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Electric power grid interconnections in Northeast Asia: A quantitative analysis of opportunities and challenges

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HIGHLIGHTS

- We developed a multi-region power system model of Northeast Asia (NEA).
- The model considers renewable energy in the Gobi Desert and eastern Russia.
- Expanding renewables for export brings CO_2 reductions and fuel cost savings in NEA.
- Economic benefits due to reduced total costs are modest.

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ABSTRACT

Power grid interconnection has gained attention in Northeast Asia (NEA) as a means to build an economically efficient power system and to effectively utilize renewable energy, such as wind and solar resources in the Gobi Desert and hydro resources in Eastern Russia.

In order to quantify the potential economic and environmental benefits from connecting power grids and developing renewables in NEA, we build an NEA-wide multi-region power system model using linear programming techniques. Our analysis considers power system characteristics, such as the seasonal and daily electric load curves of the various NEA economies.

Compared to a “no grid extension” scenario, increased access to renewables contributes significantly to emissions reductions and fuel cost savings. However, the results imply modest benefits in lowering total cost because of the large initial investments needed in developing the renewables and the transmission lines. These limited total cost savings are likely to pose an implementation challenge for NEA grid interconnections. Our results also suggest that grid interconnections become more economically attractive in higher fuel price or lower initial cost situations. The relevant planning organizations should carefully consider the initial cost and future fuel price trends when considering how to interconnect power girds in an economical manner.

1. Introduction

Over the past two decades, electric power grid interconnections have gained attention in Northeast Asia (NEA), an area that we define as four Asia Pacific Economic Cooperation (APEC) economies—China, Japan, the Republic of Korea (Korea), and Russia—and two non-APEC economies—Mongolia and the Democratic People’s Republic of Korea (DPRK). Various interconnection schemes have been proposed for NEA (Streets, 2003; Yun and Zhang, 2006; Hippel et al., 2011). Yet, while technically feasible, these cooperative proposals have been hampered by factors such as existing national policies of energy self-sufficiency and the sometimes-volatile diplomatic and political situation in the region. Thus, the only existing cross-border power cooperation projects are small in scale, linking Russia to Mongolia, Russia to China, and China to the DPRK.

However, several recent regional events, including the Fukushima nuclear disaster in Japan, the power shortage and rolling blackouts in Korea, and increased concern regarding air pollution in China, have made power grid interconnections potentially more

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attractive. Several organizations have proposed multilateral power grid interconnection concepts in NEA, i.e., *Asia Super Grid (ASG)* and *Gobitec*, with a focus on developing the abundant renewable resources in the Gobi Desert and Eastern Russia and on building a more resilient and economically efficient power system (KEPCO, 2014; Energy Charter et al., 2014; Graaf and Sovacool, 2014). The wind and PV potential in Mongolia has been estimated at 1100 GW and 1500 GW, respectively (Elliott et al., 2001; Energy Charter et al., 2014), and economically feasible hydropower potential in Eastern Russia is estimated at 690 TWh/yr (estimated by European Bank for Reconstruction and Development, see IEA (2003)).

There have been some previous economic analyses on connecting power grids in various parts of the world: Southern Africa is the focus of Bowen et al. (1999), Europe of Lilliestam and Ellenbeck (2011) and Schaber et al. (2012) and Southeast Asia of Chang and Li (2013) and Matsuo et al. (2015). Among those studies, Schaber et al. (2012) conducted a detailed analysis on the impacts of grid interconnections on regional renewable energy utilization. They employed a Europe-wide power system model with a detailed temporal resolution (hourly time slice for six representative weeks), which appropriately reproduce the actual power generation, electricity prices and cross-border power transportation.

The economics of power grid interconnection in the NEA region have also been investigated. Cost–benefit analyses of grid interconnection scenarios in NEA were performed by Hippel (2001), Podkovalnikov (2002), Lee et al. (2005), Chung and Kim (2007), Energy Charter et al. (2014) and Skoltech (2015). Analyses of power system reliability were conducted by Choi et al. (2006) and Yoon (2007). Yet, to our knowledge, few studies have focused on the whole of NEA and analyzed the impacts of grid interconnections with a focus on renewables both in the Gobi Desert and Eastern Russia considering power system characteristics (e.g. load curves, generation dispatch). Except for Energy Charter et al. (2014) and Skoltech (2015), the studies listed above covered only a part of NEA (three to four out of the six economies) and did not consider renewable energy in the Gobi Desert. Skoltech (2015) also does not take into account renewables in the Gobi Desert. As for Energy Charter et al. (2014), they proposed to install 50 GW of wind and 50 GW of solar photovoltaics (PV) in the Gobi Desert, and estimated the supply costs to other NEA economies. However, their cost assessment did not consider regional power system characteristics, such as the load curves of the importing economies and the seasonal and diurnal output variation of the solar and wind power from the Gobi Desert.

Thus, we developed a multi-region power system model, which covers the whole of NEA, in order to quantitatively evaluate the potential benefits of, and barriers to, power grid interconnection and expansion of renewable energy for export. The model seeks to minimize overall system cost, considering seasonal and daily characteristics of electric load of each region and the output patterns of renewables in the Gobi Desert. This model can determine cost-optimal grid expansion and cross-boundary power flows, as well as generation dispatch. Also, nodal marginal pricing gives us some implications for regional electricity prices. We believe that our analysis contributes to understanding of the costs and benefits of grid interconnection and large-scale renewable energy utilization in NEA from a systems viewpoint.

This paper proceeds as follows: Section 2 gives an overview of the multi-region power system model and the scenario assumptions; Section 3 presents the simulation results and discusses the economic feasibility of grid interconnections, as well as a sensitivity analysis on initial cost and energy prices; and Section 4 summarizes major conclusions and implications, and then proposes a future research agenda.

2. Methods

2.1. Overview of the multi-region power system model

We developed a multi-region power system model using linear programming techniques. Fig. 1 is a schematic diagram of this model. The model aims to minimize a single-year overall system cost, consisting of the annualized initial cost, operation and maintenance (O&M) cost, fuel cost and carbon cost for the whole NEA under various technical and political constraints. Hence, the NEA economies are assumed to cooperate fully to achieve the regional optimization. A detailed mathematical description of the model is provided in Appendix A.1. Validation of the model is discussed in Appendix A.2.

A capital recovery factor is used to annualize initial investments in generation, storage and cross-boundary transmission facilities. The assumed discount rate is 3% and lifetime assumptions are discussed in Sections 2.3.2 and 2.3.5. O&M cost includes both fixed and variable O&M cost. Fixed O&M cost, which is incurred even if the plant is not operated (i.e., landowner cost), is assumed to be in proportion to capacity, while variable O&M cost (i.e., consumables) varies with generated electricity. Carbon cost in this study considers only direct emissions from fuel combustion.

The cost of generation includes initial cost, fixed and variable O&M cost, fuel cost and carbon cost. The cost of cross-boundary transmission lines includes initial cost and fixed O&M cost. Power trade is selected by the model if its benefit (usually the savings in generation cost) is larger than the cost of cross-boundary transmission lines.

This model is formulated in a consistent way in General Algebraic Modeling System (GAMS) software. There are 75,000 equations or constraints and 38,000 endogenous variables. For our modeling work, we referred to the detailed modeling approach in Schaber et al. (2012), Komiyama and Fujii (2014) and Komiyama et al. (2015), but due to data availability we selected the temporal and geographical resolution explained below.

Regarding the temporal resolution, the model considers the hourly load curves of typical days for five seasons (Summer-peak, Summer-average, Winter-peak, Winter-average, and Intermediate) in order to model the diversity of seasonal and daily load variation among the regions. Thus, in each node, one calendar year is decomposed into 120 time segments (=24 h per day × 1 representative day per season × 5 seasons per year).

As for the geographical resolution, we divide NEA into ten nodes (Fig. 2), represented by seven city nodes (round markers) and three supply nodes (triangle markers). City nodes have electricity demand and power supply facilities, while supply nodes have only power supply facilities to export electricity. Endogenous capacity additions are allowed in both types of nodes. Five of the city nodes correspond to power grids or power service areas: North China grid (CH-N); China Northeast grid (CH-NE); Japan Hokkaido area (JP-H); Korea (KR), and Russia Far East power

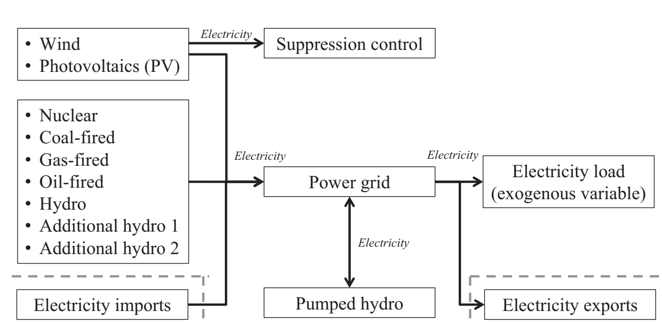

Fig. 1. Schematic diagram of the multi-region power system model.