n}[g_{n}(t)]^{2} + b_{n}[g_{n}(t)] + c_{n}$$
(9)

where  $a_n$ ,  $b_n$ ,  $c_n$  are coefficients of the units' operation cost. Subject to:

Power balance constraint is:

$$\sum_{n=1}^{NG} g_n = \sum_{m=1}^{NL} l_m$$
(10)

where *NL* is the total number of loads;  $l_m$  is load amount at load *m*.

Upper and lower bounds of the output of the unit are:

$$g_n^{\min} \le g_n \le g_n^{\max} \tag{11}$$

where  $g_n^{\min}$  and  $g_n^{\max}$  are the lower and upper generation limit of the generating unit *n*, respectively.

Transmission flow constraints are:

$$\left| GSF_{ij-k} * p_k \right| \le f_{ij}^{\max} \tag{12}$$

where  $GSF_{ii-k}$  is the generation shift factor of line *i*-*j* to the

injection of bus k and  $f_{ij}^{max}$  is the flow and thermal limit of line *i*-*j*.

The proposed economic benefit model for multinational interconnections is used not only for two interconnected countries, but also for multiple interconnected countries. And the transmission projects can be one transmission link between two countries or multiple transmission links among multiple countries. Therefore, when performing the statistics of load payment and net generation revenue, all loads and generators in the interconnected countries should be considered.

## *C. Optimization analysis of the transmission alternative of multinational interconnection*

According to the proposed economic benefit assessment model, the cost-benefit analysis of the transmission alternatives of multinational interconnections can be carried out to determine the optimal interconnection capacity with the maximum net benefit. According to the previous analysis, there are better chances for sharing cheaper resources among interconnected countries with more interconnection capacity, and the value of the benefits of lower load payment and greater generation tend to be significant. Meanwhile, with the increase of new transmission capacity, the investment cost increases. Therefore, under a certain transmission capacity, the interconnection benefit could be rapidly increasing; with transmission capacity gradually increasing, the rate of the increasing benefit may be slowing down. In this process there is a point of maximum benefit where the transmission capacity is optimal. The overall calculation process of finding optimal transmission capacity is shown in Fig. 3.



Fig. 3. Flow chart of the proposed method.

The base case of a multinational power grid interconnection system is set to B. New transmission alternatives are set to cx; and c1, c2 ... cN represents interconnection lines with different capacities in an ascending order.  $CT_{c1}$ ,  $CT_{c2}$ ... $CT_{cN}$  represent the investment cost of c1, c2 ... cN respectively. The benefit is  $NB_{cx}(x=1,2...N)$  as shown in Table I.

COST-BENEFIT ANALYSIS OF DIFFERENT TRANSMISSION ALTERNATIVES					
Case	Investment	Load	Net	Net benefit	
	cost	payment	generation		
			revenue		
В	NA	$LP_{\rm B}$	NGRB	/	
C1	$CT_{c1}$	$LP_{c1}$	$NGR_{c1}$	$NBc1=(LP_B-LP_{c1})+(G_{c1}-$	
				$G_{\rm B}$ ) - $CT_{\rm c1}$	
CN	$CT_{cN}$	$LP_{cN}$	$NGR_{cN}$	$NBcN=(LP_B-LP_{cN})+(G_{cN})$	
				$-G_{\rm B}$ )- $CT_{\rm cN}$	

Therefore, the relationship between the capacity of the new transmission lines and the interconnection benefits roughly meets the trend shown in Fig. 4. The x axis represents the total capacity of the individual transmission alternatives, and the y axis represents the net economic benefit.



Fig. 4. The relationship between the capacity and net benefits.

#### III. CASE STUDIES

#### A. Background of Power Systems of China and Gulf States

Western China has abundant coal and clean resources, whose generation resources are extremely adequate, especially in Sinkiang. In recent years, the installed capacity of wind power and PV has increased rapidly in Sinkiang. By the end of 2015, the total installed capacity of renewable generation in Sinkiang had reached 22,192 MW. In order to promote the usage of clean energy sources, Sinkiang has a plan to increase the delivery of clean energy to outside areas. Meanwhile, the Gulf States are facing the challenges of fossil energy shortages with their economy growing. And the demand for clean energy is urgent. Therefore, China and the Gulf States have very good complementarities in energy supply and demand for electricity and energy resources.

There is a need for long-distance UHV transmission lines between Sinkiang and the Gulf States. In the case study, the economic benefits of transmission interconnections between Sinkiang and the Gulf States are assessed based on the proposed model for different transmission alternatives.

The system for Sinkiang and the Gulf being interconnected is established for the year of 2030. The data models include conventional and renewable generating resources, annual sequential load, primary fuel and transmission lines between the countries. The installed capacity and peak load forecast in the Gulf States in 2030 are shown in Table II. The data for the Sinkiang power system is based on the development plan of "13th Five Year Plan," where Sinkiang's electricity delivery capacity will reach 50 million kilowatts by 2020. According to Sinkiang's clean energy development plan, there will be a total installed capacity of 42,000 MW in 2030 including wind power, photovoltaic, and hydropower.

TABLE II INSTALLED CAPACITY AND LOAD FORECASTING TABLES FOR THE GULF COUNTRIES IN 2030

Countries	Installed capacity <sup>[31]</sup> (MW)	Annual peak load (MW)	Annual electricity consumption (TWh)
Saudi Arabia	113448 <sup>[34]</sup>	74136 <sup>[30]</sup>	648.38
Kuwait	27679[35]	25062	114.16 <sup>[35]</sup>
Oman	19636 <sup>[38]</sup>	14900 <sup>[27]</sup>	84.79 <sup>[27,36]</sup>
Qatar	18934 <sup>[37]</sup>	17141 <sup>[31,37]</sup>	81.06 <sup>[37]</sup>
UAE	52000 <sup>[29]</sup>	32800 <sup>[39]</sup>	161.15 <sup>[39]</sup>
Bahrain	7341 <sup>[38]</sup>	5717 <sup>[28]</sup>	21.40 <sup>[28]</sup>

The annual sequential load profile is obtained by an interpolating method based on the historical winter, summer typical daily load curve, monthly peak load, 2030 peak load and electricity consumption forecast. The load profiles meet the 2030 peak and electricity consumption requirements, such as Kuwait's annual sequential load profile shown in Fig.5. The primary fuel prices for the Gulf States, including coal, oil, and natural gas, came from the world economic data [32-33].



Fig. 5. 2010 and 2030 annual sequential load profile in Kuwait.

In the simulation, each country is modeled as a bubble that contains system load and different types of generating resources. There are no detailed transmission lines inside the bubble. Multinational interconnection is modeled between each bubble. The bubble model is shown as Fig. 6.



Fig. 6. The bubble model of the simulation.

According to the interconnection situation of the Gulf States and the bubble model, Sinkiang can be seen as Country D, and the Gulf States can be seen as Country A, Country B, Country C and so on. Then the simplified model of the interconnected system between Sinkiang and the Gulf States is shown in Fig. 7.



Fig. 7. China and the Gulf States interconnected systems.

According to the method proposed in this paper, the chronological simulation for the whole year of 2030 for different planning schemes of the interconnected system are carried out.

#### B. Results Analysis of China and the Gulf States Interconnected System

When the capacity of an interconnection line is 5 GW, the total benefits of the load payment and net generation revenue in the interconnected system are shown in Table III. With the transmission link, in the year 2030, loads in the total interconnected system as a whole pay less by 832 M\$. Generation companies in the total interconnected system gain more net generation revenue by 3,799 M\$. The total annual benefit due to the transmission link is 4,631 M\$.

TABLE III
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	Without link	With link(5GW)	Benefit(M\$)
Load payment (M\$)	40,538	39,706	832
Generation revenue (M\$)	13,850	17,649	3,799
Total(M\$)			4,631

Considering the costs of the interconnection project, the net benefits are calculated. More cases with incremental transmission capacity are carried out and the corresponding net benefits of different interconnection capacities are shown in Table IV. As we can see from the results, as the transmission capacity increases, the interconnection net benefit increases. The relationship between the different transmission capacities and the benefits are shown in Fig. 8.

TABLE IV						
RESULTS	RESULTS OF CHINA AND THE GULF STATES INTERCONNECTED SYSTEM					
Case	Load payment (M\$)	Net generation revenue (M\$)	Capacity (GW)	Cost (M\$)	Net benefit (M\$)	
Base case	40,538	13,850				
Case 1	39,706	17,649	5	189	4,441	
Case 2	38,305	16,764	15	567	4,580	
Case 3	37,633	16,625	20	756	4,924	
Case 4	37,821	16,963	22	832	4,997	
Case 5	37,524	16,893	24	907	5,150	
Case 6	37,402	16,809	25	945	5,149	
Case 7	37,529	16,982	26	983	5,158	
Case 8	36,978	16,491	28	1,058	5,142	
Case 9	36,756	15,970	30	1,134	4,767	
Case 10	36,209	15,474	33	1,247	4,705	
Case 11	36,204	15,478	34	1,285	4,676	
Case 12	36,011	15,273	35	1,323	4,627	
Case 13	35,814	15,060	38	1,436	4,498	



Fig. 8. Results of power grid interconnection between China and Gulf States. According to the above calculation results, when the interconnection capacity of Sinkiang to the Gulf States reaches 26 GW, the benefit reaches the maximum at 5,158 M\$. For the optimal case, the power flow of this UHV transmission line is shown in Fig. 9.



Fig. 9. Power flow of the multinational transmission lines





Fig. 11. Utilization level of the multinational transmission lines.

In Fig. 9 and Fig. 11, the red and blue curves represent the chronological power flow and duration curve, respectively. The overall utilization rate of the transmission link is 49% in terms of total energy transferred on the link. The daily average power flow of the multinational transmission lines is shown in Fig. 10. As we can see from the results, due to the load characteristics of the Gulf countries with high load in summer, the electricity from Sinkiang to the Gulf States plays a role in the daily and seasonal peak shaving, which meets the load demand of the Gulf countries in summer when the transmission is heavily used and even congested.

#### IV. CONCLUSION

In the context of the global energy internet, this paper proposes an economic benefit evaluation model and its application for optimizing transmission capacity for multinational interconnection planning, which can be calculated using a chronological production cost simulation approach. First, an economic benefit evaluation model is proposed including the overall load payment among the interconnected countries, the net revenues of the generation companies, and the total cost of the interconnection projects. Then, we construct a production cost simulation model and simulate the chronological operation of a multinational power grid interconnection system using the model. In case studies, Sinkiang and the Gulf States interconnected system in 2030 is built. The simulation found the interconnection optimal capacity with the maximum benefit, which demonstrates the feasibility of the proposed method.

The economic cost benefit model proposed in this paper is of great significance to optimize the transmission capacity of the multinational and inter-continental interconnection. This method is suitable for multinational or intercontinental transmission interconnection long-term expansion planning to optimize interconnection capacity in the electricity market environment. Moreover, this method comprehensively takes into account the interests of multiple market entities and aims at maximizing the multiple benefits. And it can provide information to stakeholders to support their decision-making processes.

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