ERIA Research Project Report 2015, No. 9

Study on Power Grid Interconnection and Electricity Trading in Northeast Asia

Edited by

Yanfei Li

Shigeru Kimura

Economic Research Institute for ASEAN and East Asia

ERIA Research Project FY2015 No.09

Published in October 2016

ACKNOWLEDGEMENTS

The Economic Research Institute for ASEAN and East Asia (ERIA) is grateful to Mongolia’s Ministry of Foreign Affairs and Ministry of Energy for their initiative of encouraging ERIA to embark on this project, and for their continuous support. ERIA also appreciates the data, information, opinions, and constructive comments contributed by all members of the working group.

CONTENTS

LIST OF PROJECT MEMBERS

Project Leader : Shigeru Kimura, Economic Research Institute for ASEAN and East Asia

Project Coordinator: Yanfei Li, Economic Research Institute for ASEAN and East Asia

Working Group Members:

Azjargal Tungalag, Ministry of Energy, Mongolia

Dr Sergey P. Popov, Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences

Mr Takashi Otsuki, Asia Pacific Energy Research Centre

Prof Youngho Chang, Nanyang Technological University

LIST OF ABBREVIATIONS

APERC	Asia Pacific Energy Research Centre
CAPEX	capital expenditure
ERIA	Economic Research Institute for ASEAN and East Asia
HFO	heavy fuel oil
HVDC	high voltage direct current
MWh	megawatt-hour
MW	megawatts
NEA	Northeast Asia
PV	photovoltaic

EXECUTIVE SUMMARY

This research report analyses the costs and benefits of power grid interconnection in the Northeast Asia (NEA) region – covering north and northeast of China, Japan, Mongolia, East Russia, and South Korea – using a linear programming and optimisation model. Based on such analysis, several important observations are made on the feasibility and optimal plans of power infrastructure development for power grid interconnection in the region. Policy implications are also drawn based on these observations. It is strongly believed that these findings and policy implications are complementary to the existing literature on power grid interconnection in the NEA region.

The key research questions are as follows:

- What are the costs and benefits of power grid interconnection and the corresponding trade of electricity in the region?
- What are the priority projects that are optimised and stand as economically and financially feasible?
- What are the remaining technical, economic, and institutional barriers?
- How should standards, grid codes, and regulations for both bilateral and multilateral interconnection and trade of electricity be harmonised?

During the first year of research conducted on the issue, the Economic Research Institute for ASEAN and East Asia (ERIA) focused on the quantitative assessment of the economic benefits of power grid interconnection among the NEA countries. It addressed questions such as who will benefit and how much the benefit will be.

In the future, this study can be extended to shed light on the issue of whether the interconnection projects will be economically and financially feasible. Further studies can also indicate the optimal planning of the interconnection projects among the NEA countries, especially in terms of routes and timing.

Large-scale interconnections among Mongolia, Russia, and China are identified as needed and feasible in almost all scenarios. Savings in the total system cost of all countries vary at US$500 billion in total in about 30 years as a net present value, compared to the case of no power grid interconnection and thus no trade of electricity. This is equivalent to about 10 percent of total system cost for all countries involved. On the environment side, some 4 billion tonnes of carbon dioxide (CO_2) emissions – about 10% of the total carbon emission in the case of no interconnection – could be reduced during the same period.

Solar photovoltaic (PV), which has a better match with peak power demand, appears to be more competitive than wind power and to be developed at a large scale in Mongolia starting 2033 or 2038 depending on the scenario.

For wind power to be competitive and developed, the cost of electricity from wind power needs to be 30 percent lower in Mongolia compared to neighbouring countries, especially China. The complementary development of pump storage, battery storage, and smart grid may help improve the competitiveness of wind power.

Considering the massive scale of investment required for both renewable generation capacities and cross-border power transmission lines among NEA countries, collaborative, open, and transparent foreign investment policies – especially for the power sector – are prerequisite to realising any of the vision for power grid interconnection in the region.

Considering that countries such as China, Japan, and South Korea already have set domestic targets for renewable power generation capacity and share in total electricity generation, the demand for renewable power (both solar and wind) generated from Mongolia may come even later than currently estimated. NEA countries, thus, may need to coordinate policies on renewable energy to avoid restricting the source of renewables from domestic only; that is, the environmental benefits of imported electricity from renewable sources should be counted in setting relevant domestic policies in the importing countries.

Considering the high costs of building dedicated cross-border power transmission lines among the NEA countries, policies that encourage developing robust domestic power transmission network, and which allow near-the-border type of power grid interconnection with neighbouring countries, may stand as the most beneficial way in this region.

Last but not least, power grid interconnection enhances energy supply security in the region by improving diversity of sources and means of supply to each participating country. In the future, the impact of clean coal technology should also be further studied, as it is almost sure that as the technology matures and cost decreases, it can potentially change the fuel mix of power generation in the region while contributing significantly to decreasing greenhouse gas emissions from the power sector.

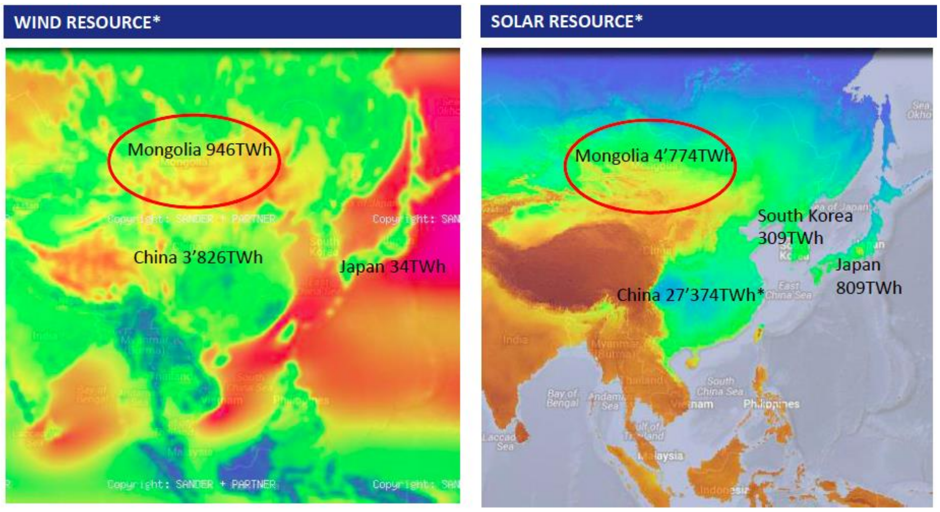
Chapter 1

Introduction

1.1 Background

Northeast Asia (NEA) has ample energy resources for power generation, including coal, oil, natural gas, and hydropower in Russia; and coal, wind, and solar resources in Mongolia. However, most of these resources are untapped due to the small population and small energy demand in Eastern Russia and Mongolia.

Figure 1: Wind and Solar Energy Resources in Northeast Asia



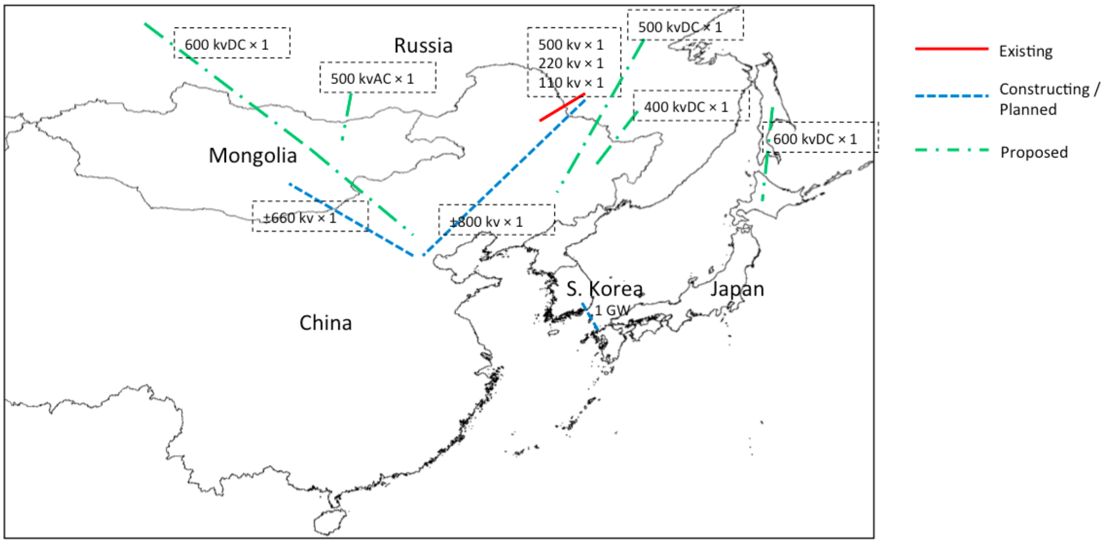
TWh = terawatt-hour.
Source: Newcom Group.

On the other hand, their three neighbours – China, Japan, and South Korea – are main energy consumers, especially of electricity. These three countries import large amounts of coal and natural gas to meet their electricity demand.

Thus, it makes sense to look into the idea of an Asian Super Grid for power grid interconnection among these countries. There are several types of potential benefits. First, it will diversify energy supply while creating new markets for the untapped energy resources. Second, it will avoid the building of expensive peak power generation capacities and using expensive fossil fuel, such as liquefied natural gas for peak power supply, to the extent that the interconnection capacity allows, as the wide geographical spread of these countries have differing peak hours and thus can mutually support each other through the power grid interconnection. Third, an integrated grid of several countries bears much higher capacity to absorb intermittent renewable energy. And fourth, the diversification and geographical proximity enhance the energy security of all participating countries.

In this regard, many institutes, such as the Asia Pacific Energy Research Centre (APERC), Japan Renewable Energy Foundation, Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, and SoftBank have conducted studies. Many bilateral cross-border transmission projects are also being carried out, especially for Russia–China, Mongolia–Russia, and Japan–South Korea.

Figure 2: Existing and Planned Power Transmission Lines in Northeast Asia



DC = direct current, GW = gigawatt, kV = kilovolt.
Source: Economic Research Institute for ASEAN and East Asia.

While bilateral projects can be easily justified by the concentration of newly developed energy reserve, such as coal or hydropower on the one end and the concentration of demand by large cities with a large population on the other end, multilateral power grid interconnection is much more complicated in terms of potential benefits; risks; and technical, regulatory, administrative, and even political complications.

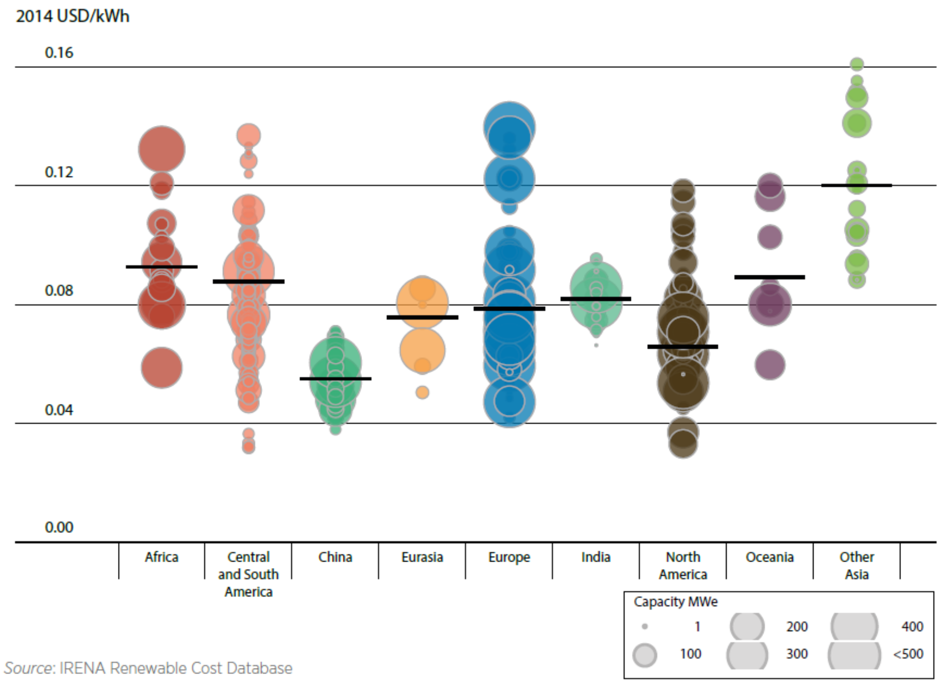
Existing studies on these issues are at preliminary stages. Thus, more detailed studies are required to establish firm grounds for policymakers as well as investors and financiers to make their decisions. Thus, the Economic Research Institute for ASEAN and East Asia (ERIA) proposes to conduct studies as described below, in collaboration with Mongolia partner institutes.

1.2 Economic Rationale

The rationale of this Mongolia-focused project is to identify feasible power grid interconnection plans so that electricity generated from the rich wind and solar resources of Mongolia could reach neighbouring countries at competitive costs. Therefore, both the costs of electricity and the transmission must be looked into.

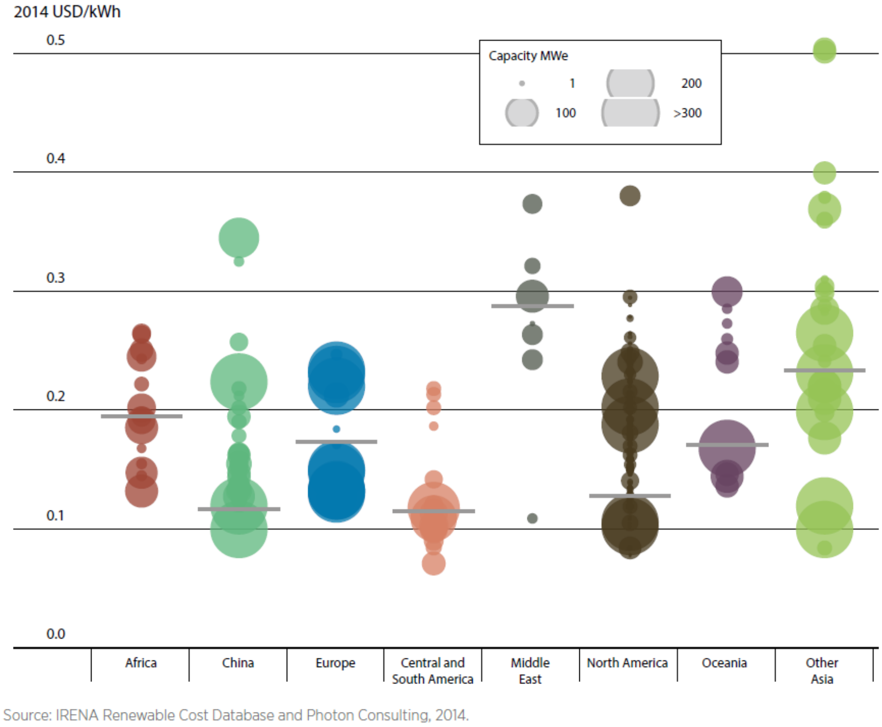
A recent study by IRENA (2015) shows the cost of electricity from utility-scale wind and solar (Figure 3).

Figure 3: LCOE and Weighted Averages of Commissioned and Proposed Wind Projects, by Country and Region, 2013 and 2014



kWh = kilowatt-hour, LCOE = levelised cost of electricity, MWe = megawatt electrical, USD = US dollar.
Source: IRENA (2015).

Figure 4: Levelised Cost of Electricity of Utility-Scale Solar Photovoltaic Systems, by Country and Region, 2013 and 2014



kWh = kilowatt-hour, MWe = megawatt electrical, USD = US dollar.
Source: IRENA (2015).

A recent study by ERIA (Li and Chang, 2015) shows the cost of transmission, which also considered establishing new trunk lines (Table 1).

Table 1: CAPEX of Power Transmission Lines and Simulated Cost of Transmission

Case	Voltage (kV)	Line Length (km)	Capacity	CAPEX (USD)	US$/MWh[a]
1	500	200	500	167,200,000	9.1
2	500	400	500	297,900,000	16.1
3	500	200	1,000	242,000,000	6.6
4	500	200	1,000	152,400,000	4.1
5	500	400	1,000	449,500,000	12.2
6	500	200	2,000	312,100,000	4.2
7	500	200	2,000	292,200,000	4.0
8	500	400	2,000	732,500,000	9.9
9	500	400	2,000	630,800,000	8.5

CAPEX = capital expenditure, km = kilometres, kV = kilovolt, MWh = megawatt-hour, USD = US dollar.

[a] Embedded assumptions include 40 years of asset life, 10 percent discount rate, load factor at 5,000 hours per year, operational costs as 2 percent of the CAPEX, and transmission loss at 2 percent.

Source: Hedgehock and Gallet (2010).

It can be observed that the levelised cost of electricity from wind and solar in Asia is mostly in the range of **US$0.05–US$0.10**/kilowatt-hour (kWh). This would especially be the case in the resource-rich areas of Mongolia. Long-distance transmission using high-voltage technologies increases the cost of transmission at less than US$0.01/kWh in most cases.[1] Thus, the cost of electricity from renewable sources from Mongolia could be cheaper than the electricity in China, Japan, and South Korea, under certain circumstances. However, such is subject to verification with careful modelling and accurate data, as the rest of this report reveals. Needless to say, the energy diversification effect will also add to the energy security of the receiving countries.

In addition, studies about power grid interconnection in other regions, such as Europe, Africa, and Southeast Asia, have all found net economic savings due to trade of electricity across the borders enabled by such interconnections. This study aims at identifying such economic rationale quantitatively for the NEA region.

[1] In the case of dedicated transmission line for power from wind and solar only, the actual utilisation will be lower than 5,000 hours per year, so the cost of transmission will be higher. In the case of very long distance transmission from Mongolia and Russia to South Korea and Japan, the cost of transmission could be 5–10 times higher, due to higher capital expenditure (CAPEX) and also higher transmission losses.

Chapter 2

Research Issues and Literature Review

2.1 Research Questions

Power grid interconnection among the NEA countries has been raised as an alternative energy solution from many years. Several studies have been done for different plans of such an interconnection, and the following key benefits were identified:

(i) It diversifies energy supply while creating new markets for the untapped energy resources.

(ii) It avoids building expensive peak power generation capacities and using expensive fossil fuel, such as liquefied natural gas.

(iii) It makes use of the wide geographical spread of these countries, which in turn incurs differing peak hours.

(iv) It results in a higher capacity to absorb intermittent renewable energy.

(v) The diversification and geographical proximity enhance energy security of all participating countries.

However, little progress has yet taken place in terms of interconnection projects and exchange or trade of electricity among the NEA countries. In view of this background, ERIA proposes studies to address the following research questions:

- What is the supply potential of PV and wind power generation?
- How is clean coal technology applied for coal power generation using domestic coal?
- What are the costs and benefits of power grid interconnection and the corresponding trade of electricity in the region?
- What are the priority projects that are optimised and stand as economically and financially feasible?
- What are the remaining technical, economic, and institutional barriers?
- How could standards, grid codes, and regulations for both bilateral and multilateral interconnection and trade of electricity be harmonised?

ERIA has established rich experiences in economic, institutional, and political issues on cross-border power grid interconnection, especially for Southeast Asia. ERIA takes a three-step approach to identify the economic, financial, institutional, and even political barriers through academic research. This approach allows ERIA to propose policies to address not only the physical level of grid interconnection but also the sophisticated design integration of electricity markets and regulatory institutions in Southeast Asia. Such is exemplified by the collaboration between the Heads of ASEAN Power Utilities/Authorities and ERIA in several research projects to establish institutional infrastructure in Southeast Asia for electricity market integration.

ERIA, therefore, is eager to bring in the experience and knowledge on power grid interconnection and electricity market integration into the NEA region, and to contribute to efficient progress in this regard.

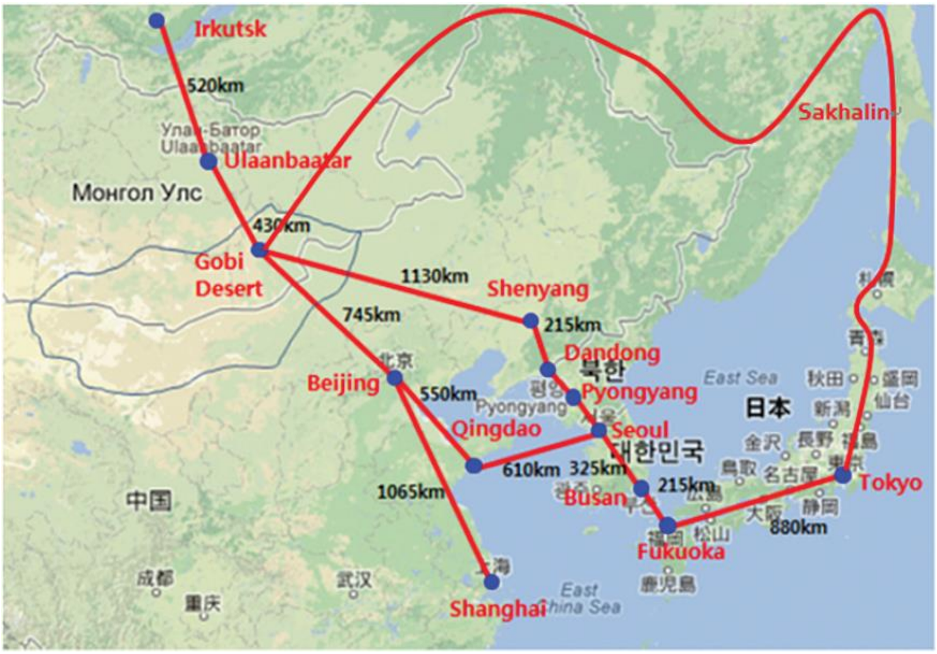
During the first year of research conducted on the issue, ERIA focused on the quantitative assessment of the economic benefits of power grid interconnection among the NEA countries. It addressed questions such as who will benefit and how much the benefit will be.

This study can be extended to shed light on the issue of whether the interconnection projects will be economically and financially feasible. Further studies can also indicate the optimal planning of the interconnection projects among NEA countries, especially in terms of routes and timing.

2.2 Literature Review

This study highlights several recent research progress made by other institutes and aims at building on these studies to push the NEA power grid interconnection further. The first report – the Energy Charter (2014) – was jointly produced by the Energy Charter Secretariat, Energy Economics Institute of the Republic of Korea, Energy Systems Institute of the Russian Federation, Ministry of Energy of Mongolia, Japan Renewable Energy Foundation, Fraunhofer Institute for Systems and Innovation Research, and Fraunhofer Institute for Solar Energy Systems. The report extensively presents the technological and legal challenges, thus comparing the costs and benefits of power grid interconnection in the NEA region under the concepts of Gobitec and Asian Super Grid (Figure 5). Specifically, it addresses the benefits and requirements for implementing the interconnection among Irkutsk in the north, Shanghai and Seoul in the south, and Tokyo in the east of the Asian Super Grid region with high voltage direct current (HVDC) transmission lines and massive scale deployment of wind and solar PV systems.

Figure 5: Gobitec and Asia Super Grid Concepts

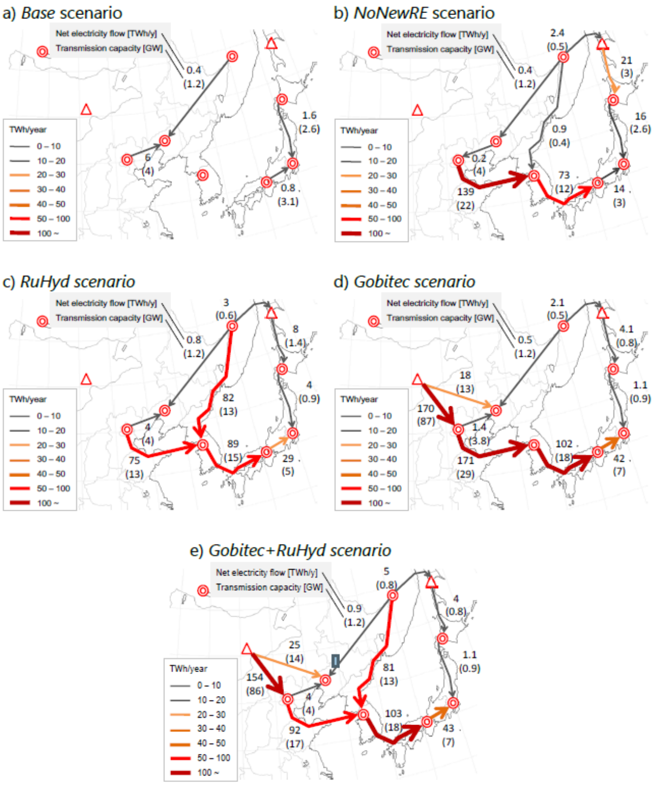


Source: Energy Charter (2014).

In general, the study implies that an HVDC with voltage higher than 1,000 kilovolt should be applied to the power grid interconnection in the region, considering the very long distances between connection points. The study also acknowledges the legislative and regulatory challenges and recommends the formation of an Energy Charter Treaty to facilitate the development of power grid interconnection in the region. Lastly, this study summarises the benefits of power grid interconnection in the region from several perspectives, including economic, social, and environmental aspects; job creation; poverty alleviation; and reduction of carbon dioxide emissions.

The other recent study was presented by APERC in 2015. This study mainly develops a multi-region power system model for NEA countries, based on linear programming. It is mainly a quantitative assessment of the economic viability of grid interconnections in NEA countries and renewable energy developments in the Gobi Desert and Eastern Russia. All grid interconnection scenarios indicate that economic benefits in the form of total cost reductions depend mainly on the fuel cost saved by shifting to cheaper fossil fuel or to renewables. Besides economic benefits, there is also the enormous potential for improving the environmental impact of the power sector in the region. Active trade situation is discussed in this study (Figure 6). An earlier study by APERC in 2004 also indicated the significant economic cost saving due to power grid interconnection, although at that time, the significant potential of renewables had not come into consideration. Thus, the APERC study in 2015 is a timely revisit of the issue, reflecting the new technology developments in renewable energy and in power transmission.

Figure 6: Cross-Boundary Electricity Flows of Electricity in Northeast Asia



Source: APERC analysis.

Chapter 3

Methodology

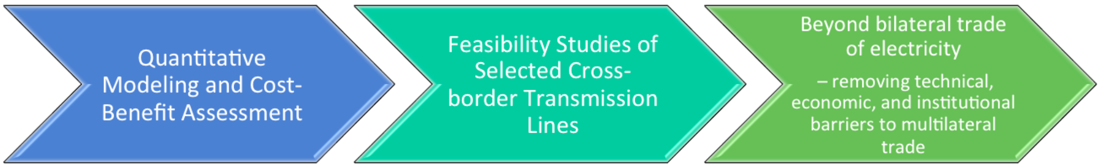
The initial step is to comprehensively survey the supply potential of solar PV, wind, coal, and natural gas power generation, and the supply and demand of electricity in China (north and northeast), Russia (east), Japan, Mongolia, and South Korea.

Figure 7: Geographical Scope of the Study

Source: Economic Research Institute for ASEAN and East Asia.

Based on ERIA's experience in the research for the ASEAN Power Grid, the three-step approach in carrying out the studies to address the research questions is proposed, as follows:

Figure 8: ERIA's Research Steps on Regional Power Grid Interconnection



Source: Economic Research Institute for ASEAN and East Asia.

(i) Conduct a quantitative modelling for cost–benefit assessment to identify an optimal overall vision for the Asian Super Grid. Depending on the availability of detailed data, the model not only addresses the overall economic rationale, it can also be used as a tool to identify future patterns of electricity trade and/or exchange, as well as priorities of specific cross-border transmission line project for power grid interconnection.

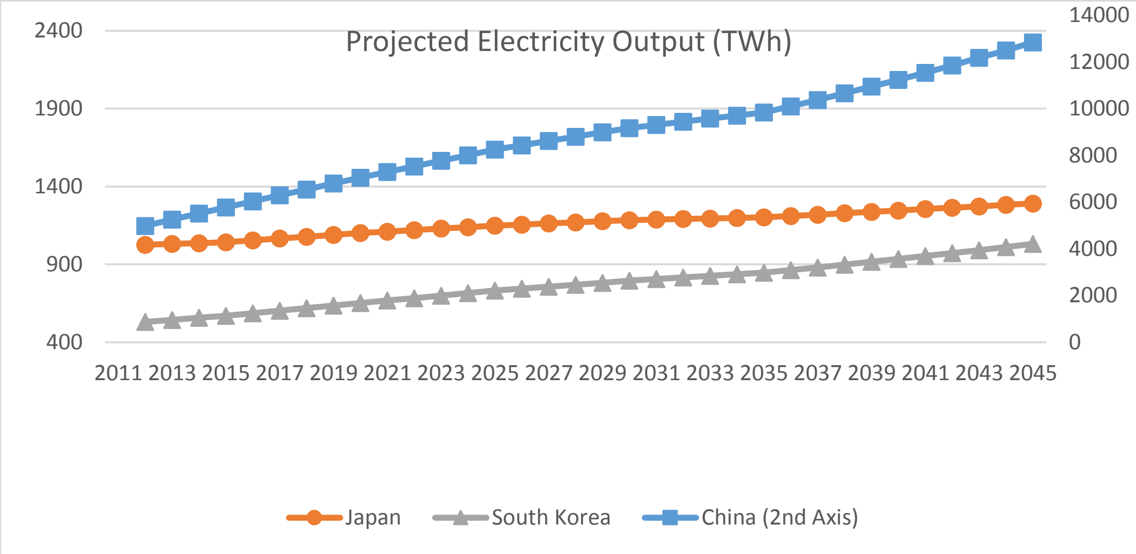
(ii) Carry out feasibility studies to assess in detail the financial feasibility of selected routes of cross-border transmission lines. This stage of study requires detailed data to estimate all costs of constructing and operating cross-border transmission lines in specific countries.

(iii) In view of the technical, regulatory, and other institutional barriers for multilateral power grid interconnection and electricity trade, conduct studies on how to harmonise these issues among the involved countries.

For the first year, ERIA will develop a quantitative model to assess the costs and benefits of power grid interconnection in the NEA region, based on cost minimisation for the region as a whole and dispatching of load by the order of merit. The model duly reflects the following key aspects of dynamics in the region's power sector in the next few decades or until 2045.

First is the growth of demand for electricity (Figures 9 and 10), and the daily and monthly patterns of demand for power (Figures 11 and 12). In the case of China and Russia, note that it is not realistic to model their overall demand for electricity. Thus, only the regional electricity demand and supply in northern China and Eastern Russia will be modelled. However, due to the unavailability of data, the growth rate for the projection of demand into the future will be assumed to be the same as the whole country, as the figures show.

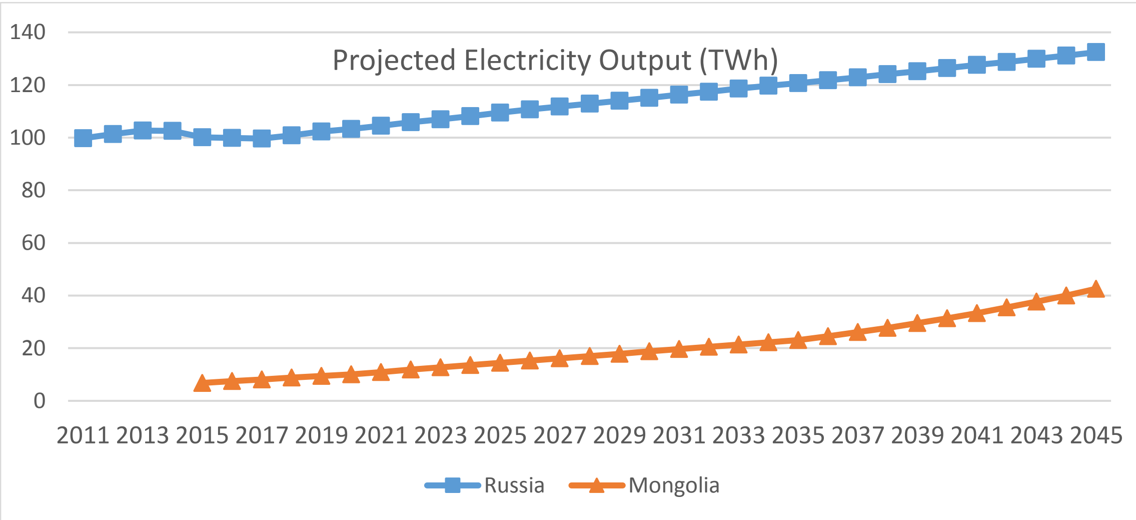
Figure 9: Projected Electricity Demand of China, Japan, and South Korea (TWh)



TWh = terawatt-hours.

Source: Economic Research Institute for ASEAN and East Asia.

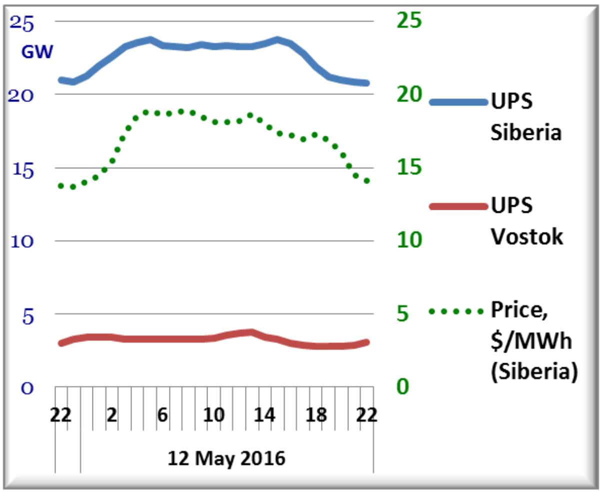
Figure 10: Projected Electricity Demand of Mongolia and Russia (TWh)



TWh = terawatt-hour.

Source: Economic Research Institute for ASEAN and East Asia based on Energy Information Administration and Asian Development Bank data.

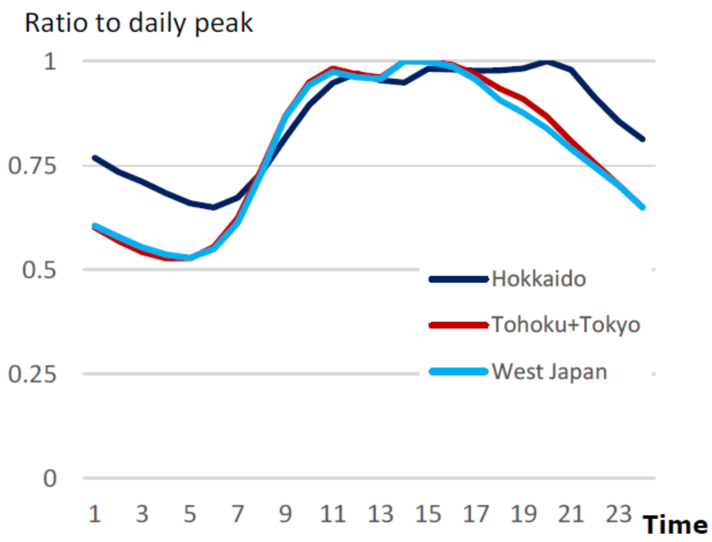
Figure 11: Hourly Consumption for UPS Siberia and UPS Vostok Prices in UPS Siberia



GW = gigawatt, MWh = megawatt-hour, UPS = uninterruptible power supply.

Source: ERIA Working Group.

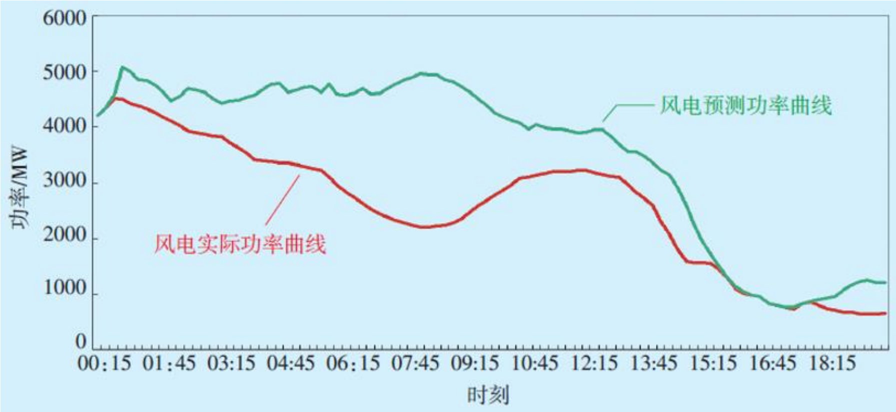
Figure 12: Typical Daily Load Curves during Summer in Japan



Source: ERIA Working Group.

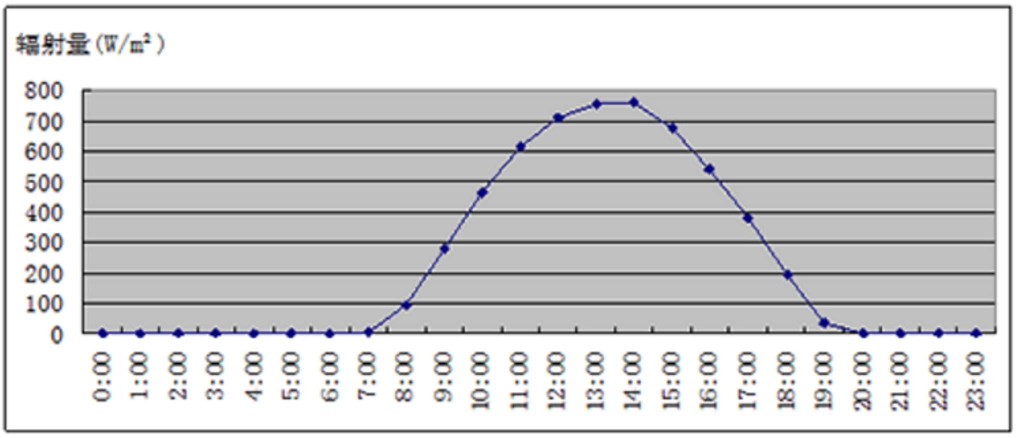
Second is availability of energy resources; daily and monthly patterns of changes in wind, solar, and hydro energy resources (Figures 13 and 14); costs of power generation of different technologies; and dynamics in the technological progresses in new and renewable energy.

Figure 13: Wind Generation Profile in Inner Mongolia*



* Vertical axis represents power in megawatts and horizontal axis represents the time of a day. Projected power profile is in green colour and actual power profile is in red colour.
Source: ERIA Working Group.

Figure 14: Solar Radiation Pattern in Baotou[a] in Summer



[a] City in Inner Mongolia.
Source: ERIA Working Group.

Third, the development of cross-border transmission capacity is imposed as constraints for the trade of electricity among NEA countries. The costs, losses, and financial viability of each transmission line are integrated into the model.

The value of transmission line should be determined by the cost of congestion in the grid and the idea of congestion charge is developed accordingly, which is the commercial value and the source of revenue of a transmission line in a competitive electricity market (Li and Chang, 2015). Figure 15 shows how the optimal amount of transmission capacity should be determined in a simplified case, which is a two-node electricity market.

The horizontal axis shows the power demanded in megawatts (MW) at nodes A and B, respectively, while the vertical axis shows the marginal cost of power generation in US$/megawatt-hour (MWh). Nodes A and B clearly have different levels of demand for power and different marginal cost curves of power generation. At node A, x MW of power is demanded, while at node B, y MW of power is demanded. Such renders different marginal costs of power at the two nodes, at levels corresponding to where points *a* and *b* are for nodes A and B, respectively.

If there is a transmission line to connect nodes A and B, node A could produce more than x MW and supply to node B at a lower marginal cost of power. If the transmission is free of cost, node A should supply as much as when its marginal cost of power is equal to that of node B at point e. This is known as the no congestion case. If transmission is costly, however, the optimal capacity of transmission is where the savings in the marginal cost (the difference between marginal cost of generation from node B and that from node A) is equal to the marginal cost of transmission capacity. Assuming that the marginal cost of transmission capacity is σ $/MWh, as shown in Figure 15, the optimal transmission capacity is determined at z MW.

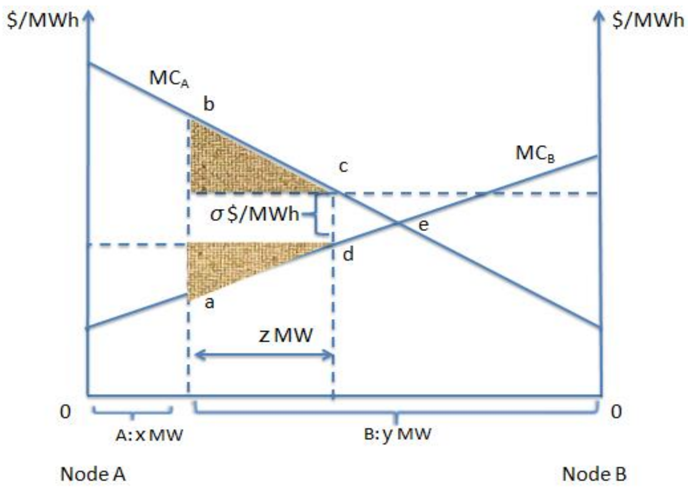
In this optimal case, σ $/MWh is equal to the congestion cost to the system and, therefore, the commercial value of the transmission line. In a competitive market, σ $/MWh should be charged accordingly for using the transmission line. The actual utilisation rate of the transmission line – which reflects how many MWh of electricity is transmitted – then determines if the investment in the transmission line could expect a reasonable return. This is usually where long-term, public–private partnership contracts come in to ensure the financial viability of the investment.

Such investments in the transmission capacity generate positive net savings to the system, which consists of nodes A and B. The savings are represented by the two shaded triangle areas in Figure 15. Such net savings prove the commercial viability of the new transmission line; otherwise, the line has no commercial value added and should not be built.

In a grid with multiple nodes, estimating the congestion cost is complicated and it is necessary to take a whole-grid/system approach. The network externality effect of new transmission lines further complicates the issue. This study takes a whole-grid/system approach in assessing the financial and commercial viability of new transmission projects with optimised pattern of power trade; the approach is also suitable for optimising the planning of new transmission capacities. First, the model integrates a 30-year-long contract for new transmission capacities, which ensures that the revenues collected over this period meet the commercial investors' requirement for a certain internal rate of return. Second, with costs of new transmission lines modelled as such, the system produces cost-minimisation planning for all power infrastructures – namely, power plants and cross-border transmission lines – to meet the growing demand for electricity in the region during the modelling period. Lastly, the minimised total system cost will be compared with the benchmark case where no new cross-border transmission line is built. Should the former be smaller than the latter, it means that net system savings resulted from the optimised planning for new cross-border transmission lines.

On net savings, recalling the simplified grid case as shown in Figure 15, power trade with the optimised planning of new transmission lines not only ensures investors' internal rate of return to be achieved but also delivers net system savings. This means that such a transmission investment plan stands both financially and commercially viable[2] as a whole. Should the net system savings be negative, it implies that the financial viability of the new projects with long-term contracts could not hold or be self-sustaining. This methodology is a major innovation and, thus, an important contribution to the literature. It enables a comprehensive assessment of financial viability of cross-border transmission investment plans from a systemic perspective.

Figure 15: Commercial Value of Transmission Line and Optimal Capacity

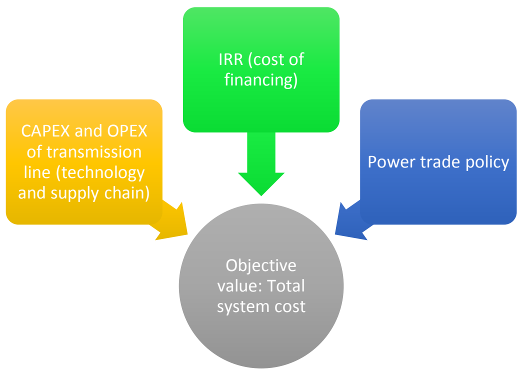


MC_A = Marginal Cost at Node A, MC_B = Marginal Cost at Node B, MW = megawatts, MWh = megawatt-hour.
Source: Li and Chang (2015).

[2] In other words, the new transmission lines have net commercial value, and the financial viability is not achieved at the expense of the total system but, in fact, by saving the total system costs.

Various policies are identified in the following subsections as key factors to the financial viability as shown in Figure 16. First, capital expenditure (CAPEX) and operating expenditure directly drive up the cost of transmission lines. Policies towards the introduction and absorption of new technologies could help reduce the cost. Other policies that help reduce lead time of the new transmission project by facilitating various logistics-related activities – such as project preparation, supply-chain coordination, construction, and grid connection – can also significantly reduce the cost of new transmission lines. Second, the financial costs of transmission line investments are very sensitive to the internal rate of return of investors, which in turn is sensitive to all project-related risks including market, technical, institutional, and political risks. Policies focusing on relieving these risks could help reduce the cost of transmission lines significantly. Third, power trade policies of countries in the region determine the demand for the import and export of power and the commercial value of the new transmission lines. In this study, such policies are modelled as the percentage of domestic power demand to be met through the trade of power with other countries.

Figure 16: Key Factors for Financial Viability of Cross-Border Transmission Lines



CAPEX = capital expenditure, IRR = internal rate of return, OPEC = operating expenditure.
Source: Li and Chang (2015).

Also in this study, scenarios were to be built where the cost of wind power, the solution and route of power grid interconnection, the financial cost of cross-border power transmission lines, and the cost of carbon vary to find under what circumstances the utilisation of renewable potential in the region, especially in Mongolia, could be maximised.

This study specifically models the power generation (from coal, diesel/ heavy fuel oil (HFO), natural gas, hydropower, small hydropower, geothermal, wind, solar PV, biomass, and nuclear) and transmission system, including cross-border transmission interconnection, of the five countries from 2013 to 2045. The model assumes that a regional carbon cost will start to be imposed on the power sector from 2020 in all NEA countries, reflecting the social cost of electricity and varying from US$1/ton to US$5/ton. The model also assumes that the cost of new renewable energy technologies – e.g. solar PV and wind power – will decline overtime while the operational cost, including fuel costs of conventional thermal such as coal, natural gas, and fuel oil generation will steadily increase overtime. More important, this model incorporates the intermittency and variation of solar PV and wind power through 24 hours in a day and four seasons in a year. The model thus optimises investment and utilisation of power infrastructure based on the optimal matching of intermittent renewable energy with the peak and non-peak demand of power through the day as well as through the season. The time difference between the five countries is also considered and modelled into the simulation. All cross-border transmission lines are assumed to apply heating, ventilating, and air conditioning (HVAC) technologies. Future studies could extend to include the option of HVDC.

Tables for the key data are presented in the appendix. It must be noted that due to lack of data inputs, wherever necessary, reasonable but still arbitrary assumptions have to be made. The research team looks forward to future research opportunities to improve the data and to deliver more solid analysis and accurate results.

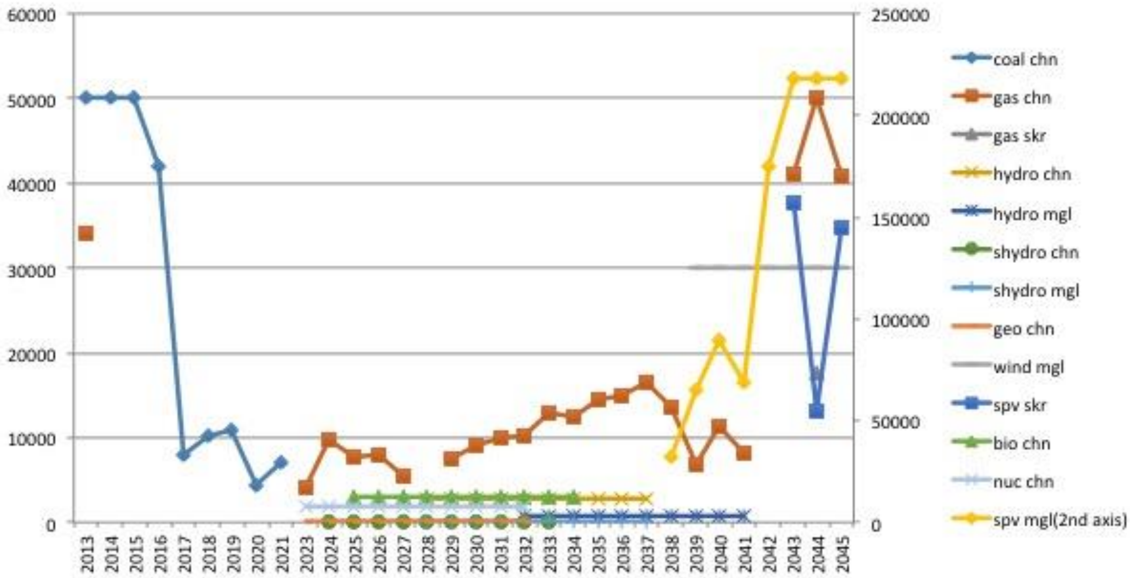
Chapter 4

Key Findings and Policy Implications

4.1 Key Findings

A linear programming model was used with the objective function of minimising the system cost of supplying power and electricity demand of all countries covered in the model. As explained in Section 3, the model achieves this by duly reflecting the cost of generation capacity, the cost of operation, and the costs and losses of transmission. By integrating the daily and monthly demand patterns for power and the supply of wind, solar, and hydropower in the countries involved, the model also works to optimise the dispatch of loads to various generation and transmission capacities in the region. Based on such considerations, the optimal plan for developing generation and cross-border transmission capacities is developed for the region. These are the key results of this model and could be used as reference in formulating relevant policies to encourage the development of power grid interconnection and even electricity market integration in the region. The following scenario is built on the assumption that the financial cost (or the required rate of return to investment) of cross-border transmission lines is heavily subsidised, and is as low as 3 percent only, and that the cost of wind power generation from Mongolia is 30 percent lower than that of China.

Figure 17: Power Generation Capacity Development with Power Grid Interconnection
(MW)



bio = biomass, chn = China, coal = coal, gas = natural gas, geo = geothermal, hydro = large hydropower, mgl = Mongolia, MW = megawatt, nuc = nuclear, shydro = small hydropower, skr = South Korea, spv = solar PV, wind = wind.
Source: Economic Research Institute for ASEAN and East Asia.

Figure 17 presents the optimal development plan of various new power generation assets in NEA countries. Some interesting observations include the following:

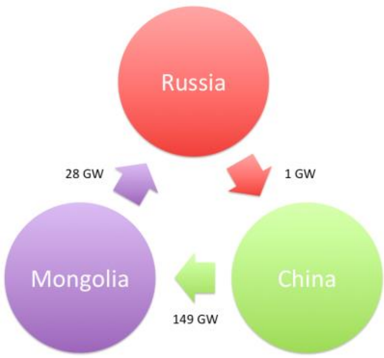
(i) Coal-fired power plants will continue to be developed in northern and northeast China until 2021.

(ii) Natural gas and hydropower dominates the development between 2023 and 2038.

(iii) After 2038, solar PV and wind will be developed on a massive scale.

The development of new cross-border power transmission capacities is mainly driven by the development of new renewables, namely, solar PV and wind, after 2038. As indicated by Figure 18, the new capacities will be concentrated in the China–Mongolia and Russia–Mongolia routes. Unfortunately, due to the high cost and high loss of power transmission to South Korea and Japan, no cross-border interconnection is envisioned to be developed to connect to these two countries during the model period 2013–2045. Such is also partly due to the saturated demand for power in Japan.

Figure 18: Cross-Border Power Grid Interconnection Capacities required by 2045[a]



[a] Arrows do not indicate the direction of trade flow. This figure indicates the capacity of interconnections only.
GW = gigawatts.
Source: Economic Research Institute for ASEAN and East Asia.

The above results are derived from one scenario; yet many possibilities exist for future scenarios. The uncertainties about the future comes from nuclear energy policies, environment and carbon emission policies, technological progress in new renewables, energy storage, high-efficiency power transmission, and changes in the demographic and economic structure of NEA countries (such as urbanisation, adoption of electric transport systems, and automation of production and application of robotics). Thus, further studies in this regard may deliver more optimistic and more aggressive results on how power grid interconnection, together with new renewable energy potentials, should be developed in this region.

4.2 Policy Implications

Large-scale interconnections among China, Mongolia, and Russia are identified as needed and feasible in almost all scenarios. Savings in the total system cost of all countries vary at around US$500 billion in total in about 30 years as a net present value, compared to the case of no power grid interconnection and, thus, no trade of electricity. This is equivalent to about 10 percent of total system cost for all countries involved. On the environment side, some 4 billion total tonnes of carbon dioxide emissions could be reduced during the same period.

Solar PV, which has a better match with peak power demand, appears to be more competitive than wind power and to be developed on a large scale in Mongolia starting 2033 or 2038, depending on the scenario.

According to the scenario results with varying assumptions, the cost of electricity from wind power needs to be 30 percent lower in Mongolia compared to neighbouring countries, especially China, for wind power to be competitive and developed after 2039. The complementary development of pump storage, battery storage, and smart grid may help improve the competitiveness of wind power.

Considering the massive scale of investment required for both renewable generation capacities and cross-border power transmission lines among NEA countries, collaborative, open, and transparent foreign investment policies – especially for the power sector – are a prerequisite to realise power grid interconnection in the region.

Considering that China, Japan, and South Korea have already set domestic targets for renewable power generation capacity and share in total electricity generation, the demand for renewable power (both solar and wind) generated from Mongolia may come even later than currently estimated. NEA countries, thus, may need to coordinate policies on renewable energy to avoid restricting the source of renewables from domestic only; that is, the environmental benefits of imported electricity from renewable sources should be counted in setting relevant domestic policies among importing countries.

Considering the high costs of building dedicated cross-border power transmission lines among the NEA countries, policies that encourage developing robust domestic power transmission network and allowing near-the-border type of power grid interconnection with neighbouring countries may be the most beneficial way in this region.

Last but not least, power grid interconnection enhances the energy supply security in the region, as it improves diversity of sources and means of supply to each participating country.

Chapter 5

Conclusions

This research report analyses the costs and benefits of power grid interconnection in the NEA region, covering north and northeast of China, Japan, South Korea, Mongolia, and East Russia. Based on such analysis, the research team drew several important observations on the feasibility and optimal plans of power infrastructure development for power grid interconnection in the region. Policy implications were also drawn based on these observations. The research team strongly believes that these findings and policy implications are complementary to the existing literature on power grid interconnection in the NEA region.

For future research, the key question would focus on what policies and how such policies could more effectively promote and accelerate the development of power grid interconnection and renewable energy in the region. Specifically, the following issues should be considered:

(i) analyse the impacts of the development of pump storage, battery storage, and smart grid in the region;

(ii) analyse the impacts of ultra-high voltage power transmission technologies;

(iii) conduct case-by-case economic and financial analyses on the feasibility of selected power plants/farms and power transmission interconnections; and

(iv) discuss the possibility of interconnected and integrated electricity market in the region, especially on addressing the institutional and regulatory barriers.

The impact of clean coal technology should also be further studied, as it is almost sure that as the technology matures and costs get lower, it can potentially change the fuel mix of power generation in the region while contributing significantly to decreasing greenhouse gas emissions from the power sector.

References

Asia Pacific Energy Research Centre (APERC) (2004), *Electric Power Grid Interconnection in the APEC Region*. Tokyo: APERC, Institute of Energy Economics, Japan.

Asia Pacific Energy Research Centre (APERC) (2015), *Electric Power Grid Interconnection in Northeast Asia: A Quantitative Analysis of Economic and Environmental Benefits*. Tokyo: APERC, Institute of Energy Economics, Japan.

Energy Charter (2014), *Gobitec and the Asian Supergrid for Renewable Energy Sources in Northeast Asia.* Available at: http://www.energycharter.org/what-we-do/investment/investment-thematic-reports/gobitec-and-the-asian-supergrid-for-renewable-energy-sources-in-northeast-asia-2014/ (accessed 16 May 2016).

Hedgehock, J. and X. Gallet (2010), 'Facilitating Regional Power Trading and Environmentally Sustainable Development of Electricity Infrastructure in the Greater Mekong Subregion', ADB workshop presentation slides, 29 Sept. –1 Oct. 2010, Shangri-La Hotel, Bangkok, Thailand. Available at: International Renewable Energy Agency (IRENA) (2015), *Renewable Power Generation Cost in 2014*. Abu Dhabi, UAE. http://www.irena.org/documentdownloads/publications/irena_re_power_costs_2014_report.pdf (accessed 16 May 2016).

Li, Y. and Y. Chang (2015), 'Infrastructure Investments for Power Trade and Transmission in ASEAN + 2: Costs, Benefits, Long-term Contracts and Prioritized Developments', *Energy Economics*, 51(September 2015), pp. 484–492. Available at: http://dx.doi.org/10.1016/j.eneco.2015.08.008 (accessed 16 May 2016).

Appendix

Data Inputs

Table A1: Current Power Generation Capacity (MW)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
Coal	233,369	11,620	20,780	16,150	1,050	26,273.6
Diesel/HFO	0	16,166	11,374	0	0	2,950
Natural gas	2,109	31,353	37,797	16,150	18.4	27,296
Hydro	13,595	8,383	12,140	28,600	0	1,644
Small hydro	11	156	141	0	15.05	122.8
Geothermal	4.2	264	219	3.6	0	0
Wind	34,509	1,424	1,434	0	50	641.5
Solar PV	194	8,143	14,916	15.2	0.88	1,894.2
Biomass	0	1196	1361	0	0	500
Nuclear	0	19,056	25,208	48	0	20,716

HFO = heavy fuel oil, MW = megawatts, PV = photovoltaic.
Source: Authors.

Table A2: Load Factor

	North China (%)	Japan (East) (%)	Japan (West) (%)	East Russia (%)	Mongolia (%)	South Korea (%)
Coal	85	80	80	70	70	80
Diesel/HFO	85	50	50	85	85	50
Natural gas	85	74	74	85	85	74
Hydro	52	60	60	52	52	60
Small hydro	30	45	45	30	30	45
Geothermal	85	83	83	85	85	83
Wind	30	25	25	30	30	25
Solar PV	11	13	13	11	11	13
Biomass	85	87	87	85	85	87
Nuclear	85	80	80	85	85	80

HFO = heavy fuel oil, PV = photovoltaic.
Source: Authors.

Table A3: Current Capital Cost of Generation Capacity (million US$/MW)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
Coal	2.079	2.526	2.526	2.4948	2.4948	2.2734
Diesel/HFO	1.139	1.995	1.995	1.3668	1.3668	1.7955
Natural gas	1.054	1.202	1.202	1.2648	1.2648	1.0818
Hydro	4.933	6.385	6.385	5.9196	5.9196	5.7465
Small hydro	2.3	8.979	8.979	2.76	2.76	8.0811
Geothermal	6.18	7.882	7.882	7.416	7.416	7.0938
Wind	2.187	3.919	3.919	2.6244	1.5309	3.52665
Solar PV	1.5	3.283	3.283	1.8	1.05	2.95425
Biomass	4.027	3.971	3.971	4.8324	4.8324	3.5739
Nuclear	5.0	4.083	4.083	6.0	6.0	3.6747

HFO = heavy fuel oil, MW = megawatts, PV = photovoltaic.
Source: Authors.

Table A4: Current Operational Cost including Fuel Costs (US$/MWh)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
Coal	31.86	87.7	87.7	38.2	38.2	78.9
Diesel/HFO	229.75	58	58	275.7	275.7	52.2
Natural gas	43	62	62	51.6	51.6	55.8
Hydro	4.32	80	80	5.2	5.2	72
Small hydro	4.68	602	602	5.6	5.6	541.8
Geothermal	14.23	314	314	17.1	17.1	282.6
Wind	20.58	135.5	135.5	24.7	14.4	121.95
Solar PV	19.52	34.5	34.5	23.4	13.7	31.05
Biomass	28.87	257	257	34.6	34.6	231.3
Nuclear	30	173	173	36.0	36.0	155.7

HFO = heavy fuel oil, MWh = megawatt-hour, PV = photovoltaic.
Source: Authors.

Table A5: Growth Rate of Capital Cost of Generation Capacity

	North China (%)	Japan (East) (%)	Japan (West) (%)	East Russia (%)	Mongolia (%)	South Korea (%)
Coal	3.0	3.0	3.0	3.0	3.0	3.0
Diesel/HFO	3.5	3.5	3.5	3.5	3.5	3.5
Natural gas	2.5	2.5	2.5	2.5	2.5	2.5
Hydro	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Small hydro	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Geothermal	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Wind	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0
Solar PV	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0
Biomass	0.8	0.8	0.8	0.8	0.8	0.8
Nuclear	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5

HFO = heavy fuel oil, PV = photovoltaic.
Source: Authors.

Table A6: Growth Rate of Operational Cost of Generation Capacity

	North China (%)	Japan (East) (%)	Japan (West) (%)	East Russia (%)	Mongolia (%)	South Korea (%)
Coal	3.0	3.0	3.0	3.0	3.0	3.0
Diesel/HFO	3.5	3.5	3.5	3.5	3.5	3.5
Natural gas	2.5	2.5	2.5	2.5	2.5	2.5
Hydro	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Small hydro	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Geothermal	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
Wind	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0
Solar PV	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0
Biomass	0.8	0.8	0.8	0.8	0.8	0.8
Nuclear	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5

HFO = heavy fuel oil, PV = photovoltaic.
Source: Authors.

Table A7: Life of Generation Capacities (Years)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
Coal	40	40	40	40	40	40
Diesel/HFO	30	30	30	30	30	30
Natural gas	30	30	30	30	30	30
Hydro	80	80	80	80	80	80
Small hydro	50	50	50	50	50	50
Geothermal	30	30	30	30	30	30
Wind	25	25	25	25	25	25
Solar PV	25	25	25	25	25	25
Biomass	25	25	25	25	25	25
Nuclear	40	40	40	40	40	40

HFO = heavy fuel oil, PV = photovoltaic.
Source: Authors.

Table A8: Maximum Additional Generation Capacity Allowed (MW)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
Coal	No limit	No limit	No limit	No limit	No limit	No limit
Diesel/HFO	No limit	No limit	No limit	No limit	No limit	No limit
Natural gas	No limit	No limit	No limit	No limit	No limit	No limit
Hydro	28,000	0	0	0	6,300	0
Small hydro	3.6	539	1,000	0	314.8	0
Geothermal	1,000	394	4,929	0	0	0
Wind	98,000	1,715	10,000	0	300,000	25,000
Solar PV	100,000	17,800	50,000	0	2,180,000	450,000
Biomass	30,000	163	200	0	0	0
Nuclear	18,000	0	0	0	0	44,000

HFO = heavy fuel oil, MW = megawatts, PV = photovoltaic.
Source: Authors.

Table A9: Existing Transmission Capacity (MW)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
North China	No limit	0	0	800	120	0
Japan (East)	0	No limit	1,200	0	0	0
Japan (West)	0	1,200	No limit	0	0	0
East Russia	800	0	0	No limit	230	0
Mongolia	120	0	0	230	No limit	0
South Korea	0	0	0	0	0	No limit

MW = megawatts.
Source: Authors.

Table A10: Capital Cost of Cross-Border Transmission Capacity (US$ per MW*km)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
North China	0	1,086	1,086	1,086	1,086	1,086
Japan (East)	1,086	0	1,086	1,086	1,086	1,086
Japan (West)	1,086	1,086	0	1,086	1,086	1,086
East Russia	1,086	1,086	1,086	0	1,086	1,086
Mongolia	1,086	1,086	1,086	1,086	0	1,086
South Korea	1,086	1,086	1,086	1,086	1,086	0

km = kilometre, MW = megawatts.
Source: Authors.

Table A11: Operational Cost of Cross-Border Transmission Capacity (US$ per MW*km per annum)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
North China	0	2	2	2	2	2
Japan (East)	2	0	2	2	2	2
Japan (West)	2	2	0	2	2	2
East Russia	2	2	2	0	2	2
Mongolia	2	2	2	2	0	2
South Korea	2	2	2	2	2	0

km = kilometre, MW = megawatts.

Source: Authors.

Table A12: Length of Required Cross-Border Transmission Line (km)

	North China	Japan (East)	Japan (West)	East Russia	Mongolia	South Korea
North China	0	1,500	900	300	300	600
Japan (East)	1,500	0	50	600	3,000	550
Japan (West)	900	50	0	1,500	2,400	300
East Russia	300	600	1,500	0	300	300
Mongolia	300	3,000	2,400	300	0	1,600
South Korea	600	550	300	300	1,600	0

km = kilometre.

Source: Authors.

Table A13: Expected Rate of Power Losses along the Cross-Border Transmission Line

	North China (%)	Japan (East) (%)	Japan (West) (%)	East Russia (%)	Mongolia (%)	South Korea (%)
North China	0	8	5	8	5	5
Japan (East)	8	0	3	5	8	5
Japan (West)	5	3	0	8	8	3
East Russia	8	5	8	0	3	5
Mongolia	5	8	8	3	0	8
South Korea	5	5	3	5	8	0

Source: Authors.