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Doctoral Dissertation

Comprehensive analysis of cross-border electricity trade between Japan and South Korea's electric power companies

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Comprehensive analysis of cross-border electricity trade between Japan and South Korea's electric power companies

By

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Submitted to the Department of Transdisciplinary Science and Engineering in fulfillment of the requirements for the Doctoral Degree of

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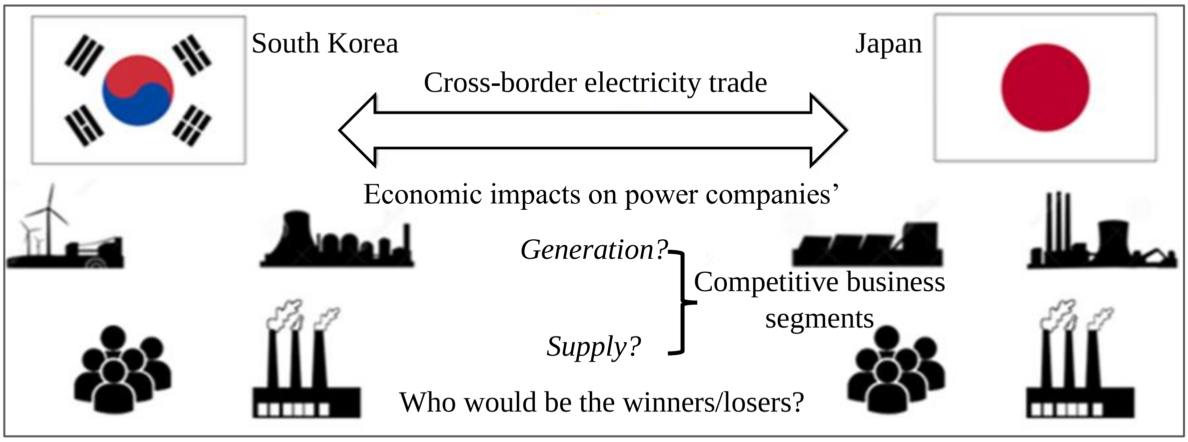
Abstract

In comparison to many regions worldwide, international power system interconnections have been less developed in Northeast Asia. In particular, Japan and South Korea are not interconnected with any neighboring countries despite previous works demonstrating that interconnecting these two countries should be technically feasible and economically profitable. In Japan, in addition to energy security concerns related to possible geopolitical tensions, the business structure of electric power companies and the fears about the impacts of international competition on their competitive generation and supply business segments slow down progress. This dissertation has mainly assessed the economic impacts of interconnecting with South Korea on Japanese electric power companies' competitive business segments using innovative and complementary research methodologies; quantitative analyses both empirical (comparison of power exchange prices) and theoretical (computer simulation of interconnected power systems), and qualitative analysis (survey of energy experts). The key finding of the quantitative analyses is that cross-border electricity trade would benefit the Japanese electric power companies under the current conditions. Moreover, the qualitative analysis has identified and explained threats and opportunities related to cross-border electricity trade in the context of a Japan-South Korea interconnection. From an environmental perspective, future work may evaluate more thoroughly the impacts of cross-border electricity trade on Japan and South Korea's recently announced 2050 carbon neutrality goals.

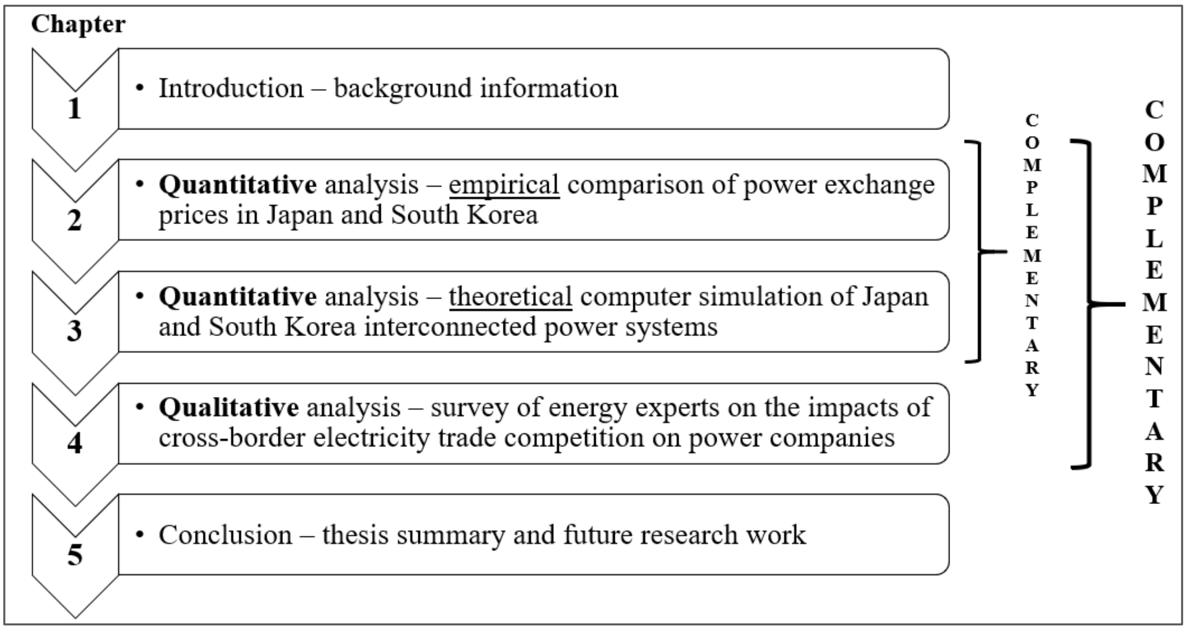
Keywords: Japan, South Korea, power companies, cross-border electricity trade, interconnection, competition

Graphical Abstract

Research questions:



Path to answers:



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Submitted to the Journal of Asian Energy Studies in August 2021; Zissler R, Cross JS. Japan's nuclear power 2030 projections unmet and replacement with international electrical interconnections.

Submitted to the 11th Solar & Storage Integration Workshop in August 2021; Zissler R, Wakeyama T, Cross JS. International electrical interconnection to unlock solar photovoltaic potential and accelerate progress towards carbon neutrality in Japan and South Korea [extended abstract accepted in June 2021].

List of Appendices

List of Abbreviations

CO_2: Carbon dioxide
EDF: Électricité de France
EPCO: Electric power company
GHG: Greenhouse gas
GW: Gigawatt
JEPX: Japan Electric Power Exchange
JPY: Japanese yen
KEPCO: Korea Electric Power Corporation
km: Kilometer
KPX: Korea Power Exchange
KRW: South Korean won
kWh: Kilowatt-hour
LCOE: Levelized cost of electricity
m: Meter
MOU: Memorandum of Understanding
MWh: Megawatt-hour
OCCTO: Organization for Cross-regional Coordination of Transmission Operators
PV: Photovoltaic
RE: Renewable energy
T&D: Transmission and distribution
TEPCO: Tokyo Electric Power Company
TSO: Transmission system operator
TWh: Terawatt-hour

Chapter 1:

Introduction

1.1 Cross-border electricity trade status, with a focus on Northeast Asia and Japan

1.1.1 Global developments

In many regions worldwide, international power system interconnections, which are physical electrical grid infrastructure enabling cross-border electricity trade, have been well developed. In Europe in 2018, for example, there were over 400 cross-border transmission lines [1] through which about 454 terawatt-hours (TWh), or almost 11% of the continent's total electricity production, were traded [2]. Cross-border electricity trade is also dynamic in North America, Central & South America, Africa, and Southeast Asia [3].

1.1.2 Situation in Northeast Asia

In comparison, cross-border electricity trade developments in Northeast Asia, defined as: China, Japan, Mongolia, Russia (far east), and South Korea, have been rather slow until now. Cross-border electricity trade only takes place between China, Mongolia, and Russia, and it is limited [4]. Japan and South Korea do not trade electricity with any of their neighboring countries, which are exceptional situations among developed economies, only shared by Australia, Iceland, and New Zealand (all island countries far away from land). The situation in Northeast Asia is all the more striking that this region hosts three of the world's top 10 largest national power systems: China #1, Japan #5, and South Korea #9 – which together accounted for more than one-third of the world's total electricity production in 2019 [5].

It has been recognized that in Northeast Asia implementing new international power system interconnections and reinforcing existing ones may provide three key benefits: (1) Economic, thanks to increased competition in electricity generation and supply thereby reducing electricity prices; (2) technical, thanks to the strengthening of electrical grid networks and electricity generation capacity sharing resulting in improved stability of power supply; and (3) environmental, thanks to electrical grid expansions indirectly supporting the adoption of low-cost renewable energy (RE) on a large-scale [4]. In the past decade, RE has established itself as one of the primary options, alongside energy efficiency, to advance sustainable economic development and environmental protection. A pathway that China, Japan, and South Korea are now all embracing having announced in 2020 their intentions to reach carbon neutrality, by 2050 for Japan and South Korea, and by 2060 for China [6].

Cross-border electricity trade is, however, sometimes considered with skepticism especially because of perceived energy security risks. Most notably, the fear of a unilaterally decided abrupt interruption supply of power can be of great concern. History has shown that this hypothesis cannot be completely ruled out, especially in regions destabilized by military conflicts (which are well beyond the scope of commercial conflicts) [7]. A more pragmatic approach should consider not only energy security risks related to international electrical interconnections, but also their energy security benefits, among which: backup supply in case of domestic shortage during emergency situations and energy procurement risk diversification.

In addition, it may be noted that in the case of bidirectional trade, interdependence should be an effective safeguard against a unilaterally decided abrupt interruption supply of power. Building trust is thus recognized as a prerequisite to the establishment of international electrical interconnections, and it is understood that this could be achieved by considering associated risks and benefits more broadly. Ultimately, if successfully implemented, it may even be envisioned that cross-border electricity trade could play an important role as a diplomatic bridge with the potential to dissipate possible geopolitical tensions.

The concept of international power system interconnections across Northeast Asia is not new. Over the past 20-25 years, several initiatives have been proposed: In 1998, Northeast Asian Electrical System Ties [8]; in 2009, Gobitec [9]; in 2011, Asia Super Grid [10]; and in 2016, Smart Energy Belt [11].

Fig. 1-1 [10] shows an illustration of one of these initiatives, the Asia Super Grid by Renewable Energy Institute, in which different Asian countries are interconnected from India to Japan crossing China, Mongolia, Russia, and South Korea for examples.

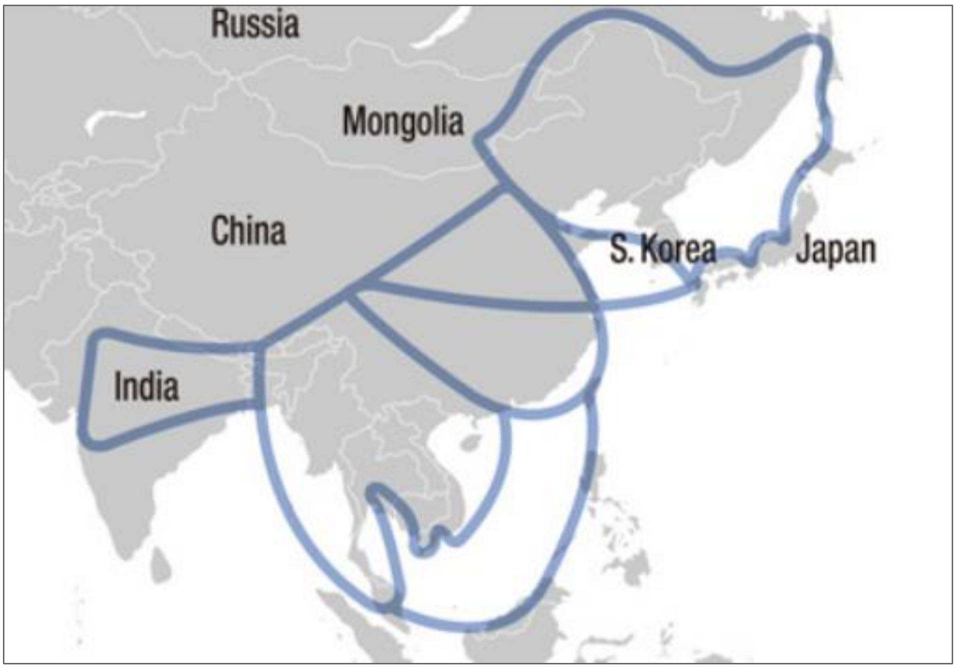


Fig. 1-1 Illustration of the Asia Super Grid initiative. *Courtesy of Renewable Energy Institute.*

All these initiatives have, however, achieved limited success to date. The slow progress may be explained by the challenges to overcome from planning to implementation, as well as problems with international diplomacy, which remains a hot topic in the region [12]. In 2016, nevertheless, a major milestone was reached when major companies from China (State Grid Corporation of China), Japan (SoftBank), Russia (Rosseti), and South Korea (Korea Electric Power Corporation (KEPCO)) signed a joint memorandum of understanding (MOU) to cooperate on research and planning for an interconnected power grid spanning Northeast Asia [13]. It is important to note that only the Japanese signatory to this MOU is not a major state-owned electricity transmission system operator (TSO). Indeed, SoftBank's business focuses largely on information technology and telecommunication services.

1.1.3 Situation in Japan

In Japan, the national energy policy is based on the principle of 3E+S: energy security, economic efficiency, environment + safety [14], to which international electrical interconnections can all contribute. However, Japanese policy makers reluctantly consider cross-border electricity trade primarily because of the fear of a unilaterally decided abrupt interruption supply of power from the interconnected counterpart, and to some extent unfounded domestic trade protectionism (i.e., there is no opposition to the participation of Japanese companies in overseas international electrical interconnection projects such as that between France and the United Kingdom in which Hitachi ABB Power Grids takes part in [15]).

Another important issue is the absence of a Japanese electricity TSO in the enterprise of establishing international power system interconnections. This slows down concrete progress in Japan and may even prevent the realization of such projects. Therefore, the participation of one or more Japanese TSOs is also imperative. Japanese TSOs are parts of larger electric power companies (EPCOs) – ten former regional monopolies in the regions of Chubu, Chugoku, Hokkaido, Hokuriku, Kansai, Kyushu, Okinawa, Shikoku, Tohoku, and Tokyo – even after the implementation in 2020 of legal unbundling (as a part of the national electricity system reform), separating in different companies the competitive business segments of generation and supply from the non-competitive business segment of transmission & distribution (T&D).

Fig. 1-2 [16] shows the example of Tokyo Electric Power Company (TEPCO)'s new business structure after unbundling. Despite being separated in different companies: Two power generation companies "TEPCO Fuel & Power" (focusing on fuel & thermal power) and "TEPCO Renewable Power" (focusing on RE power), one power T&D company "TEPCO Power Grid," and one electricity retail company "TEPCO Energy Partner," the competitive and non-competitive business segments are still all parts of only one holding company, "Tokyo Electric Power Company Holdings."

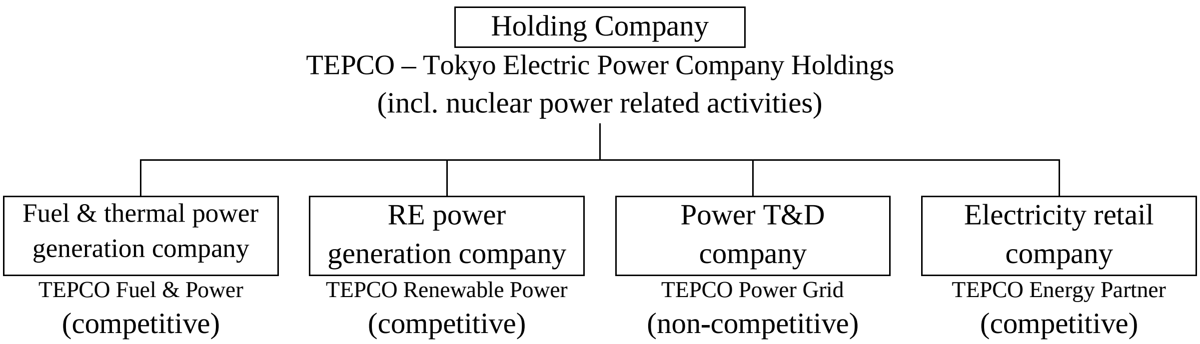


Fig. 1-2 Tokyo Electric Power Company simplified new business structure after unbundling.

Thus, the interest and involvement of these EPCOs as a whole should be stimulated. Since by definition the non-competitive business segment will not be impacted by competition resulting from international power system interconnections, the critical research contribution to provide is an assessment of the impacts of interconnecting with a neighboring country on the competitive business segments of Japanese EPCOs. This has not been done yet.

Various studies on international power system interconnections in Northeast Asia have been more or less recently conducted, including qualitative and qualitative analyses. Recently, between 2015 and 2018, in [17-19] the potential economic and environmental benefits from international power system interconnections in Northeast Asia have been analyzed at the regional level. About a decade earlier in 2006, in [20] the potential cost-effectiveness of an interconnection between Japan and South Korea has been revealed. And in [21] published in 2003, the power flows for an interconnection between these two countries have also been analyzed.

Despite the insights obtained from these studies, they do not comprehensively assess the current potential impacts of interconnecting with a neighboring country on the competitive business segments of Japanese EPCOs for three reasons: (1) In the case of recent studies, the absence of focus on a specific realistic starting point for interconnecting Japan; (2) in the case of earlier studies, the impossibility to include up-to-date key developments such as national energy policies and costs of electricity generation capacity; and (3) in the case of both recent and earlier studies, the absence of dedicated analyses on the impacts of international power system interconnections on competitive business segments of EPCOs.

This doctoral dissertation aims at filling in these gaps, and doing so providing answers on whether international power system interconnections would rather be opportunities or threats to Japanese EPCOs. The results reached should either reinforce their conservatism or encourage progressive action towards international power system interconnections.

In this quest for answers, this dissertation combines several original approaches. First and foremost, recognizing the key role power companies have to play in developing electrical interconnection projects, it seeks to understand what would be the impacts of cross-border electricity trade on the generation and supply segments of power companies. This is a step beyond the previous relevant research works mentioned above which focuses were limited at analyzing consequences for interconnected countries, not market participants. Then, having observed the fact that previous research works were only conducted based on theoretical computer simulations of power systems, this dissertation proposes a new conceptual approach complementary to theoretical calculations; an empirical comparison of power exchanges prices, which has not been explored before (Chapter 2). Finally, to provide the most comprehensive analysis possible, not only quantitative analyses are considered, but also an innovative qualitative analysis based on a survey of energy experts. This survey is a source of novelty because it focuses on the impacts of cross-border electricity trade in the framework of a Japan-South Korea interconnection, a topic not qualitatively covered until now.

Table 1-1 [17-21] briefly presents the most relevant previous research works considering international electrical interconnections between Japan and South Korea, and emphasizes the differences within the dissertation to highlight its originality.

Table 1-1 Previous research works considering international electrical interconnections between Japan and South Korea and differences with the doctoral student's dissertation.

Year	Authors	Main topics covered	Differences with the doctoral student's dissertation – highlighting originality
2018	Wan H, Cao Y, Wang W, Yang Q, Lee D, Ding T, Zhang H	Quantitative theoretical analysis presenting a model of dynamic economic dispatch and focusing on renewable energy integration. All Northeast Asian countries are considered to be interconnected. Only impacts on countries are studied.	In addition to a quantitative theoretical analysis, an innovative quantitative empirical analysis based on a comparison of power exchange prices is conducted (Chapters 2). Complementary to these quantitative analyses, a new qualitative analysis is also advanced (Chapter 4). Only considers a Japan-South Korea interconnection as a starting point. Impacts on countries as well as on market participants are considered.
2016	Otsuki T, Binti Mohd Isa A, Samuelson RD.	Quantitative theoretical analysis presenting a model to measure the potential economic and environmental benefits from international electrical interconnections. All Northeast Asian countries are considered to be interconnected. Only impacts on countries are studied.	Same as above
2015	Breyer C, Bogdanov D, Komoto K, Ehara T, Song J, Enebish N	Quantitative theoretical analysis presenting a model to measure the potential economic benefits from international electrical interconnections with a focus on renewable energy cost competitiveness. All Northeast Asian countries are considered to be interconnected. Only impacts on countries are studied.	Same as above
2006	Kanagawa M, Nakata T	Quantitative theoretical analysis presenting a model to measure the potential economic and environmental benefits from international electrical interconnections. Only considers a Japan-South Korea interconnection. Only impacts on countries are studied.	In addition to a quantitative theoretical analysis, an innovative quantitative empirical analysis based on a comparison of power exchange prices is conducted (Chapters 2). Complementary to these quantitative analyses, a new qualitative analysis is also advanced (Chapter 4). Impacts on countries as well as on market participants are considered.
2003	Lee S-S, Park JK, Moon S-I	Quantitative theoretical analysis presenting a model to measure power flows between interconnected countries. Notably considers a Japan-South Korea interconnection.	Same as above

The power system of Japan may be interconnected to those of Russia (in the east or north of Japan) and South Korea (in the west of Japan). However, an interconnection with Russia is currently unlikely because of evident diplomatic reason – no peace treaty has been ratified between Japan and Russia to formally end World War II hostilities – and because of persistent economic and energy security concerns. Comparatively, an interconnection with South Korea is more likely, even if diplomatic relationships between Japan and South Korea are not always set fair. Therefore, interconnecting Japan and South Korea should be prioritized as the decisive first step towards international power system interconnections in Japan.

As demonstrated in [22], complementarity of power systems is key for international power system interconnections to provide benefits. The second section of this chapter analyzes the complementarity of the power systems of Japan and South Korea, considering electricity generation mixes and electricity demand patterns.

1.2 Power system complementarities between Japan and South Korea

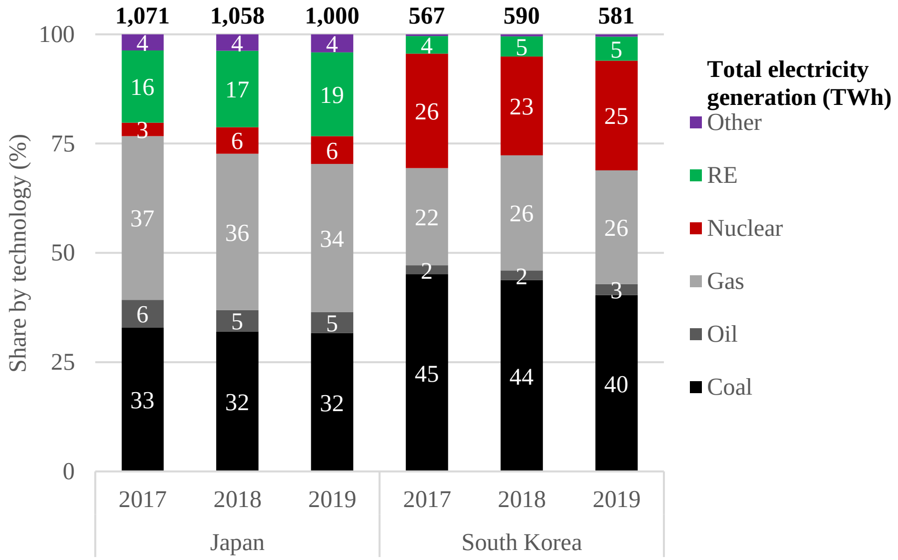
1.2.1 Complementarity of electricity generation mixes

There is an existing complementarity in terms of electricity generation mixes between the power systems of Japan and South Korea, and it is expected to continue to some extent at least in the medium-term (horizon 2030).

On next page, **Fig. 1-3** [23], [24] shows the electricity generation mixes of Japan and South Korea from 2017 to 2019[a]. In Japan in this period, most electricity (total gross electricity generation of about 1,000-1,100 TWh per year) was generated from gas (34-37%), coal (32-33%), and RE (16-19%). In South Korea during the same period, most electricity (total gross electricity generation of about 550-600 TWh per year) was generated from coal (40-45%), gas (22-26%), and nuclear (23-26%).

Although Japan and South Korea both heavily rely on coal and gas for electricity generation (each for roughly two-thirds of their total electricity generation), the most widely used fossil fuel differs between these countries. Japan is more dependent on gas (34-37%) and South Korea on coal (40-45%). Furthermore, when it comes to low-carbon electricity generation, whereas RE (16-19%) is mostly used in Japan, nuclear (23-26%) is mostly used in South Korea. Thus, the electricity generation mix of Japan is characterized by flexible (gas) and fluctuating (RE) electricity generation, and that of South Korea by baseload (coal and nuclear) electricity generation.

[a] Unless otherwise noted, throughout this dissertation data for Japan are reported on a fiscal year basis, from April 1st to March 31st.

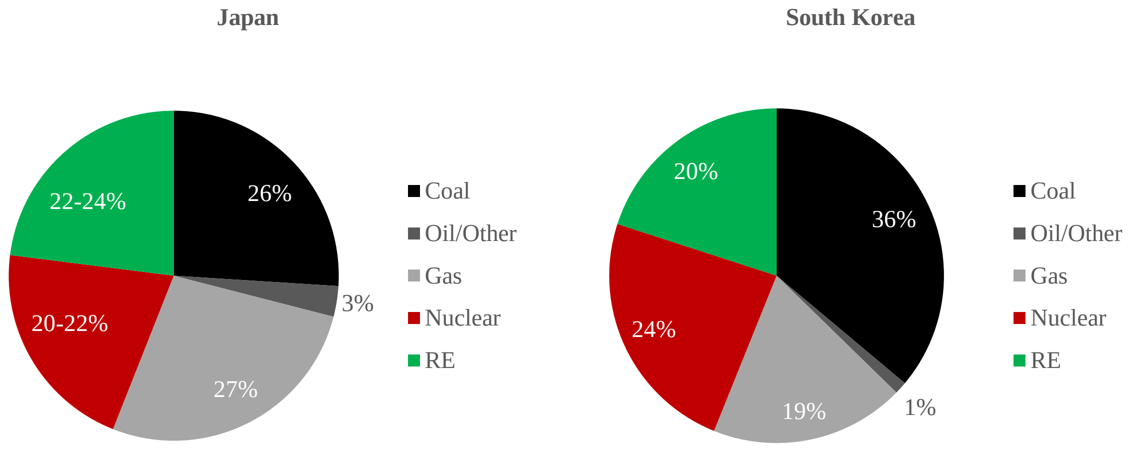


Notes: "RE" includes biofuels & renewable waste, geothermal, hydro, solar photovoltaic, tide, and wind. "Other" includes non-renewable waste and unspecified sources.

Fig. 1-3 Gross electricity generation mixes of Japan and South Korea 2017-2019.

On next page, **Fig. 1-4** [25], [26] shows the electricity generation mixes currently targeted by Japan and South Korea for 2030. Some of the aforementioned existing differences may be attenuated, but are likely to persist. For instance, Japan targets nuclear and RE to account for 20-22% and 22-24%, respectively, of its total electricity generation in 2030. And South Korea's objectives are relatively similar 24% for the former and 20% for the latter. However, Japan is very unlikely to meet its target for nuclear power as demonstrated in [27][b]. The projected lack of low-carbon electricity from nuclear power may foster further RE deployment for Japan to meet its goal to counteract climate change: A 46% reduction of the country greenhouse gas (GHG) emissions by 2030 compared to 2013 [28].

[b] Peer-reviewed research paper submitted to the Journal of Asian Energy Studies in August 2021; Zissler R, Cross JS. Japan's nuclear power 2030 projections unmet and replacement with international electrical interconnections.



Note: "Oil/Other" is oil for Japan and other for South Korea.

Fig. 1-4 Electricity generation mixes of Japan and South Korea 2030 targets.

Moreover, **Fig. 1-5** [29-31] shows that in the case of RE, compared to South Korea, Japan is more supportive of the expansion of solar photovoltaic (PV) – which it has successfully installed in the past decade, to the extent that the country's 2030 target was already within reach in 2019, thanks to the introduction of a generous feed-in tariff scheme in 2012 – than that of wind. Indeed, whereas Japan targets to install 64 gigawatts (GW) of solar PV and 10 GW of wind by 2030, the plan of South Korea is more balanced as it aims for 37 GW of solar PV and 18 GW of wind.

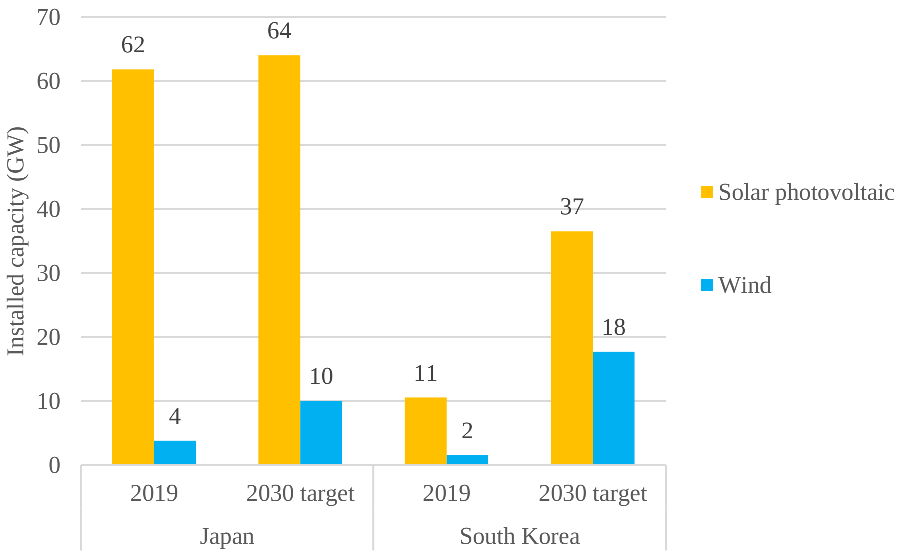


Fig. 1-5 Solar photovoltaic and wind installed capacity in Japan and South Korea in 2019 and 2030 targets.

Finally, both countries plan to reduce their reliance on fossil fuels. However, Japan will keep (slightly) prioritizing gas (27%) over coal (26%), and South Korea coal (36%) over gas (19%).

As a result, if these developments take place as expected differences in terms of electricity generation mixes will remain in the future.

1.2.2 Complementarity of electricity demand patterns

The complementarity in terms of electricity demand patterns between the power systems of Japan and South Korea may also be relevant for a possible interconnection.

Fig. 1-6 [32], [33] shows monthly electricity peak demands of Japan and South Korea during the calendar year 2019. In both countries, electricity demand patterns are marked by a clear seasonality with power systems presenting demand peaks in summer and in winter. For instance, in the calendar year 2019, the summer peak demand for Japan was 165 GW [32], and that for South Korea 90 GW [33]. These demand peaks are related to cooling needs because of hot temperatures typically occurring during the months of July and August (in the case of Japan, possibly lasting until September as well). As for the winter peak demands, still in the calendar year 2019, they reached 146 GW and 85 GW in Japan and South Korea, respectively. These demand peaks are related to heating needs because of cold temperatures especially during the months of January and February (in the case of South Korea, possibly starting from December as well).

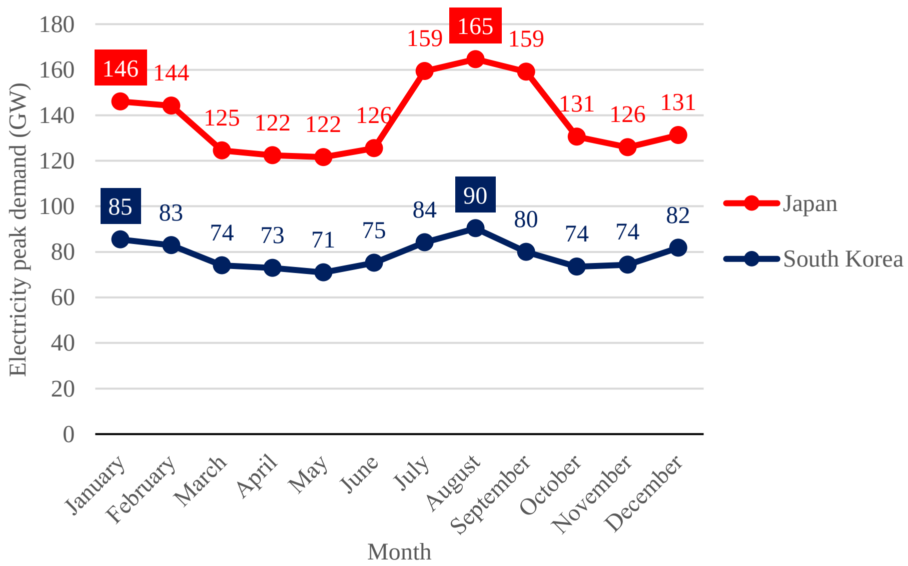


Fig. 1-6 Monthly electricity peak demand in Japan and South Korea in the calendar year 2019.

On next page, **Table 1-2** [32], [33] shows that despite seasonality, empirically electricity peak demand events in Japan and South Korea usually occur on different days – the 7th of August 2015 being an exception in the period between the calendar years 2015 and 2019. This observation suggests some complementarity.

Table 1-2 Date and time of electricity peak demand events occurrence in Japan and South Korea from the calendar year 2015 to 2019.

Calendar year	Season	Electricity peak demand event date and time (peak demand in GW)	
		Japan	South Korea
2015	Summer	August 7th at 3PM (165)	August 7th at 2 PM (77)
	Winter	– Not available –	February 9th at 10 AM (79)
2016	Summer	August 9th at 3 PM (156)	August 12th at 4 PM (85)
	Winter	January 25th at 10 AM (152)	January 21st at 10 AM (83)
2017	Summer	August 24th at 3 PM (156)	July 21st at 4 PM (85)
	Winter	January 24th at 7 PM (149)	December 12th at 9 AM (85)
2018	Summer	August 3rd at 3PM (165)	July 24th at 4 PM (92)
	Winter	January 25th at 7 PM (156)	February 6th at 9 AM (88)
2019	Summer	August 2nd at 3 PM (165)	August 13th at 4 PM (90)
	Winter	January 10th at 10 AM (146)	January 9th at 9 AM (85)

Furthermore, **Table 1-2** not only shows that electricity peak demand events tend to occur on different days, but also at different hours.[c] For instance, in summer, both in Japan and South Korea peak demand takes place in the afternoon, but not at the same time exactly: Always at 3 PM in Japan, and rather at 4 PM in South Korea (always since 2016). As for winter, Japan's peak demand either takes place in the morning at 10 AM or in the evening at 7 PM, and that of South Korea always in the morning at 9-10 AM. This additional observation also suggests some complementarity.

Looking beyond these specific most tensed seasonal peak demand events by year, through which power systems critically need to go through, it is also interesting to consider more normal conditions. In this framework, the correlation coefficients of hourly peak demand in Japan and South Korea for each day of typical summer and winter months have been calculated. For illustrative purposes, the months of January and August 2019 have been selected. The correlation coefficients obtained are 0.31 for January and 0.42 for August, which are both moderate – suggesting again some complementarity, more in winter than in summer. These findings are consistent with the observations presented in the previous paragraph.

1.3 Possible power system interconnections for west Japan – mainland South Korea

1.3.1 Considered interconnection routes

In the remaining of this dissertation the only possible interconnection routes considered are between west Japan (including the regions of Chubu, Chugoku, Hokuriku, Kansai, Kyushu,

[c] There is no time difference between Japan and South Korea.

and Shikoku) and mainland South Korea (excluding the small power system of Jeju which has its own system price). This choice is justified by the geographical proximity of these two areas, as well as that of their main electricity demand centers (especially those in the Kansai region as for examples the cities of Kobe, Kyoto, and Osaka), and the availability of transmission capacity to supply demand centers.

Further transmitting electricity to east Japan (including the regions of Hokkaido, Tohoku, Tokyo) is not considered because all the electricity that could be imported from South Korea is expected to be consumed in west Japan.

When relevant (Chapter 3: Theoretical quantitative analysis based on a computer simulation of Japan and South Korea interconnected power systems), three interconnection routes are specifically referred to. These routes result from the most comprehensive and up-to-date research work led on this issue in Japan, by the Asia International Grid Connection Study Group. Established in 2016, this Study Group consists of experts in electrical grid, energy policies and RE from academics, business and research related fields [34].

On next page, **Fig. 1-7** [35] shows these three interconnection routes, avoiding areas with established fishery rights and rocky seabeds, and assuming to have the capacity to transmit 2 GW of direct current power[d] (this technology is selected because it has a lower transmission loss rate than alternating current, and it enables the frequency to be controlled in individual regions). The transmission capacity is estimated to be 2 GW mainly in view of the countries' supply capacities of renewable energy and the impact on the supply-demand balance in Japan (i.e., unlikely to compromise stability of supply in case of disruption) as well as expected economies of scale. The first route is between Maizuru (Kansai, Japan) and Busan (South Korea). It is long of 627 kilometers (km) and as deep as 200 meters (m) in the sea. The second one is between Matsue (Chugoku, Japan) and Busan (South Korea). It is long of 372 km and as deep as 150 m in the sea. Finally, the third one is between Imari (Kyushu, Japan) and Busan (South Korea). It is long of 226 km and as deep as 120 m in the sea.

[d] As a reference, the Cross-Channel undersea interconnection between France and England also has a capacity of 2 GW [36].

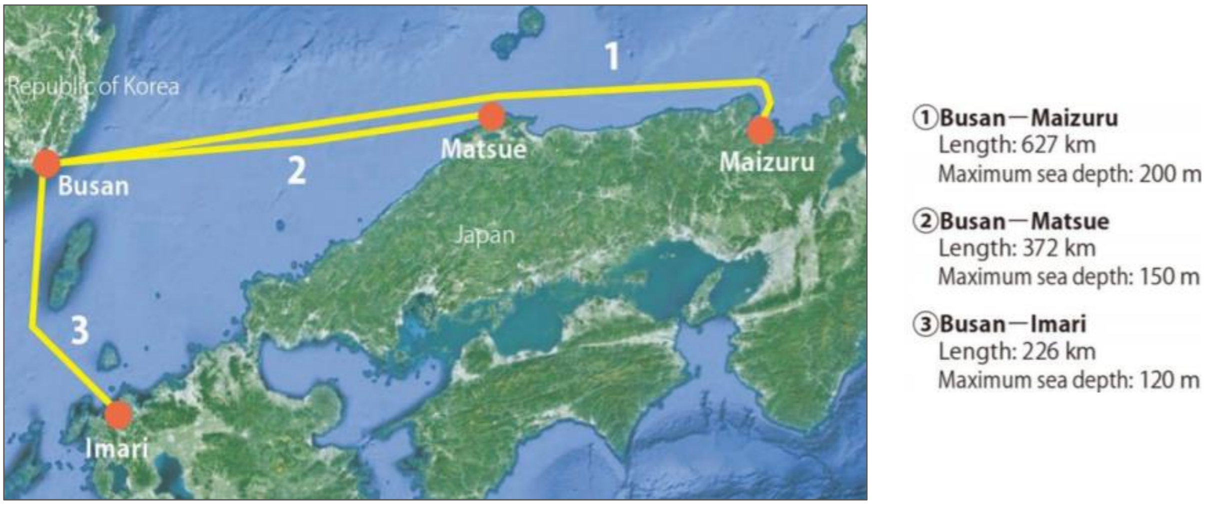


Fig. 1-7 Illustration of the three possible interconnection routes between west Japan and mainland South Korea. *Courtesy of Asia International Grid Connection Study Group.*

Thus, the first route is the longest and deepest, and the third one the shortest and shallowest. In the case of electricity imports, the first route offers the best access to the demand centers of west Japan in the Kansai region. The second and third routes require domestic grid reinforcements within Japan to fully utilize the import capacity of the interconnection. In the case of electricity exports, from surplus solar PV in the Kyushu region notably [36], the third route is definitely an interesting option.

It may be noted that the single connection point considered in South Korea is Busan. This is because in the southern part of the country some power plants, including the Samcheonpo thermal power plant and the Kori nuclear power plant, are expected to be permanently shut down, and it could be determined that the transmission facilities and substations used for those power plants could be efficiently converted for an interconnection.

Given the fact that to maximize the value of both electricity import and export flows transmission of electricity should be as efficient as possible within countries upon reaching connection points, and that this condition is not fulfilled in Japan, with the exception of the first route landing in Maizuru, domestic grid reinforcements are necessary for the second and third routes landing in Matsue and Imari, respectively.

On next page, **Fig. 1-8** [35] shows the three interconnection routes including domestic grid reinforcements in Japan when necessary. In the case of the second route, only grid reinforcements (41 km of overhead lines) between Matsue and Hino are required. In the case of the third route, because there is insufficient transmission capacity (only 1 GW is available) between Kyushu and Chugoku to transmit all the electricity that could be imported up to Kansai, the construction of an inter-regional connection (a 70 km undersea cable of 1 GW) between Kyushu (Oita) and Shikoku (Ikata) to transmit electricity to Kansai through Shikoku is considered (there is no need for grid reinforcements within Shikoku and between Shikoku and Kansai).

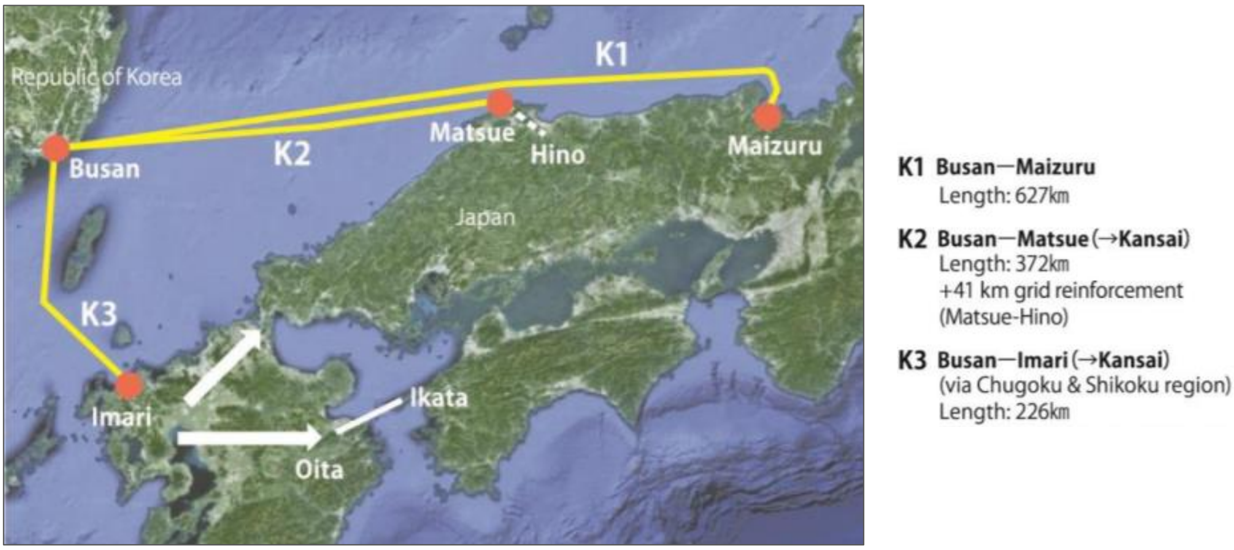


Fig. 1-8 Illustration of the three possible interconnection routes between west Japan and mainland South Korea, including domestic grid reinforcements in Japan when necessary. *Courtesy of Asia International Grid Connection Study Group.*

1.3.2 Preliminary analysis of technical feasibility

Empirical evidences tend to prove that there should be no insurmountable technical challenges in realizing the envisioned interconnection routes aforementioned, even the longest and deepest: Busan-Maizuru – 627 km long/200 m deep.

Indeed, across the world in the past 10-15 years, concrete examples of such successful projects have been demonstrating the actual feasibility of long and deep undersea transmission cables:

- NorNed, an undersea cable long of 580 km and laid at a depth of 410 m between the Netherlands and Norway in operation since 2008 [37],
- Sardinia Island – Italian Peninsula (SAPEI), an undersea cable long of 420 km and laid at a depth of 1,650 m between mainland Italy and Sardinia in operation since 2012 [38], and
- Basslink, an undersea cable long of 295 km and laid at a depth of 80 m between the States of Tasmania and Victoria in Australia in operation since 2006 [39].

Moreover, technological progress has continued since then and new ongoing projects are even more impressive. Among these, the North Sea Link projects between Norway and the United Kingdom is 730 km long (commissioning is expected for 2021) [40]. And in Asia Pacific, the Australia-Association of Southeast Asian Nations Power Link project proposes to interconnect Australia and Singapore via a 3,711 km (!) undersea cable from 2027 [41].

1.3.3 Preliminary analysis of economic profitability

As for the technical dimension, preliminary analysis of economic profitability for the possible power system interconnections between west Japan and mainland South Korea is rather positive.

Table 1-3 [35] indicates the total estimated costs, including both the costs of the international electrical interconnection and of domestic grid reinforcements – when necessary, for the three possible interconnection routes referred to. It is estimated that the second route Busan-Matuse-Hino would have the lowest cost at Japanese yen (JPY) 202.4 billion, and that the first route Busan-Maizuru would have the highest cost at JPY 246.5 billion, 22% more than the second route, because of the long and deep undersea cable required. The cost of the third route Busan-Imaru & Oita-Ikata is estimated at JPY 212.3 billion, 5% more than the second route. The relatively lower cost of the shortest and shallowest international interconnection is more than counterbalanced by the higher cost of the necessary domestic grid reinforcement compared to the second route.

Table 1-3 Estimated costs of the three possible interconnection routes between west Japan and mainland South Korea

(#) Route	Costs (JPY billion)		
	International interconnection	Domestic grid reinforcement	Total
(1) Busan-Maizuru	246.5	Not applicable	246.5
(2) Busan-Matsue-Hino	171.8	30.6	202.4
(3) Busan-Imari & Oita-Ikata	129.0	83.3	212.3

Based on these costs ranging between JPY 202.4 billion and JPY 246.5 billion, and considering various types of investment recovery models, [35] finds that it should be possible to make economically profitable all the three interconnection routes depending on hypotheses retained. From an investor perspective, the economic profitability of a project is an obvious required condition to its realization. In the case of an interconnection project, however, complexity is exacerbated by the fact that within a same EPCO the non-competitive business segment in charge of T&D (including interconnections) and those competitive which would face increased competition may have divergent interests. Therefore, it is complicated, if not impossible, to clearly define a Group strategy towards interconnections until the impacts of such projects on competitive business segments are well-identified.

1.4 Purpose of the research

With the background information made available in this chapter it is now understood that advancing a power system interconnection project between west Japan and mainland South Korea does not only make sense, but should also raise interest, particularly from power companies responsible for electricity transmission. This has not been the case in Japan yet, on the one hand because of energy security concerns related to possible geopolitical tensions, on the other hand because of the business structure of EPCOs and the fears about the impacts of international competition on their competitive business segments. The former issue is noted and largely made abstraction from in this dissertation because it is beyond what scientific research can solve. The latter is the main critical research unknown targeted here.

Thus, the value of this dissertation lies in its complementary creative attempts to bring answers to the fundamental question: *What will be the impacts of an international electrical power interconnect with South Korea on Japanese EPCOs' competitive business segments?*

1.5 Structure of the dissertation

Following the introduction providing background information (Chapter 1), this dissertation includes two complementary quantitative analyses, focusing on the one hand on an innovative empirical comparison of power exchange prices in Japan and South Korea – a methodology never explored before to the best knowledge of the doctoral student (Chapter 2), on the other hand on a theoretical computer simulation of Japan and South Korea interconnected power systems (Chapter 3). It then includes a novel qualitative analysis based on a survey of recognized energy experts on the topic of the impacts of competition on power companies in the framework of international electrical interconnections, specifically focusing on cross-border electricity trade between Japan and South Korea, which had also not been done before (Chapter 4). Finally, building upon quantitative and qualitative key findings are summarized and result in forward-thinking conclusions (Chapter 5).

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Chapter 2:

Empirical Quantitative Analysis Comparison of Power Exchange Prices

2.1 Introduction[e]

2.1.1 Advantages and drawbacks

Quantitatively analyzing the impacts of an international electrical interconnection between Japan and South Korea power systems on EPCOs' competitive business segments by comparing domestic power exchange prices is an innovative conceptual approach. To the best of one's knowledge, it has never been done before. Indeed, previous studies considering an interconnection between Japan and South Korea's power systems, as those mentioned in Chapter 1 [1], [2] only relied on theoretical computer simulations of power systems. Thanks to the recent increase in the market liquidity of Japan's power exchange, it has become possible to advance the new concept presented in this chapter which by relying on empirical observations innovatively provides complementarity and additional insights to the previous works.

It is important to note that this approach comes with advantages and drawbacks:

On the upside, power exchange prices provide empirical power systems day-ahead electricity prices with a great level of details: For each half-hour in the case of Japan and each hour for South Korea – both over several years, and by relevant geographic area. Also, these data are freely accessible to all ensuring transparency and greatly facilitating replicability of the results by any stakeholders.

On the downside, comparing prices from power exchanges regulated by different mechanisms and assuming that trade may take place between the two countries without affecting domestic electricity price impacts the accuracy of the analysis to some extent [3]. Nevertheless, the latter may be limited in this study due to the relatively small smize of the interconnection considered: 2 GW same as in [4]. The problems potentially arising from the methodology explored in this chapter are properly addressed later in this dissertation (Chapter 3: Theoretical quantitative analysis based on a computer simulation of Japan and South Korea interconnected power systems).

Since this stage in our research represents an early effort to understand how cross-border electricity trade can be implemented between Japan and South Korea and what could be the consequences on the competitive business segments of EPCOs the abovementioned problems are temporarily disregarded.

[e] The doctoral student has supported the analysis presented in this chapter in a peer-reviewed research paper which has been deemed worthy of a publication in an academic Journal.
Zissler R, Cross JS. (2020) Impacts of a Japan – South Korea power system interconnection on the competitiveness of electric power companies according to power exchange prices. Global Energy Interconnection 3(3), 292–302. DOI: 10.14171/j.2096-5117.gei.2020.03.010.

2.1.2 Power exchange characteristics

The power exchange of Japan is the Japan Electric Power Exchange (JEPX) and that of South Korea is the Korea Power Exchange (KPX). These power exchanges share some key similarities and differences.

On the one hand, the most important common point of these two power exchanges is that in both countries the day-ahead electricity prices offered on the power exchanges result from the dispatch of power plants based on the merit order principle (i.e., power plants are ranked in ascending order of price, and the exchange price is set by the power plant with the highest marginal cost being awarded a successful bid).

On the other hand, there are two main differences between these power exchanges. First, the fact that participation is voluntary in the JEPX [5] and mandatory in the KPX (with a few exceptions) [6]. Second, the degree of freedom for generating units in setting their selling bids. In the case of the JEPX, the bidding prices of generating units are almost freely determined, the only requirement being to be within the wide range of JPY 0.01-999.00 per kilowatt-hour (kWh) [7]. In contrast, in the case of the KPX, the variable costs of power plants are regulated by the Generation Cost Assessment Committee [8].

These characteristics have consequences on both the market liquidity and price volatility of the power exchanges.

Fig. 2-1 [9], [10] shows that despite a rapid increase in recent years, thanks to the efforts related to the ongoing electricity system reform in Japan, the liquidity of the JEPX has "only" reached a moderate level for now. Indeed, the volume of electricity traded on the JEPX has increased from a very low 15 TWh in 2015, or 1% of Japan's annual total net electricity supply to 209 TWh in 2018 and 293 TWh in 2019, equivalent to 20% and 30%, respectively, of the country's annual total net electricity supply.

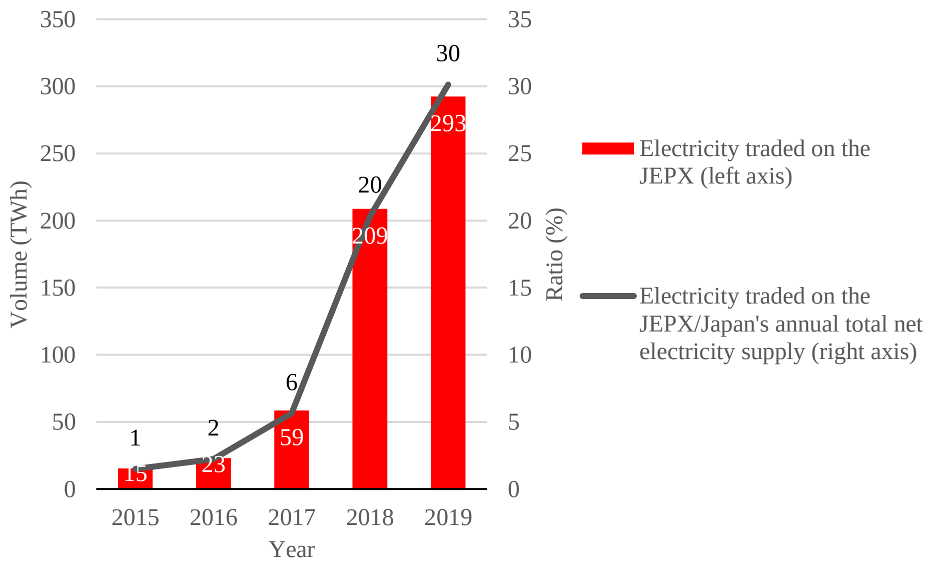


Fig. 2-1 Market Liquidity of the JEPX 2015-2019.

In comparison, the KPX is almost a perfectly liquid market, with usually between 495 and 537 TWh of electricity traded on the power exchange every year (period 2015-2019) [11], representing approximately 94-95% of South Korea's annual total net electricity supply [10].

Since the market liquidity is sufficiently meaningful in both countries only for the years 2018 and 2019, the following analysis only considers this period (on a calendar year basis, for Japan as well from now on in this chapter).

Fig. 2-2 [12], [13] shows that regarding the price volatility, in west Japan and mainland South Korea, our electricity price areas of interest, in the period from January 1, 2018 to December 31, 2019: Prices in west Japan were more evenly distributed and reached extremes relatively frequently (i.e., below JPY 5/kWh and at least JPY 15/kWh) almost 10% of the time [12] compared to mainland South Korea, which prices essentially concentrated around JPY 7-11/kWh, and reached extremes few times [13].

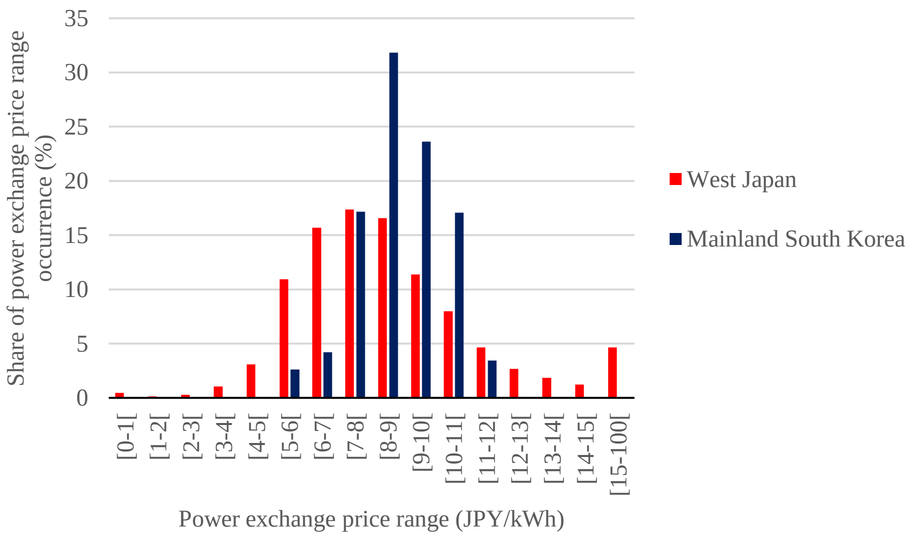


Fig. 2-2 Price volatility of JEPX and KPX 2018-2019.

2.2 Methodology

Electricity price areas are selected based on the possible power system interconnections described in Chapter 1: West Japan (including the regions of Chubu, Chugoku, Hokuriku, Kansai, Kyushu, and Shikoku) and mainland South Korea (excluding Jeju).

Like in Chapter 1 as well, the interconnection capacity is assumed to be 2 GW and its cost (including domestic grid reinforcements when necessary) between JPY 202.4 billion and JPY 246.5 billion.

The electricity prices calculated for west Japan are based on those from the six west regions. As the electricity prices in 77% of the half-hours over the 2-year period studied (2018-2019) are equal across the six regions, and variations usually remain within a small range of JPY 0.5/kWh, the electricity price for the west Japan area is obtained as the average price among these six regions.

The necessary day-ahead electricity prices for west Japan [12] and mainland South Korea [13] have been gathered and stored as raw data on January 1, 2020.

Some simple adjustments to conduct a comparative analysis have been applied. Specifically, mainland South Korea data have been split into half-hourly prices to agree with the division in half-hourly prices of west Japan. In addition, South Korean won (KRW) has been converted into JPY based on the average monthly exchange rates observed between January 2018 and December 2019: JPY 1 = KRW 10.325 [14].

Three important assumptions for our analysis are: (1) A 100% availability of the 2 GW west Japan – mainland South Korea interconnection, (2) sufficient and similar available marginal generating capacity on both sides of the interconnector to provide electricity at the same price levels in the importing and exporting country, and (3) no harmonization of power exchange rules.

The assumptions regarding the interconnection availability and prices may be considered optimal.

The assumption about sufficient available generating capacity is reasonable. Indeed, as shown in **Table 2-1** [15], [16], had an additional power export demand of 2 GW been added to the actual domestic summer and winter peak demands, there would always have been reserve margins of at least about 4% in Japan and South Korea in the period studied. This reserve margin level is above the minimum of 3% required for stable supply of electricity across Japan [17]. It is below the 10% reserve margin considered to ensure stable supply of electricity in South Korea, but above the 5% reserve margin threshold (except for the 4.4% margin on August 13, 2019), below which a supply warning is issued [18].

Table 2-1 Hypothetical reserve margins adding 2 GW of power exports to actual domestic peak demand in Japan and South Korea 2018-2019.

Year	Season	Reserve margin adding 2 GW of power exports to domestic peak demand	
		Japan	South Korea
2018	Summer	12.4% on August 3rd	5.4% on July 24th
	Winter	7.2% on January 25th	12.1% on February 6th
2019	Summer	11.5% on August 2nd	4.4% on August 13th
	Winter	8.8% on January 10th	15.4% on January 9th

The assumption on the harmonization of rules is for practical purpose. Again, this analysis aimed to provide a first, relatively simple attempt to address the particularly complicated problem of international electrical interconnection without undermining correctness.

It is then assumed that cross-border electricity trade proceeds as follows. Every half-hour, 2 GW of power is exported/imported from/to the market with the lower/higher electricity price to/from that with the higher/lower electricity price at the lower price. The results of this half-hour trading are aggregated in terms export/import volumes and export/import amounts over the years 2018 and 2019.

Finally, the gains/losses of market participants (i.e., generators and suppliers) are estimated in two scenarios, either with or without cross-border electricity trade. Without trade, the generators sell to the suppliers 2 GW of power in their respective domestic markets at the corresponding power exchange price every half-hour. With trade, the generators in the market presenting lower price sell an extra 2 GW of power at their power exchange price to the suppliers in the market presenting the higher price every half-hour. The generators in the market presenting the higher price do not sell the 2 GW, which is imported by the suppliers. The results from these scenarios are aggregated and compared over the studied period, which is a common methodology of assessing the impacts of international electrical interconnections in the academic literature as for example in [19].

Fig. 2-3 illustrates the concept of this innovative methodology and summarizes the key assumptions for the calculations.

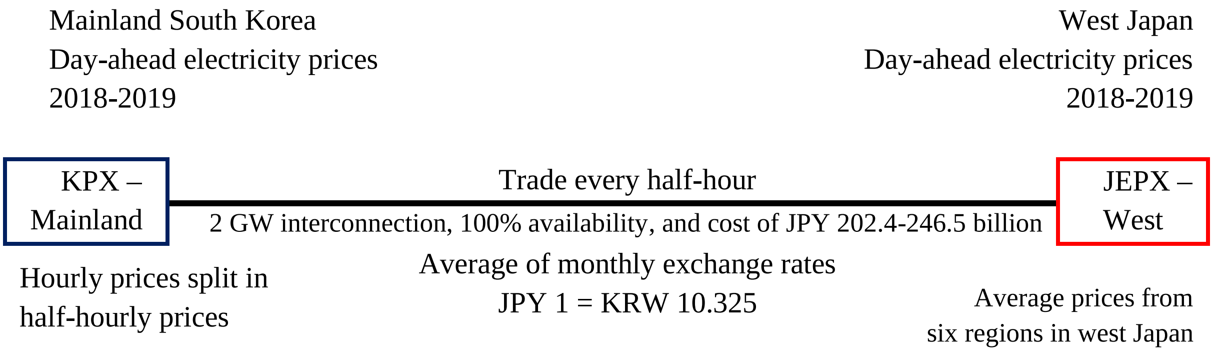


Fig. 2-3 Diagram of the proposed methodology for a west Japan – mainland South Korea interconnection analysis and its key assumptions.

2.3 Estimation results and discussion

2.3.1 Price comparison and potential savings

On next page, **Fig. 2-4** [12], [13] shows the west Japan and mainland South Korea day-ahead electricity prices every half-hour over 2018 and 2019. Two important observations can be made: (1) As expected, west Japan prices were more variable and presented more extreme values compared with mainland South Korea prices. In fact, west Japan prices varied between JPY 0.01/kWh and JPY 99.99/kWh, whereas mainland South Korea prices varied between JPY 4.95/kWh and JPY 19.95/kWh. (2) In addition, the west Japan prices were below the mainland South Korea prices in some periods and vice versa. This signals clear opportunities for bidirectional electricity trade as both countries would benefit from importing and exporting electricity depending on the situation of their domestic power system.

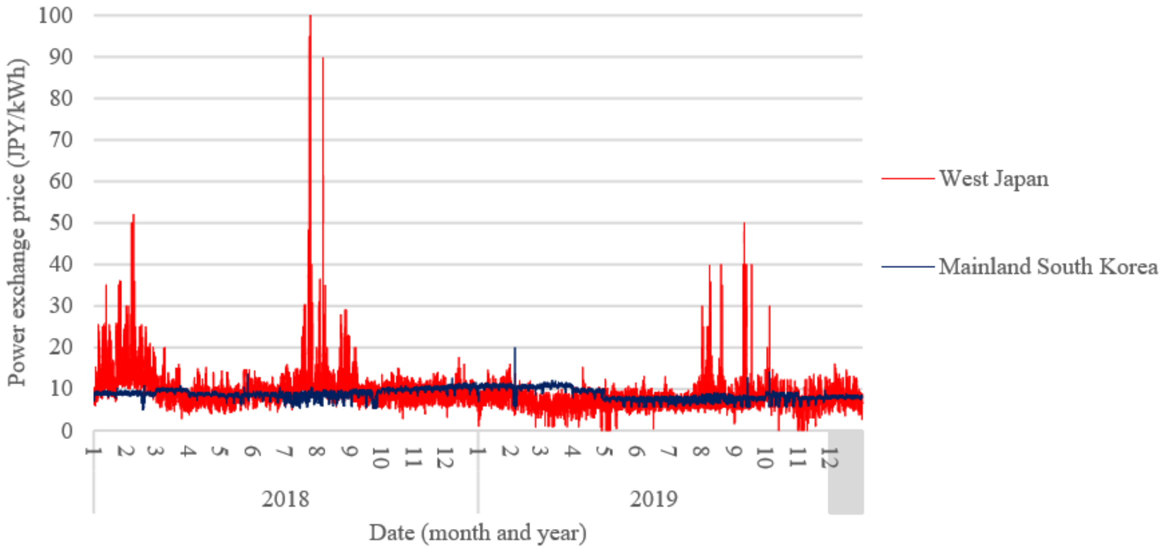


Fig. 2-4 Day-ahead half-hourly power exchange prices in west Japan and mainland South Korea 2018-2019.

On next page, **Fig. 2-5** [12], [13] shows the periods when the west Japan prices were higher and lower than the mainland South Korea prices in order to illustrate the potential cross-border electricity trade flows through the interconnection. During the shoulder seasons, spring and autumn, when the electricity consumption for heating and cooling is moderate because of the mild weather, the west Japan prices were often lower (68% of the time in these periods) than the mainland South Korea prices. This was particularly evident from March to May 2019, when low-carbon emission, low-marginal cost electricity was generated from hydro, solar PV, and the nine nuclear reactors in Kansai (Ohi-3&-4 and Takahama-3&-4), Kyushu (Genkai-3&-4 and Sendai-1&-2), and Shikoku (Ikata-3) [20] to satisfy a moderate demand, resulting in frequent low prices, below JPY 5/kWh, in west Japan. Such level of low-price was rarely seen in mainland South Korea. Moreover, at around 6 PM on July 25, 2018, when a very high demand occurred in west Japan for cooling during a heatwave [21], the price difference in favor of mainland South Korea was enormous, exceeding JPY 90/kWh (!), indicating that west Japan could have saved a substantial amount had an interconnection between the two countries been available at that time.

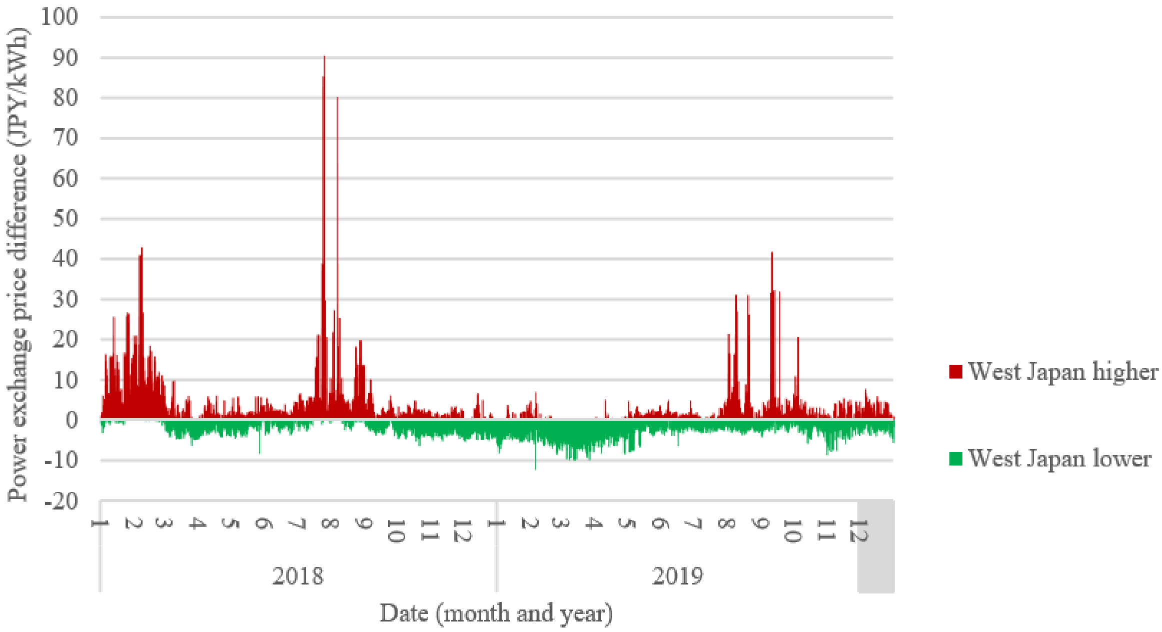
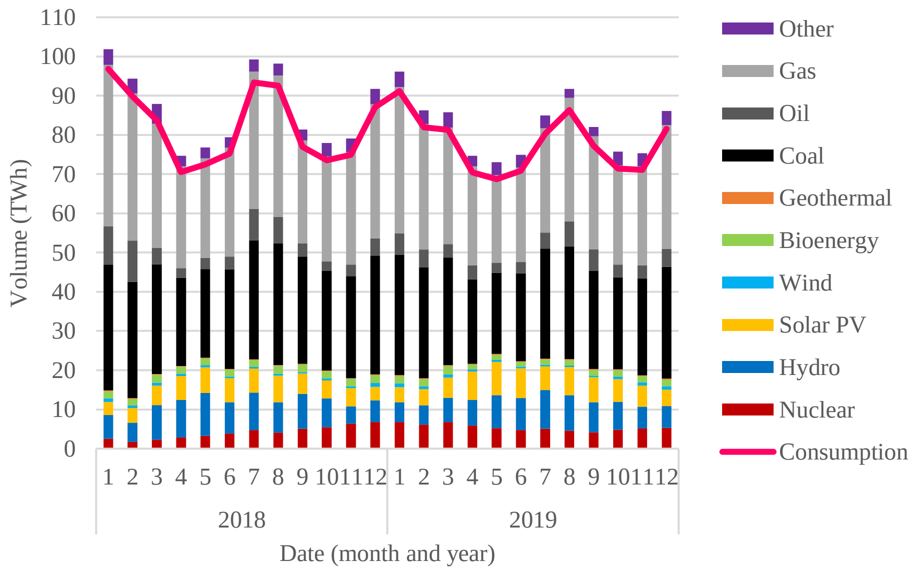


Fig. 2-5 Day-ahead half-hourly power exchange price differences between west Japan and mainland South Korea 2018-2019.

Fig. 2-6 [22] provides complementary information to **Fig. 2-5** and the analysis above by showing Japan's monthly electricity generation by source and electricity consumption in the period studied.



Notes: "Other" includes non-renewable waste and unspecified sources. To obtain "Consumption" the volumes of electricity used for pumped storage and transmission & distribution losses are subtracted from total net electricity generation.

Fig. 2-6 Monthly net electricity generation by source and electricity consumption in Japan 2018-2019.

In 2018 and 2019, the frequent price divergences between west Japan and mainland South Korea were significant, with mean of JPY 2.4/kWh and standard deviation of JPY 3.3/kWh.

Under the assumptions of this study, the total savings from the proposed interconnector would have amounted to JPY 85 billion. This amount would cover 35-42% of the interconnection estimated costs (depending on the chosen route) in only 5% of its lifetime, considering a 40-year lifetime, which is commonly assumed for such projects in Europe [23].

Furthermore, cross-border electricity trade could be valuable from an environmental perspective. This could be true both at times of abundant electricity generation from low-carbon, low-marginal cost generating technologies (including RE such as geothermal, hydro, solar PV, and wind, as well as nuclear) and moderate demand, and during situations of high demand. In fact, under high demand, power plants with the highest marginal costs (e.g., oil-fired power plants in Japan and South Korea) generate electricity and emit massive volumes of GHG. Thanks to an international electrical interconnection it could be possible to replace the output of these polluting power plants by cheaper and less carbon-intensive imports. Imports of electricity generated from flexible gas power plants, rather than from coal power plants operated for baseload, could be a theoretical example. Therefore, the proposed interconnection could also contribute to mitigating climate change, which is a goal both countries are actively pursuing by having committed to achieve carbon neutrality by 2050 [24].

These findings are consistent with the expectations from [25], a qualitative analysis of the economic efficiency of cross-border electricity trade between Japan and South Korea, and of its contribution to reduce GHG emissions.

2.3.2 Outcomes for participants

Table 2-2 [12], [13] indicates the relevant information regarding a hypothetical cross-border electricity between west Japan and South Korea in the period 2018-2019. First, the number of periods with lower day-ahead half-hourly power exchange prices were more frequent in west Japan (61% of the time) than in mainland South Korea, resulting in possible higher export volumes from west Japan to mainland South Korea (export volumes of 22 TWh and 14 TWh, respectively). Second, the amount of exports from west Japan to mainland South Korea would be higher than that of imports (JPY 150 billion against JPY 116 billion). Therefore, cross-border electricity trade would have resulted in a positive commercial balance for west Japan and a negative one for mainland South Korea (JPY 34 billion and JPY -34 billion, respectively). Thus, the position of Japanese EPCOs against an international electrical interconnection with South Korea – that would benefit their business – seems unjustified.

Table 2-2 Hypothetical cross-border electricity trade outcomes between west Japan and mainland South Korea 2018-2019.

Area	Number of periods with		Export volume	Import volume	Export amount	Import amount	Commercial balance
	Lower prices	Higher prices	(TWh)	(TWh)	(JPY billion)	(JPY billion)	(JPY billion)
West Japan	21,515	13,525	22	14	150	116	34
Mainland South Korea	13,525	21,515	14	22	116	150	-34

Table 2-3 [12], [13] shows the potential impacts of cross-border electricity trade between west Japan and mainland South Korea on the competitive business segments of EPCOs in the period 2018-2019. While generators would lose from such trade, suppliers would benefit from it. This outcome would be exacerbated in mainland South Korea, where generators' losses could have amounted to JPY 79 billion, against losses of JPY 6 billion in west Japan. In contrast, suppliers would have gained JPY 45 billion in mainland South Korea, and JPY 40 billion in west Japan.

Table 2-3 Potential impacts of cross-border electricity trade between west Japan and mainland South Korea on EPCOs' competitive business segments 2018-2019.

Area	Generation losses (JPY billion)	Supply gains (JPY billion)
West Japan	-6	40
Mainland South Korea	-79	45

From a theoretical point of view, these results are expected because increasing the competition among generators on both sides of the interconnection would benefit the most competitive ones, leaving the others out of the market. In consequence, the efficiency increases and overall generation costs decrease, thereby deteriorating the economic situation of generators but reducing the procurement costs for suppliers. These latter ones may then decide how to share these gains with their customers depending on their business strategies and the state of competition in the corresponding markets. In this regard, it is worth noting that the combined market shares of new suppliers reached 18% in Japan in June 2020 [26], and that the majority state-owned KEPCO monopolizes the supply market in South Korea [27].

2.4 Conclusion

In this chapter an innovative methodology based on an empirical comparison of power exchange prices has been advanced to assess the potential impacts of cross-border electricity trade between west Japan and mainland South Korea on EPCOs' competitive business segments. The key findings are that: If an international electrical interconnection had existed between the two areas considered in the period 2018-2019, it would have benefited to Japanese EPCOs thanks to gains from lower procurement costs for suppliers, overcompensating the losses of generators due to increased competition.

Despite its advantages, availability and transparency of accurate and detailed data, and its relative simplicity, the methodology proposed is confronted to one major drawback that is the impossibility to measure the impact of cross-border electricity trade on domestic prices. For this reason, a complementary theoretical quantitative analysis has been led by developing a computer simulation of Japan and South Korea interconnected power systems. It is presented in the next chapter of this dissertation.

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Chapter 3:

Theoretical Quantitative Analysis Computer Simulation of Interconnected Power Systems

3.1 Introduction

3.1.1 Advantages and drawbacks

Quantitatively analyzing the impacts of an international electrical interconnection between Japan and South Korea power systems on EPCOs' competitive business segments by leading a computer simulation of interconnected power systems also presents advantages and drawbacks.

On the upside, it enables to measure the impact of cross-border electricity trade on domestic prices at the whole system level (i.e., unconstrained by limited liquidity and taking into account available transmission capacity within Japan), which is critical in the framework of this dissertation. In addition, it allows to consider different international electrical interconnection scenarios, and provides additional insights on the impact of this trade on electricity generation and environmental consequences. Finally, combining this new quantitative analysis with the one already led in the previous chapter based on another methodology (i.e., comparison of power exchange prices), offers the possibility to verify if the results obtained are consistent theoretically and empirically, which ideally should be the case.

On the downside, a computer simulation of power systems is sophisticated and requires a lot of data input. In this chapter, the engineering tool used to perform the computer simulation (see 3.1.2 Electricity market simulation software) has not been developed by the doctoral student, and is not available to the public for free, thereby limiting the number of researchers who can try to replicate the results presented. Regarding data input, it is typically a time-consuming, heavy process which is not facilitated by the fact that in Japan there is no dedicated repository for computer simulation of power systems.[f] This issue has been raised by the doctoral student in an inquiry to the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry in June 2021. A reply has been received shortly after the inquiry was sent indicating that the development of such repository is currently not under consideration.

3.1.2 Electricity market simulation software brief description

The analysis presented in this chapter uses a commercial electricity market simulation software called "PROMOD," provided by the company Hitachi ABB Power Grids [1]. This software incorporates an algorithm that notably enables to simulate electricity prices by area and transmission flows between areas, which are key to our research focus.

PROMOD performs a unit commitment and a chronological dispatch algorithm that minimizes costs while simultaneously satisfying a number of operating constraints, among which:

[f] The doctoral student has presented the need to develop a national dedicated repository for computer simulation research to shape Japan's climate and energy future in the framework of the 8th United Kingdom – Japan Engineering Education League workshop held on February 26-27, 2021 (see Appendix A on page 94 for the extended abstract).

electricity consumption, generating unit characteristics, transmission grid limits, fuel and environmental considerations, and ancillary service requirements.

Into more details: Electricity demand may be modelled by area on an hourly or sub-hourly basis. Any number and type of generating units (i.e., fossils, nuclear, RE) may be configured. Generator operating characteristics includes installed capacity and heat rates for examples. Interregional transmission lines are modelled and power transmission between regions are constrained by transmission capacity of the lines. Fuel costs may be inputted for each type of generating units. The dispatch of power plants is based on the merit order principle.

3.1.3 Electricity market simulation software obtention and supervision of research

The license to use PROMOD, including a dedicated dataset for Japan's power system, was obtained by Associate Professor Tatsuya Wakeyama, Kyushu University. Professor Wakeyama has been actively involved in the research work presented in this chapter. His expertise in computer simulation, direct contribution in data input and output, as well as his supervision of the analysis of the results by the doctoral student have been invaluable. The doctoral student is very thankful to Professor Wakeyama's participation in this research.

3.2 Methodology

The areas and period covered by the analysis are: Mainland Japan (excluding Okinawa) and mainland South Korea (excluding Jeju) in the calendar year 2018.

Regarding computer simulation (of power systems in our case), two preliminary steps are usually typically necessary: (1) The creation of a model and (2) data input. The analysis being performed in this chapter being based on an existing model; the first step was not led by the doctoral student. The data input being "only" partially provided with the model (i.e., dataset for Japan's power system); the second step consisted in: (1) Verifying the data available and making corrections when necessary, and (2) adding missing data (for South Korea's power system especially, but not only). This work was entirely conducted by using publicly available information.

More specifically, in the case of Japan, all the necessary input to perform a computer simulation of the country's power systems was immediately available, but some required corrections (e.g., list of power plants), and to increase comparability with reality updated empirical data was inputted (e.g., hourly electricity consumption, hourly electricity generation from RE, hourly available transmission capacity between areas, and monthly fuel prices). In this framework multiple resources were used. These notably included EPCOs' numerous corporate materials, TSOs [2] and the Organization for Cross-regional Coordination of Transmission Operators (OCCTO), Japan [3]'s datasets, and the Petroleum Association of Japan's statistics [4].

It may be noted here that OCCTO is an important stakeholder contributing to shape Japan's power system future [5]. Established in the framework of the country's electricity system reform in 2015, this organization pursues three goals: securing stable electricity supply, suppressing electricity rates to the maximum extent possible, and expanding choices for consumers and business opportunities. Among its important roles, OCCTO is in charge of formulating long-term policy and cross-regional network development plan, notably.

In the case of South Korea, no input was originally available. This means that all the necessary data had to be inputted when possible. In this task, the Electric Power Statistics Information System website [6] has been of great help providing key information about power plants (start of operation, installed capacity, energy source…) and fuel costs, for examples. Other important information such as electricity demand was downloaded from KPX [7]. It must be noted that some information was not available. This information was sometimes rather basic and not absolutely necessary because having a relatively limited impact (e.g., list of bioenergy power plants), and thus remained missing. And sometimes very specific and technical, and quite important for the well-functioning of the simulation (e.g., start-up cost, minimum run time… for individual power plants). In this case similar assumptions as those used for Japan were retained.

As mentioned, a couple of pages above, the data input process has been quite time-consuming and actually been spread over several months from the software initial test run (i.e., process to verify the software works properly) to obtaining satisfying results for the interconnection scenarios. Collection, verification and – when necessary – correction of data, as well as multiple test runs are continuously conducted until satisfying results are reached. Just to share a telling example of the heavy workload this task represents; more than 1,700 power plants are modelled in our computer simulation, each with their own specificities (energy source, location, installed capacity, operation start date…).

Fig. 3-1 indicates all the necessary successive steps through which our computer simulation work has gone through.

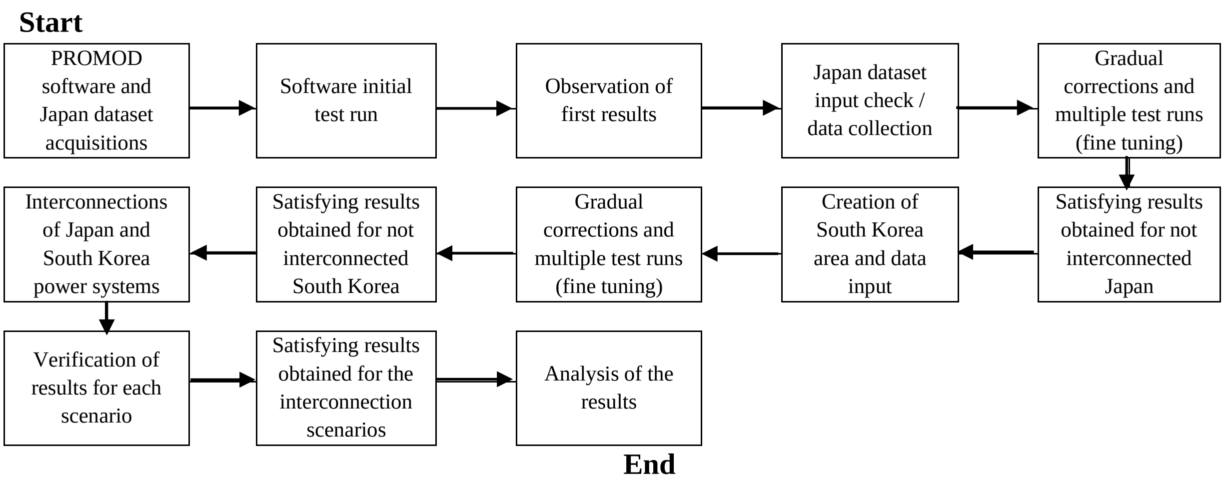


Fig. 3-1 Diagram of the computer simulation process flow steps.

After the two not interconnected power systems were separately set up, the preparatory work for the analysis of interconnected power systems was organized.

Like in the first two chapters of this dissertation, the interconnection capacity between Japan and South Korea was assumed to be 2 GW and its cost (including domestic grid reinforcements between JPY 202.4 billion and JPY 246.5 billion (depending on routes).[g]

An important difference between the quantitative analyses of Chapter 2 and Chapter 3, however, is that whereas in Chapter 2 west Japan is considered to be interconnected with mainland South Korea, in Chapter 3 three interconnection scenarios are studied: Chugoku – South Korea, Kansai – South Korea, and Kyushu – South Korea, based on the three interconnection routes presented in Chapter 1. In this regard, our theoretical computer simulation explores more in-depth and provides additional information than our empirical comparison based on power exchange prices.

Like in Chapter 2 an optimal 100% availability of the 2 GW interconnection between Japan and – mainland South Korea is assumed.

Cross-border electricity trade takes place on an hourly basis and is allowed up to 2 GW per hour. The results of this hour trading are aggregated in terms export/import volumes and export/import amounts over the studied period.

Finally, like in Chapter 2, the gains/losses of market participants (i.e., generators and suppliers) are estimated in two scenarios, either with or without cross-border electricity trade. Without trade, the generators only sell the simulated volumes of power requested by the suppliers in their respective domestic markets at the corresponding simulated market prices every hour. With trade, exporting generators sell an extra simulated volume of power at the simulated market price in their area to importing suppliers every hour. The generators in the importing market do not sell the simulated volume which is imported by the suppliers. The results from these scenarios are aggregated and compared over the studied period, which – again – is a common methodology of assessing the impacts of international electrical interconnections in the academic literature as for example in [8].

On next page, **Fig. 3-2** illustrates the concept of the methodology used in this chapter and summarizes the key assumptions for the calculations.

[g] Because the grid reinforcements between Matsue and Hino (Chugoku interconnection scenario) could not be modelled (only transmission capacity between, not within, areas are considered), the decision was made not to model grid reinforcements at all, but to keep referring to their costs which is a rather conservative approach.

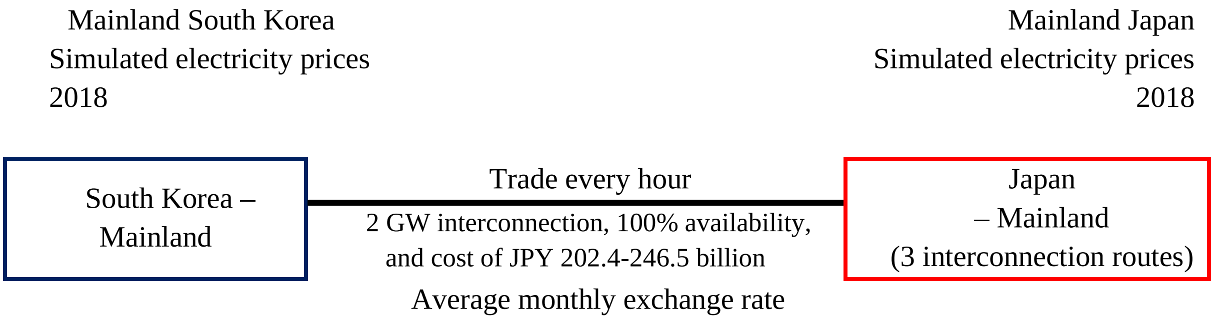


Fig. 3-2 Diagram of the proposed methodology for a Japan – South Korea interconnection analysis and its key assumptions.

Before presenting the advanced targeted estimation results of the computer simulation, the next section focuses on explaining why we recognize the basic output of this simulation reasonable. This intermediate step is necessary to ensure the credibility of the whole analysis.

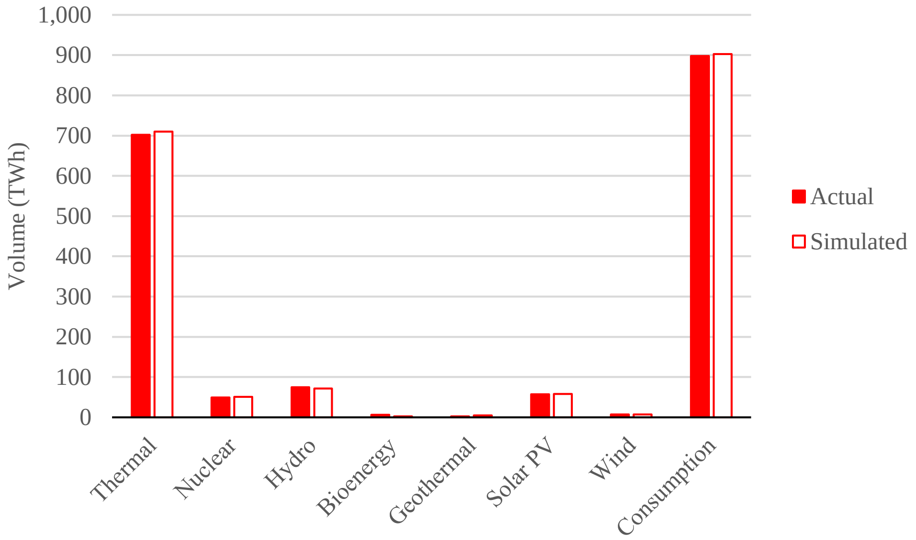
3.3 Validation process

3.3.1 Not interconnected power systems

In order to validate the results of our analysis the first points to consider are whether or not the outcomes of the computer simulation are reasonable in terms of electricity generation & consumption, and price when the power systems of Japan and South Korea operate independently – as it is the case in reality. In this regard, corresponding actual data offer a good basis for comparison.

It should be noted that in our computer simulation it is possible to identify the volume of electricity generated by each power plant. To obtain the total volume of electricity generated by an energy source all that is necessary to do is to aggregate the volume of each power plant with the same energy source. Annual results are obtained by aggregating hourly results of the entire period considered.

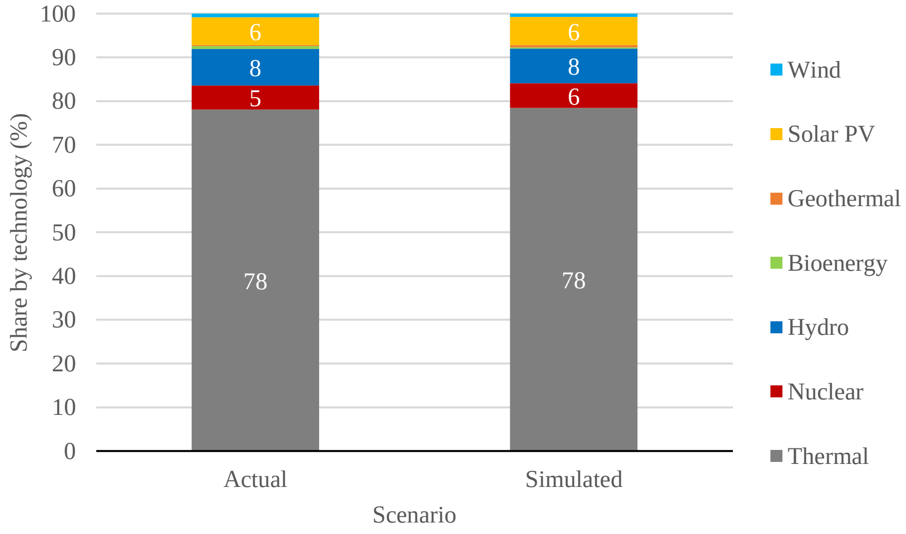
As for electricity generation & consumption in Japan, on next page, **Fig. 3-3** [2] (the reference indicates the source for actual data) shows that the computer simulation replicates well the actual outputs of the country's power system in 2018.



Note: In the case of actual data no breakdown is available for "Thermal" (i.e., coal, oil, and gas). In the case of simulated data this breakdown is available and has been aggregated here for comparison purposes.

Fig. 3-3 Comparison of electricity generation by source and electricity consumption Japan 2018 – actual and simulated scenarios.

Fig. 3-4 [2] shows that – unsurprisingly given the previous finding – the electricity generation mix of Japan for the year 2018 is also well replicated in our computer simulation.



Note: In the case of actual data no breakdown is available for "Thermal" (i.e., coal, oil, and gas). In the case of simulated data this breakdown is available and has been aggregated here for comparison purposes.

Fig. 3-4 Comparison of electricity generation mix Japan 2018 – actual and simulated scenarios.

As for electricity generation & consumption in South Korea, on next page, **Fig. 3-5** [9] (the reference indicates the source for actual data) shows that the computer simulation replicates rather well the actual outputs of the country's power system in 2018. It must, however, be noted that in our simulation electricity generation from coal is a little higher than it was in reality.

Two explanations may be advanced: (1) It was not possible to model all power plants of South Korea in the computer simulation because of missing information (i.e., bioenergy and other power plants) and their output is replaced by the cheapest available alternatives (i.e., mainly coal, nuclear being already operated close to its maximum), and (2) the economic dispatch of the model favored coal over oil.

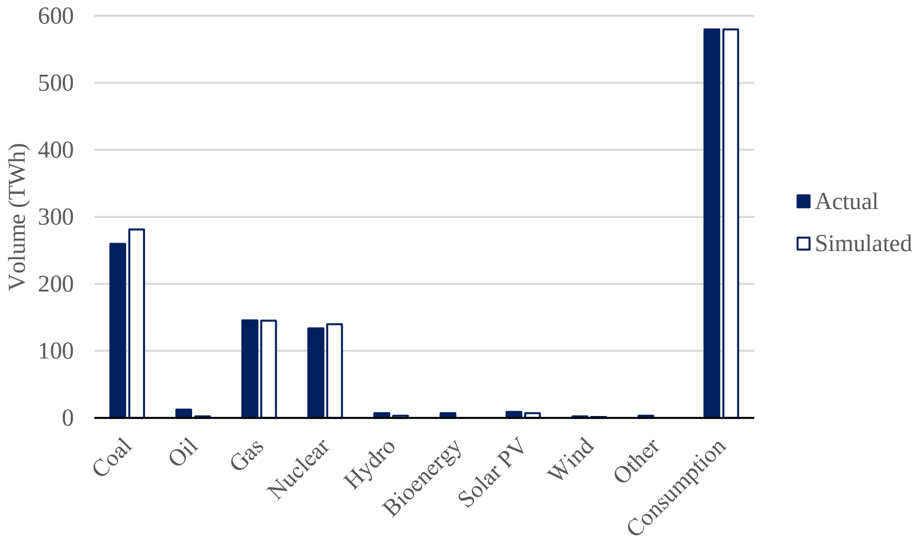


Fig. 3-5 Comparison of electricity generation by source and electricity consumption South Korea 2018 – actual and simulated scenarios.

Fig. 3-6 [9] shows that – unsurprisingly given the previous finding – the electricity generation mix of South Korea for the year 2018 is also rather well replicated in our computer simulation.

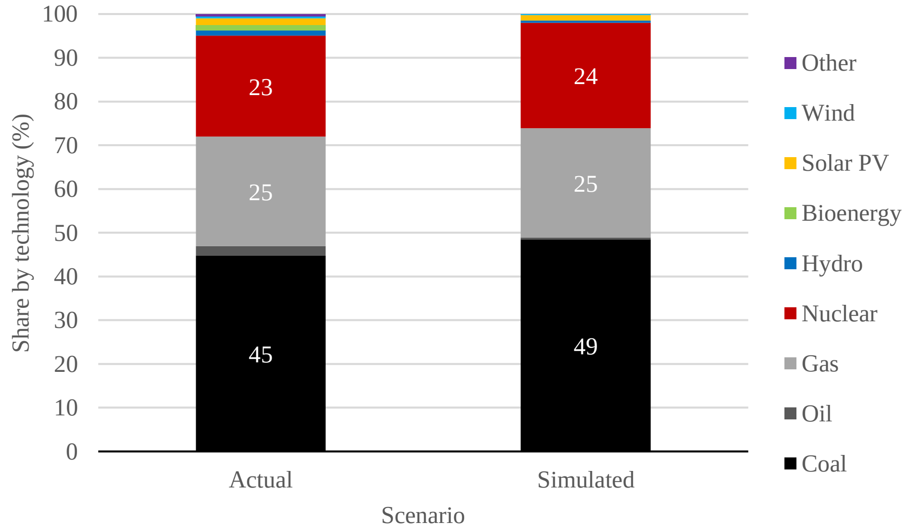
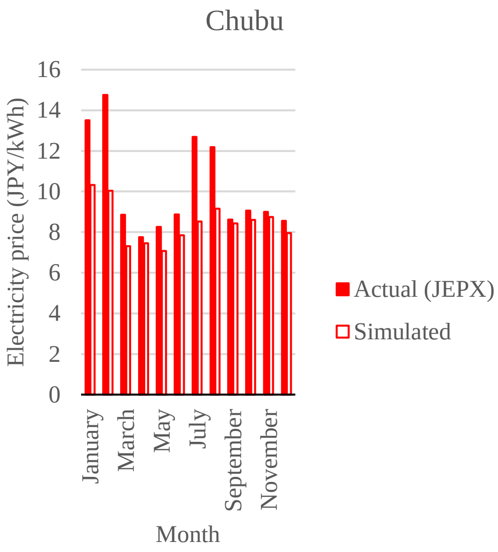


Fig. 3-6 Comparison of electricity generation mix South Korea 2018 – actual and simulated scenarios.

As for electricity prices in Japan and South Korea, on the next two pages, **Fig. 3-7** [10], [11] (the references indicate the sources for actual data) shows that the computer simulation replicates rather well the actual outputs of the countries' power exchanges in 2018.

Regarding electricity price determination by computer simulation, as in reality, it is the result from the law of supply and demand. On the supply side, among the most important factors are the availability of installed generating capacity and their marginal costs (since the dispatch of power plants is based on the merit order principle). The critical role of gas prices in electricity price formation in our computer simulation may be briefly stressed here because gas is the fuel predominantly ranked last in the merit order of Japan and South Korea's power systems. Thus, simulated electricity prices are sensitive to inputted gas prices. This description is consistent with empirical developments. For instance, in 93% of all the hours of the year 2018, gas power plants set electricity prices in KPX [12] (no such similar data have been found for Japan). It is also consistent with dedicated literature on the impact of fuel costs on electricity prices, as for example [13].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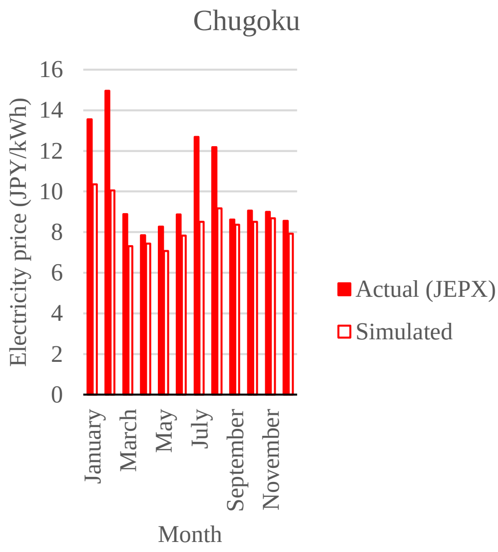
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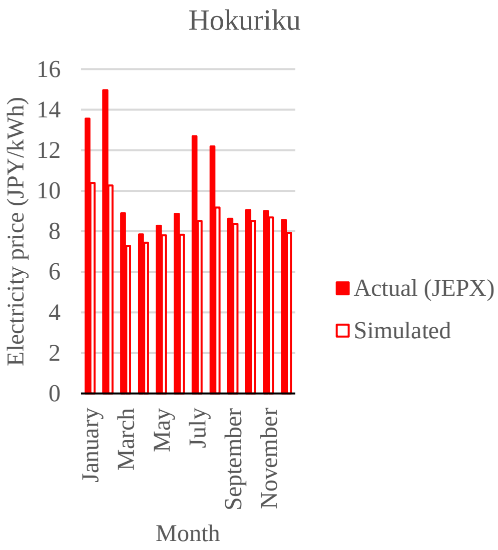
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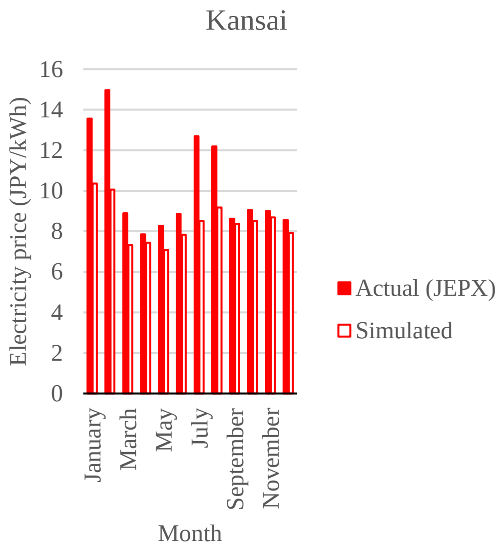
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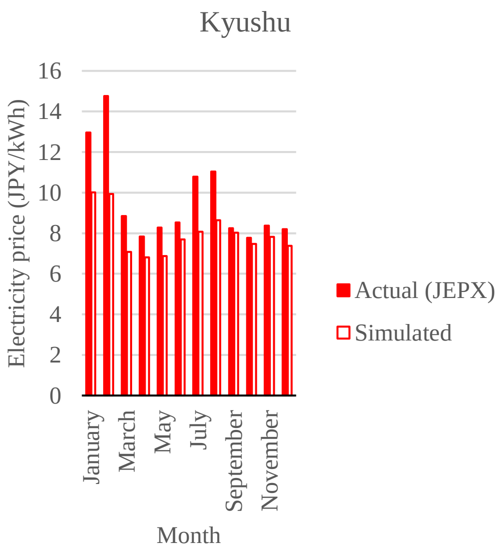
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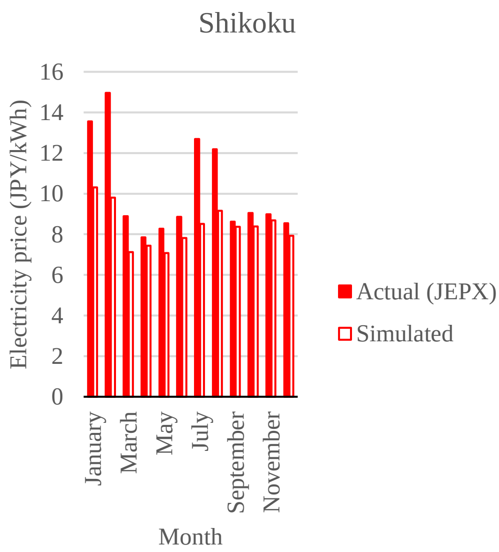
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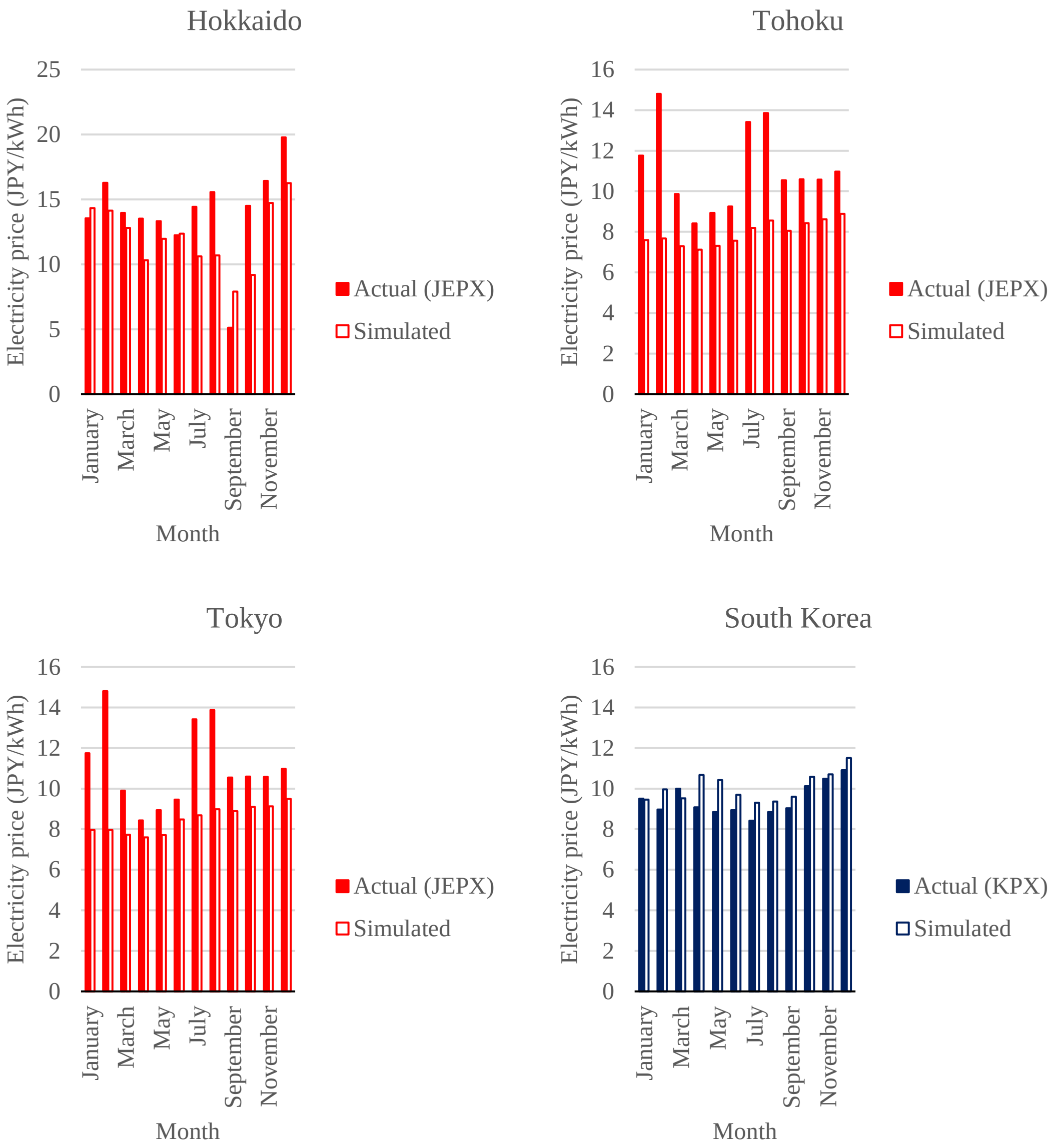

Fig. 3-7 Comparison of average monthly electricity prices Japan and South Korea 2018 – actual and simulated scenarios.

It must, however, be noted that in our simulation electricity prices are in some months significantly lower than those actually observed. This is especially true across Japan during the months of January, February, July, and August.

On next page, **Fig. 3-8** [10], using the example of Kansai's hourly electricity prices during the month of January 2018, shows that this is the result of punctual price spikes happening on JEPX, but not in the simulation.

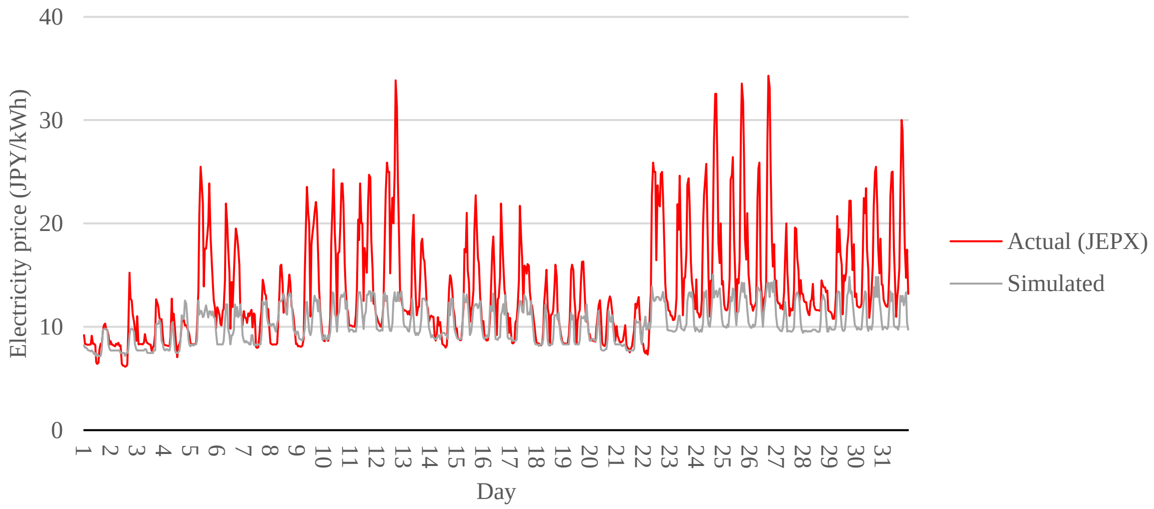

Fig. 3-8 Comparison of hourly electricity prices in Kansai during the month of January 2018 – actual and simulated scenarios.

Price spikes on JEPX may not reflect the actual situation between supply and demand in the power system for three key reasons: (1) market participants' behaviors, (2) uncertainty in supply and demand forecasts, and (3) power exchange limited liquidity. Regarding the first factor, suppliers need to procure enough electricity to meet their customers' needs. When there are fears of tight supply, suppliers' willingness to pay increases, especially since they face hefty penalties (i.e., imbalance fees) if they fail to procure enough electricity. Generators are well-aware of this fact and may take advantage of it when opportunities occur, which is typically the case in winter and summer as electricity consumption for heating or cooling increases. As for the second factor, in reality though improvements take place in the field of forecasting, there are still uncertainties in forecasting supply (especially electricity generation from RE) and demand. Hedging against these risks implies costs which translate into higher prices, an issue that may be exacerbated at times of tensions on the power exchange. These risks are excluded in our computer simulation. Finally, the third and last factor, though liquidity of JEPX has increased and become meaningful in recent years, it reached "only" 20% in fiscal year 2018, which means it remained a sample of power system prices that may not always be perfectly representative of the whole system prices. This issue was already identified in the previous chapter.

3.3.2 Interconnected power systems

In order to fully validate the results of our analysis the complementary points to consider are whether or not the outcomes of the computer simulation are reasonable in terms of electricity generation & consumption, price, and cross-border electricity trade flow when the power systems of Japan and South Korea are interconnected. In this regard, interpreting the results of the interconnected scenarios in light of those of the not interconnected scenario is quite useful, as well as other more theoretical and practical considerations.

In this sub-section only three key evidences justifying the fact that the results obtained are perfectly logical and thus entirely satisfying are briefly presented. Advanced targeted estimation results are presented in the next section.

The first convincing proof that the outcomes of the interconnected power systems scenarios are satisfying is that total generation in each country decreases/increases accordingly to the volume of electricity that is imported/exported, and that the most expensive ways to generate electricity are displaced by available cheaper ones.

The second compelling argument is that cross-border electricity trade results in lower price in the importing country and higher price in the exporting country which is completely expectable. In this regard, it has been checked on an hourly basis for all interconnected scenarios that electricity always flows from the country with the lower price to that with the higher price.

Finally, the third and last forceful evidence is that cross-border electricity trade always takes place within the 2 GW interconnection capacity designed. This has also been verified on an hourly basis for all interconnected scenarios.

3.4 Advanced targeted estimation results and discussion

3.4.1 Price comparison and potential savings

On next page, **Fig. 3-9** shows for each interconnected scenario (Chugoku, Kansai, and Kyushu) the hourly electricity prices in Japan (only the interconnected areas) and mainland South Korea (hereinafter only referred to as "South Korea" in this chapter) in 2018. Two important observations can be made: (1) Electricity prices in the Japanese interconnected areas are sometimes below the prices in South Korea and vice versa. This signals clear opportunities for bidirectional electricity trade as both countries would benefit from importing and exporting electricity depending on the situation of their domestic power system. A similar conclusion was reached in the empirical quantitative analysis of Chapter 2. (2) In addition, across the three scenarios, simulated prices are similar, especially those for the Chugoku and Kansai interconnection scenarios. This is rather unsurprising insofar as power exchange prices across west Japan areas are in reality usually well correlated (as mentioned in Chapter 2), indicating sufficient interregional interconnection capacity (this is often, but not always true in the case of Kyushu which explains some price differences as for example the absence of a price spike of JPY 18/kWh occurring in Chugoku and Kansai, but not in Kyushu in early February).

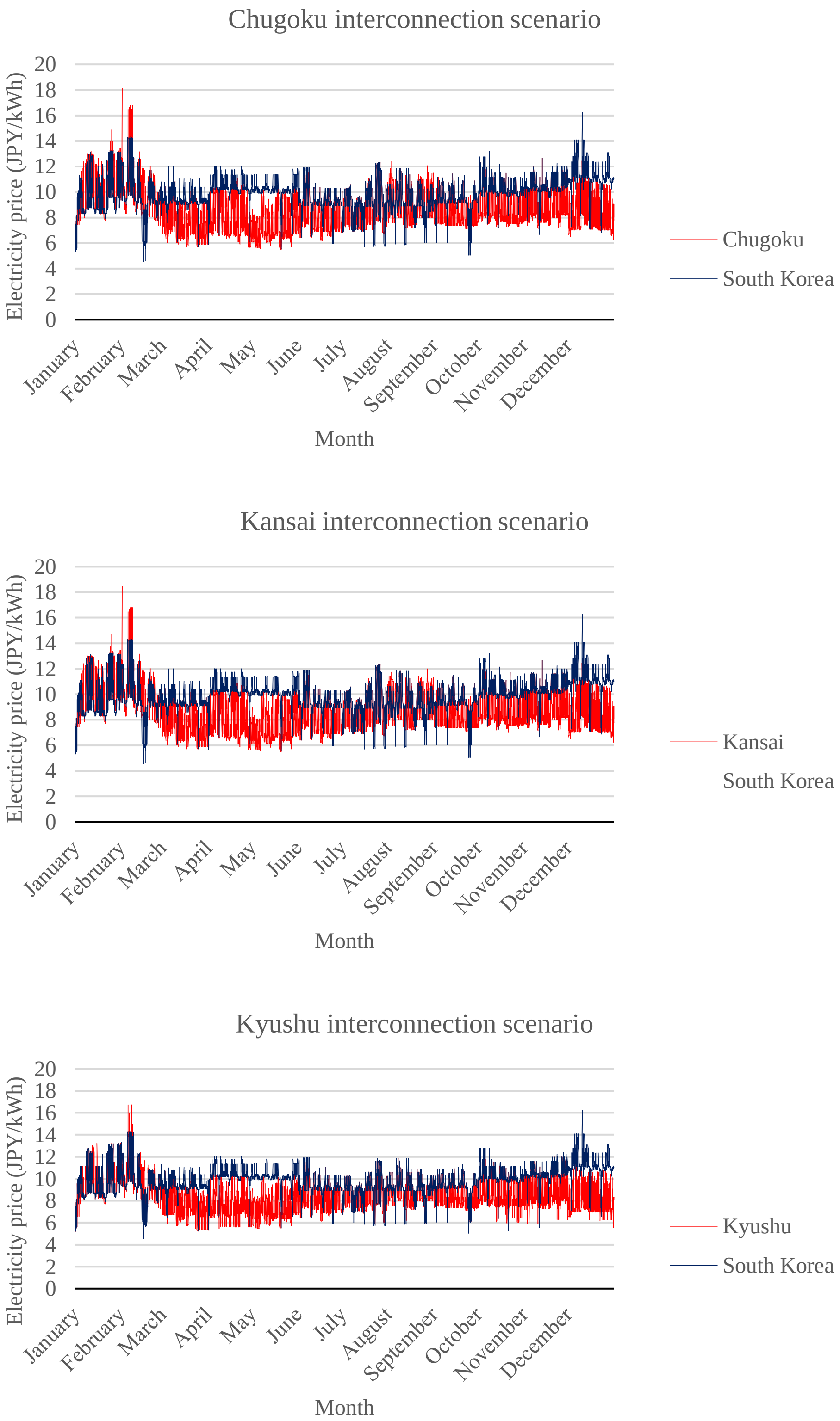

Fig. 3-9 Hourly electricity prices in the interconnected areas of Japan and South Korea considering the three different interconnection scenarios 2018.

On page 47, **Fig. 3-10** shows the hourly cross-border trade power flows between the areas of Japan (Chugoku, Kansai, and Kyushu) and South Korea in 2018. In all scenarios, the power flows always take place within the 2 GW interconnection capacity designed. This available capacity is very frequently fully utilized in all scenarios. More precisely: 75% of the time in the Chugoku and Kansai interconnection scenarios and 73% of the time in the Kyushu interconnection scenario. Another important point is that in most hours electricity is exported from Japan to South Korea in all scenarios. Into more details, 81% of the time in the Chugoku and Kansai interconnection scenarios and 85% of the time in the Kyushu interconnection scenario. Furthermore, it may also be noted that during the periods of electricity peak demand in winter and summer, the interconnection with South Korea provides cheaper electricity procurement options for Japan in all scenarios.[h]

Table 3-1 shows the annual total volumes of electricity which are traded cross-border from Japan (Chugoku, Kansai, and Kyushu) to South Korea, from South Korea to Japan (Chugoku, Kansai, and Kyushu), and the net trade from each country's perspective in 2018. Under all scenarios about 13-14 TWh are exported from Japan to South Korea, and around 2-3 TWh are exported from South Korea to Japan. These result in net exports/imports of approximately 10-12 TWh for Japan/South Korea. Again, the similarity of the results among the different scenarios is not surprising because electricity prices in west Japan are rather well correlated. What may be added here is simply the fact that both in our simulation and in reality, electricity prices in Kyushu are a little lower than in the rest of west Japan which explains why the Kyushu interconnected scenario results in the highest net exports from Japan to South Korea (further developed when describing savings from the different interconnection scenarios on pages 51-52).

Table 3-1 Cross-border electricity trade flow volumes and net trade results considering the three different interconnection scenarios 2018.

Interconnection scenario	Electricity flow from Japan to South Korea (TWh)	Electricity flow from South Korea to Japan (TWh)	Net trade Japan (TWh)	Net trade South Korea (TWh)
Chugoku	13.0	2.5	10.5	-10.5
Kansai	13.0	2.5	10.5	-10.5
Kyushu	13.8	1.7	12.1	-12.1

These observations indicate significant opportunities for cross-border electricity trade between the two countries, and especially for power exports from generators in Japan to suppliers in South Korea, regardless of the interconnection area in Japan.

[h] In our simulation the interconnection between Kyushu and Chugoku is almost never congested which raises questions about the immediate necessity of grid reinforcements between Kyushu and Shikoku. This also means that our choice not to model the grid reinforcements, including the aforementioned one, has no impact on the power flow results.

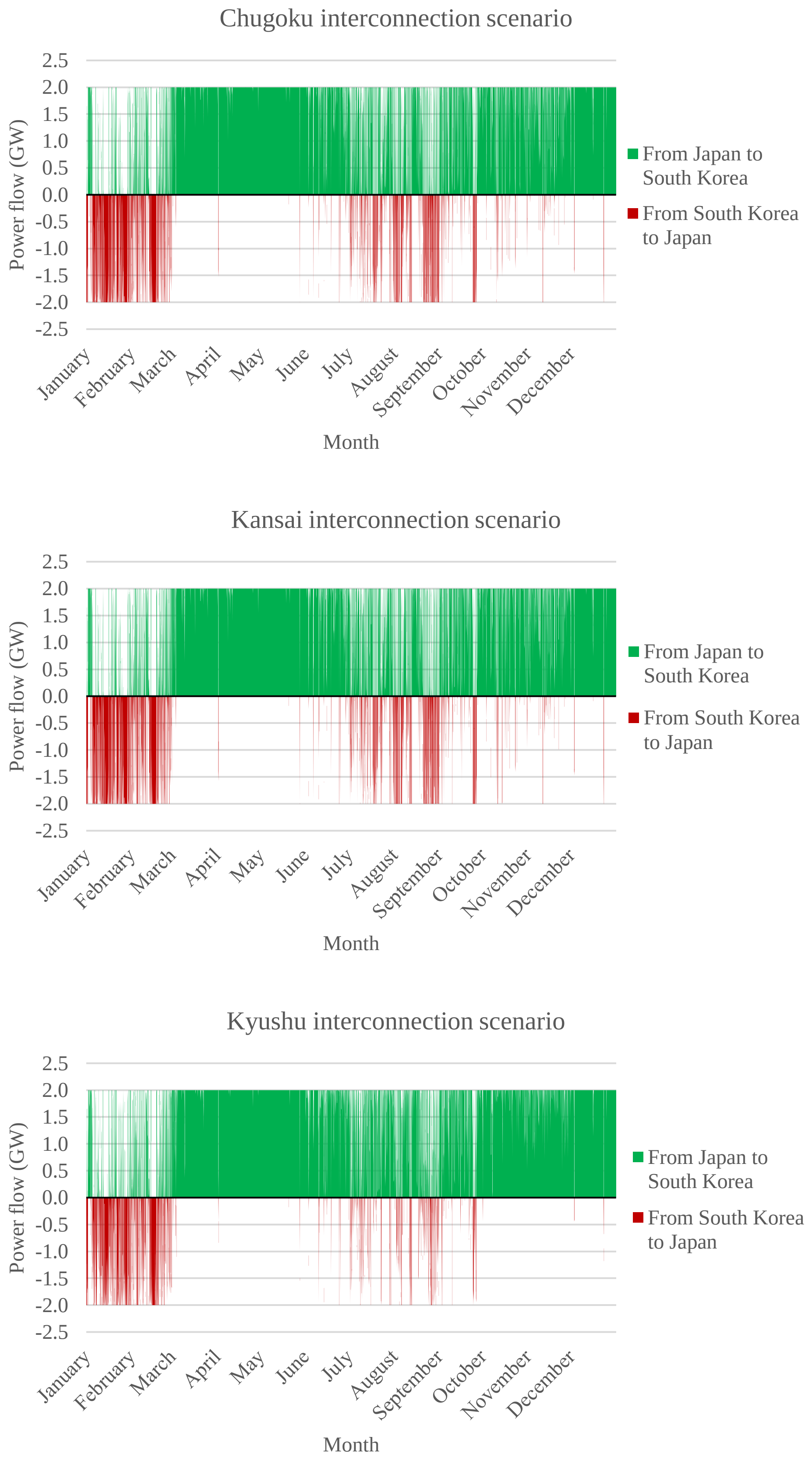

Fig. 3-10 Hourly cross-border trade power flows between the interconnected areas of Japan and South Korea considering the three different interconnection scenarios 2018.

On page 50, **Fig. 3-11** shows how cross-border electricity trade impacts electricity generation in Japan and South Korea in the three considered scenarios. It is found that in Japan the increased electricity demand from South Korea mainly results in higher electricity generation from gas (about 9 TWh across the scenarios), and to a lesser extent coal (around 2 TWh in the Chugoku and Kansai scenarios and 3 TWh in the Kyushu scenario). In South Korea, electricity imports from Japan essentially result in lower electricity generation from gas (around 11 TWh in the Chugoku and Kansai scenarios and 12 TWh in the Kyushu scenario). The replacement of electricity generated from gas in South Korea, mainly by electricity generated from gas in Japan is explained by the fact that the cost of this fuel is higher in South Korea than in Japan [14], [15]. It may be noted here that electricity generation from gas is overall decreasing when combining the results of the two countries (by about 2 TWh in the Chugoku and Kansai scenarios and 3 TWh in the Kyushu scenario), which is unsurprising insofar as it has been previously noted that gas is the main marginal fuel in Japan and South Korea, making it the likeliest to be replaced by alternative generating technologies with lower marginal costs in a more competitive framework such as that of an international electrical interconnection. In addition, though electricity generation from coal is cheaper than gas, the increase in electricity generation from coal is limited by available capacity. Since coal power plants are operated in baseload mode, already at or close to their maximum capacity, there is not a lot of room to further increase their outputs for international trade.

Among other interesting findings: the possibility to import electricity from South Korea results in a little lower electricity generation from oil in Japan (a decrease of less than 1 TWh across all scenarios). Generating electricity from oil is expensive and it is done when supply is tight. The interconnection with South Korea offers a cost-efficient alternative to oil generation in Japan and may even lead to the closures of some oil-fired power plants throughout the entire year modelled, thereby reducing the need for spare generating capacity as observed in reality in Europe. Moreover, it may be noted that nuclear and RE (in particular geothermal, solar PV, and wind) being the generating technologies with the lowest marginal costs they are already fully utilized when the countries are not interconnected, which explains why their outputs are not impacted (or only marginally, in the cases of hydro and bioenergy, because their outputs can be adjusted either for power system needs or to take advantage of economic opportunities in the market) in the interconnection scenarios. In a competitive framework, these low-carbon technologies may thus be identified as “safe bets” since they are always economically dispatched based on the merit order principle. To put these findings into perspectives, it is therefore understood that in a dynamic time frame increasing electricity generation from nuclear and RE would displace fossil fuels, and especially gas.

Finally, from an environmental perspective, the impact of the simulated international electricity trade between Japan and South Korea is unlikely to be significant, neither positively nor negatively. This is because there is a large decrease in electricity generation from gas in South Korea that is mostly displaced by a smaller increase in electricity generation from gas in Japan, and an increase in electricity generation from coal – the most cost competitive and polluting fossil fuel – in Japan. A decrease in electricity generation from oil in Japan is also observed. Across the three scenarios, there are thus rather marginal increase in coal and decreases in gas and oil, the latter two have a relatively lower carbon content than the former. This development should result in slightly higher GHG emissions. The results of our computer simulation thus illustrate a case of economic efficiency detrimental to the environment, which is hardly satisfying with regards to climate change mitigation, but logical given the fact that the objective function pursued is cost minimization and not GHG minimization.

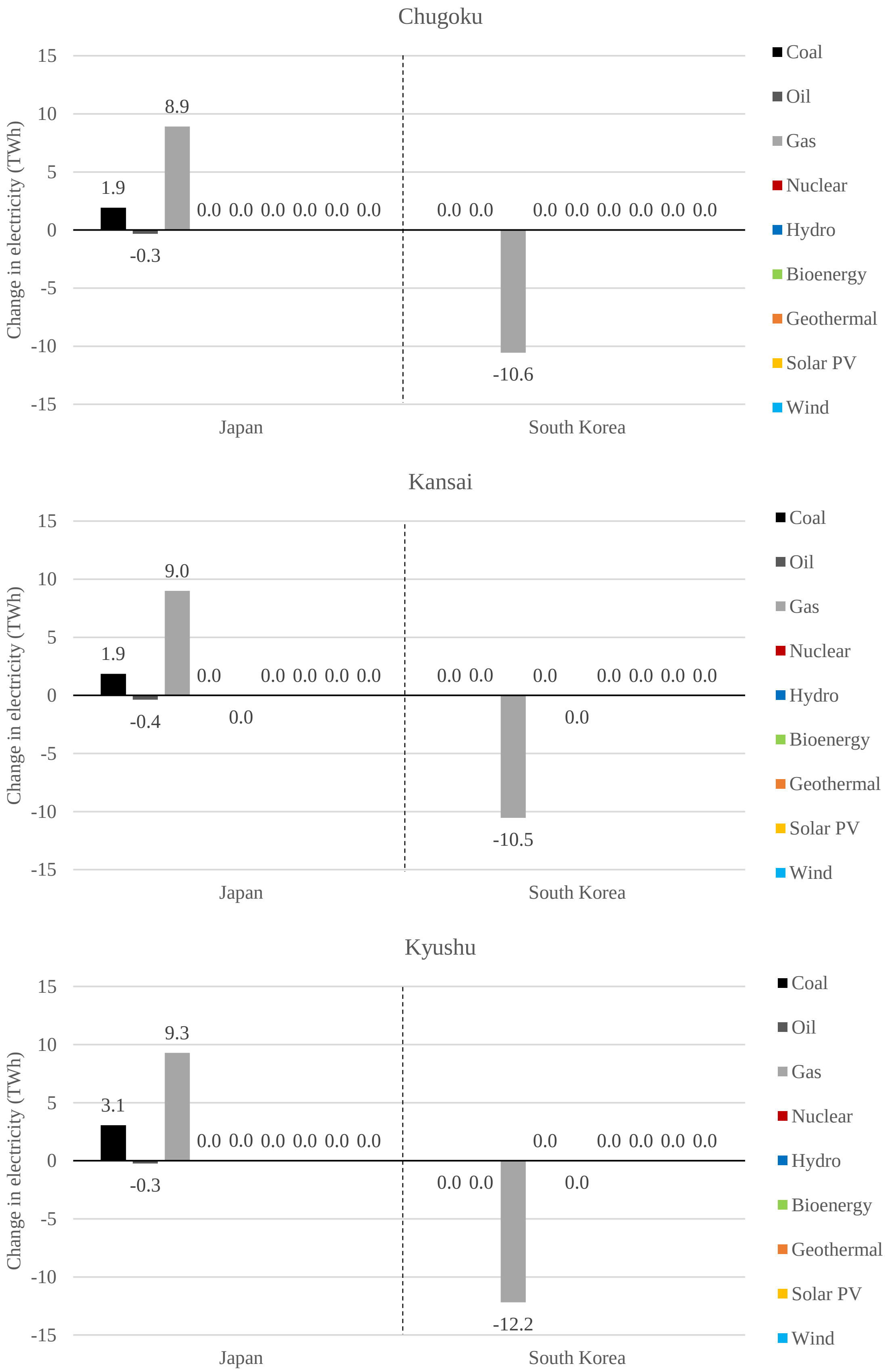

Fig. 3-11 Impacts of cross-border electricity trade on electricity generation in Japan and South Korea considering the three different interconnection scenarios 2018.

In 2018, the frequent price divergences between Japan and South Korea are not negligible, with mean of JPY 1.5/kWh and standard deviation of JPY 1.3-1.4/kWh across the different scenarios considered. These values are lower than in the case of the empirical quantitative analysis of Chapter 2 (mean of JPY 2.4/kWh and standard deviation of JPY 3.3/kWh). This is because the price spikes observed on JEPX are not replicated in our simulation as previously explained.

For each interconnection scenario it is possible to estimate savings compared to the not interconnected scenario. The calculation framework is described as follows: First, in all scenarios, hourly area electricity supplied volumes are multiplied by corresponding hourly area prices and aggregated for each of the 8,760 hours of the 2018 year modelled. In the case of the interconnected scenarios, hourly cross-border electricity trade is included by multiplying the hourly volume of electricity traded cross-border by the hourly price observed in the exporting area. In a second step, the annual results of the supply procurement costs of the all areas combined are compared. Savings are obtained by subtracting the annual total supply procurement costs of the interconnected scenarios with those of the not interconnected scenario.

Table 3-2 briefly illustrates the first part of the calculations described above in the case of the Kyushu interconnection scenario.

Table 3-2 Brief illustration of the first step to calculate savings – case of the Kyushu interconnection scenario.

Hour	Chubu electricity supplied volume (MW) × area price (JPY/kWh)	All other areas of Japan electricity supplied volume (MW) × area price (JPY/kWh)	South Korea electricity supplied volume (MW) × area price (JPY/kWh)	Cross-border trade electricity traded volume (MW) × exporting area price (JPY/kWh)	Total (JPY billion)
1	11,914 × 7.84	…	61,098 × 7.84	453 × 7.84	1.205
…	…	…	…	…	…
8,760	13,097 × 8.32	…	68,148 × 11.07	2,000 × 8.32	1.663
Total	1,205	…	5,625	127	13,627

Table 3-3 indicates the annual total supply procurement costs of all scenarios.

Table 3-3 Annual total supply procurement costs in all considered scenarios.

Scenario	Annual total supply procurement costs (JPY billion)
No interconnection	13,680.5
Chugoku interconnection	13,650.8
Kansai interconnection	13,650.7
Kyushu interconnection	13,627.5

On next page, **Table 3-4** shows that in our simulation savings from the interconnection scenarios amount to about JPY 30-53 billion, with the Kyushu interconnection scenario delivering the most economic savings (around JPY 23 billion more than the Chugoku and Kansai scenarios). The Kyushu interconnection scenario delivers the most savings because this scenario results in the most competitive procurement costs. In this regard, it may additionally be noted that Kyushu is the area where electricity prices are the lowest thanks to the combination of the following factors: moderate electricity demand in the area, large shares of low-cost electricity generation; coal, nuclear, and solar PV (and conversely a rather small share of more expensive gas), and because there is the possibility to significantly increase the capacity factors of coal and especially gas power plants. Across the three scenarios studied, savings would cover approximately 12-25% of the interconnection estimated costs in only 2.5% of its lifetime, considering a 40-year lifetime, which is commonly assumed for such projects in Europe [16]. In this regard, it may be highlighted that the Kyushu interconnection would deliver the shortest cost recovery period (just four years, should the results simulated for 2018 be replicated again) because it is not only the interconnection providing by far the most savings, but also because it is relatively cheap to build. This means that, should an interconnection be built between the two countries, the best option – from a neutral point of view – would be to interconnect Kyushu in Japan to mainland South Korea.

It may be briefly noted here that in our computer simulation enormous savings are not achieved in short periods of time under extreme circumstances as sometimes empirically observed in Europe. This is because such circumstances, contrarily to normal operations, are not focused on in our simulation. As a result, no punctual very significant price difference is observed between the interconnected areas throughout the entire period studied in all the scenarios considered. However, savings are not completely stable throughout the entire period either.

Table 3-4 Simulated savings and interconnection cost recovery considering the three different interconnection scenarios 2018.

Interconnection scenario	Cost of interconnection (JPY billion)	Simulated savings (JPY billion)	Cost recovered/recovery period (% / years)
Chugoku	202.4	29.7	15 / 7
Kansai	246.5	29.8	12 / 8
Kyushu	212.3	53.1	25 / 4

These results are similar with those presented in Chapter 2: estimated savings amounting to JPY 85 billion over a two-year period (or about JPY 43 billion per year), notably. This confirms the strong economic potential of an international electrical interconnection project between Japan and South Korea.

In the light of these encouraging findings, it may be questioned why OCCTO's does not consider international electrical interconnections in the current version of its wide area interconnection system master plan [17]. Indeed, in this key document for Japan's power system transmission planning the focus is essentially on how to integrate new massive RE capacity by reinforcing domestic grids, i.e., without exploring the possibilities of international electrical interconnections. This is all the more surprising that the latter would not only stimulate competition among power plants on both sides of the interconnectors, but also ease RE integration (notably in Kyushu where excess solar PV already faces curtailment), which is at the heart of OCCTO's master plan. The inclusion of comparisons between domestic grid reinforcements and international electrical interconnections in OCCTO's analysis would thus certainly strengthen it.

3.4.2 Outcomes for participants

On next page, **Fig. 3-12** shows the impacts of cross-border electricity trade on monthly electricity prices by areas across the three different scenarios in 2018. Key observations can be shared. The first and most important which could not be established in Chapter 2 is that cross-border electricity trade has a certain impact on prices, especially in the interconnected regions, but not only. In the case of the Chugoku and Kansai interconnection scenarios, increased demand from South Korea (i.e., net exports from Japan to South Korea) results in higher prices, especially in these two areas as well as in Chubu, Hokuriku and Shikoku – three areas which are all well interconnected with Chugoku and Kansai, and to a lesser extent in Kyushu. In these scenarios, prices also rise in east Japan and particularly in Tokyo which is interconnected with Chubu. In the case of the Kyushu interconnection scenario, increased demand from South Korea results in higher prices especially in Kyushu as well as in the rest of west Japan to a lesser extent. In this scenario, prices in east Japan are almost not impacted by cross-border electricity trade. On the other side of the interconnection, across the three scenarios, South Korea always benefits, with the exception of January, from lower prices thanks to its net imports. These are critical findings to understand the impacts of cross-border electricity trade on the competitive business segments of EPCOs.

It may be noted here that higher prices for suppliers in Japan may not necessarily mean higher prices for customers. Indeed, theoretically, suppliers' losses may be more than compensated by generators' gains – in the case of a positive commercial balance – and depending on the situations in the competitive markets of generation and supply the difference of the gains and losses may be shared between power companies and/or used to lower prices to customers.

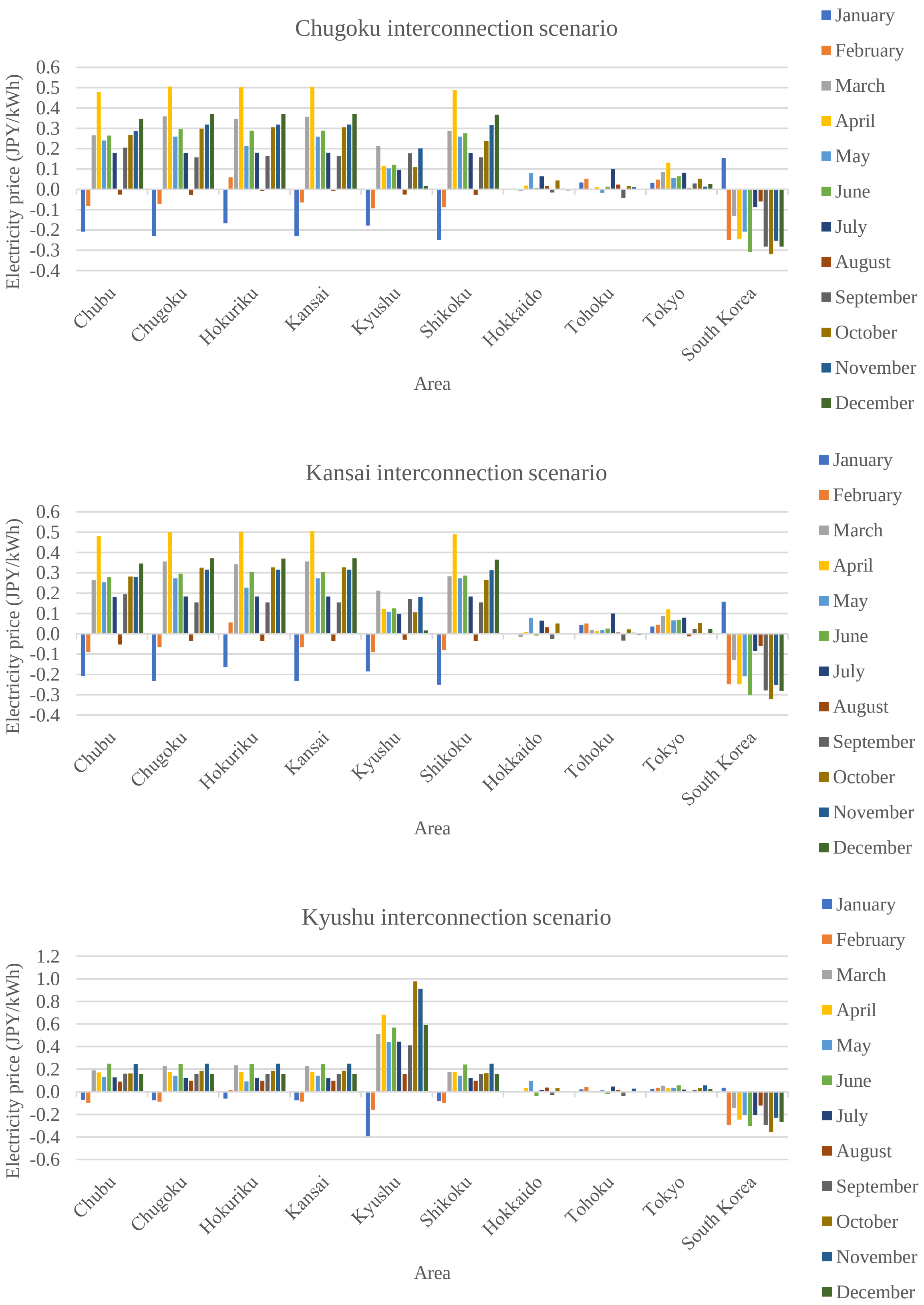

Fig. 3-12 Impacts of cross-border electricity trade on monthly electricity prices by area considering the three different interconnection scenarios 2018.

Table 3-5 indicates the economic values of exports and imports, and resulting commercial balance from the cross-border electricity trade between Japan and South Korea across the different scenarios in 2018. These values are obtained by multiplying the hourly volume of electricity traded cross-border by the hourly price observed in the exporting area, and aggregating these hourly results over the entire year considered. In all scenarios the amounts of exports from Japan to South Korea exceed by far those of imports, resulting in positive commercial balances between JPY 82-83 billion (Chugoku and Kansai scenario) and JPY 97 billion (Kyushu scenario). From a Japanese perspective, the Kyushu interconnection option could thus possibly be selected because it delivers the most benefits to the country. Reciprocally, cross-border electricity trade results in negative commercial balances for South Korea.

These results confirm to some extent the results obtained in Chapter 2: a positive commercial balance of JPY 34 billion for Japan and a negative one of JPY 34 billion for South Korea over the period 2018-2019. In fact, they are even more impressive thanks to more pronounced net exports in the simulation compared to the empirical comparison of power exchange prices (10-12 TWh in a single year and 8 TWh over two years, respectively).

Thus, this reinforces our recognition that the position of Japanese EPCOs against an international electrical interconnection with South Korea – that would benefit their business – seems unjustified.

Table 3-5 Amount of exports and imports, and resulting commercial balance from the cross-border electricity trade between Japan and South Korea considering the three different interconnection scenarios 2018.

Interconnection scenario	Country	Export amount (JPY billion)	Import amount (JPY billion)	Commercial balance (JPY billion)
Chugoku	Japan	106	24	83
	South Korea	24	106	-83
Kansai	Japan	106	24	82
	South Korea	24	106	-82
Kyushu	Japan	112	15	97
	South Korea	15	112	-97

On next page, **Table 3-6** shows the impacts of cross-border electricity trade between Japan and South Korea on the competitive business segments of each country's EPCOs across the different scenarios in 2018. Like in Chapter 2 – and for the same reason; increasing competition among generators on both sides of the interconnection – generators would overall lose from such trade, and suppliers benefit from it. Generators' total losses amount to JPY 30 billion in the Chugoku and Kansai interconnections scenarios and up to JPY 53 billion in the Kyushu scenario. Conversely, suppliers' total gains are equivalent to the losses of the generators.

In contrast with the outcomes of Chapter 2, however, the results of our simulations indicate that the fates of generators and suppliers in not the same in Japan and South Korea. Indeed, on the one hand, while in Japan generators benefit from an international interconnection, with gains ranging from JPY 181-182 billion in the Chugoku and Kansai interconnections scenarios to JPY 196 billion in the Kyushu scenario, the situation of generators in South Korea deteriorates, with losses of JPY 211-212 billion in the first two scenarios aforementioned and of JPY 249 billion in the last one. This is mainly because generators relying on cheaper gas in Japan outcompete their peers in South Korea. On the other hand, while in Japan suppliers suffer from losses due to cross-border electricity trade, with losses of JPY 99 across the different scenarios, the situation of suppliers in South Korea improves, with gains of JPY 129 billion in the Chugoku and Kansai interconnection scenarios and of JPY 153 billion in the Kyushu scenario. This development may be explained by the fact that increased demand for cheaper power generated in Japan from South Korea allows suppliers in South Korea to decrease their procurement costs, but also increases prices in Japan and thus procurement costs for suppliers in Japan. In light of the results presented in Fig. 3-12 (page 54), this outcome was expected.

Table 3-6 Impacts of cross-border electricity trade between Japan and South Korea on EPCOs' competitive business segments considering the three different interconnection scenarios 2018.

Interconnection scenario	Country	Generation (JPY billion)	Supply (JPY billion)
Chugoku	Japan	182	-99
	South Korea	-212	129
	Total	-30	30
Kansai	Japan	181	-99
	South Korea	-211	129
	Total	-30	30
Kyushu	Japan	196	-99
	South Korea	-249	153
	Total	-53	53

Note: A positive number indicates a gain, and a negative number a loss.

These critical findings are very important given the structures of the main EPCOs in the two countries. In Japan, as seen in Chapter 1, the competitive segments of EPCOs are integrated within a holding company which means the losses of a company may theoretically be compensated by the gains of another company. In the framework of our simulation, the generators' gains overcompensate the suppliers' losses. This should encourage Japan EPCOs to take action in favor of cross-border electricity trade. In South Korea, however, the situation is a little different. Indeed, KEPCO predominantly focuses on T&D of electricity as well as its supply being the unique grid operator and electricity supplier of the country. KEPCO also owns generating subsidiaries facing competition from independent power producers domestically. According to the results of our simulation, suppliers in South Korea would benefit from cross-border electricity trade with Japan, but generators lose from it. KEPCO's inclination for T&D and supply activities could explain why as a Group it is a fervent supporter of international electricity interconnections despite the real reluctance from its generating subsidiaries which has been confirmed by South Korean stakeholders. The interest of KEPCO in international electrical interconnections is well-known, the Group having not only signed the joint MOU to cooperate on research and planning for an interconnected power grid spanning Northeast Asia mentioned in Chapter 1 [18], but also proposed its own vision of international electrical interconnections; the Smart Energy Belt, a concept which shows South Korea being interconnected with Japan, notably [19].

3.5 Further considerations

From the obtained results, several considerations deserve particular attention, especially low-carbon low-marginal costs RE and nuclear, which have been identified as “safe bets” because they are always in the position of being economically dispatched based on the merit order principle.

Regarding RE, investing in increasingly cost-competitive solar PV and wind may strengthen the generation segment of EPCOs. In fact, according to recent estimates of the levelized cost of electricity (LCOE) for the second half of 2020 [20], most competitive new solar PV and onshore wind power plants are now as low as JPY 7.3/kWh and JPY 9.2/kWh, respectively, in Japan, and as low as JPY 7.5/kWh and JPY 7.8/kWh, respectively, in South Korea. These LCOE are competitive with the power exchange prices in these two countries: on average JPY 8.4/kWh in Japan [21] and JPY 8.6/kWh in South Korea [22] in the calendar year 2019.

Moreover, an international electrical interconnection should help integrating variable renewable energy (i.e., solar PV and wind) into power systems. For instance, surplus electricity generated in Kyushu could be exported to South Korea, where it would replace gas, instead of being curtailed in Japan [23][i]. In fact, the risk of future curtailment has recently discouraged the installation of new solar PV in Kyushu. Hence interconnections may be promoted to support further expansion of RE in this area.

In addition, taking into account customers’ preferences, a cross-border electricity trade based on RE may result attractive for consumers on both sides of an interconnector. For instance, South Korean residential electricity customers are willing to increase their electricity consumption from RE sources due to its safety and environment-friendly attributes [24]. In Japan, residential electricity consumers also prefer RE sources for the same reasons [25]. Regarding businesses, several Japanese companies from various areas (e.g., AEON, Fujitsu, Panasonic, Ricoh – the pioneer – and Sony) have announced their commitment for 100% RE usage to conduct their activities given its economic and environmental benefits [26].

As for nuclear, the situation is more complicated, especially due to negative developments in Japan. In the aftermath of the Fukushima Daiichi nuclear accident in 2011, 22 nuclear reactors have been permanently shut down in the country [27]. As of January 2021, of the remaining 33 reactors only 9 had restarted commercial operation. A wide restart of other reactors is quite

[i] Peer-reviewed research paper submitted to the 11th Solar & Storage Integration Workshop in August 2021; Zissler R, Wakeyama T, Cross JS. International electrical interconnection to unlock solar photovoltaic potential and accelerate progress towards carbon neutrality in Japan and South Korea [extended abstract accepted in June 2021].

uncertain and faces two main challenges: (1) rising costs due to safety upgrades, and (2) social acceptance. Clarifications about the future role of nuclear in the country are necessary. In this regard, decisions on how to reach carbon neutrality should provide clear directions. Until then, uncertainty will impede simple predictions on the future results of cross-border electricity trade between Japan and South Korea.

From environmental and energy security perspectives, internationally trading electricity generated from RE and nuclear should contribute to decrease GHG emissions and reduce the fossil fuel import dependences of both countries. It may be noted that air quality has become a major sociopolitical problem in South Korea given the severe fine dust pollution in the country [28]. Therefore, it is likely that South Korea would rather favorably consider importing low-carbon electricity from RE, for example, generated in Japan than domestically generating electricity from polluting fossil fuels.

Finally, if an international power system interconnection between Japan and South Korea is realized, regulatory decisions may impose electricity trade via the interconnector, like the Nord Pool power exchange in Europe, which imposes cross-border trade [29]. Such regulations may provide multiple benefits, including the increase in power exchange liquidity (more relevant in Japan), stabilization of power exchange prices (also more relevant in Japan), stimulation of investments in competitive power plants, and increased competition from new suppliers, possibly reducing the electricity prices for customers [30].

3.6 Conclusion

In this chapter a second quantitative analysis, this time based on a computer simulation of Japan and South Korea interconnected power systems has been advanced considering three different scenarios (Chugoku, Kansai, Kyushu). Complementary to the empirical quantitative analysis of Chapter 2 this theoretical analysis also assesses the potential impacts of cross-border electricity trade between Japan and South Korea on EPCOs' competitive business segments, making use of new possibilities such as measuring the impact of cross-border trade on electricity prices which was not possible to calculate until now. The key findings differ a little from those of the previous chapter. Indeed, though in both analyses cross-border electricity trade would benefit to Japanese EPCOs, the new analysis led in this chapter shows that higher generators' sales would overcompensate the losses of suppliers facing higher procurement costs due to increased electricity prices resulting from South Korea's net imports.

Having extensively assessed the potential impacts of cross-border electricity trade between Japan and South Korea on EPCOs' competitive business segments, from a quantitative perspective, the next chapter proposes to offer a new and complementary dimension to this dissertation by presenting the insights of a qualitative analysis based on a survey of energy experts.

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Chapter 4:

Qualitative Analysis

Survey of Energy Experts

4.1 Introduction

4.1.1 Relevance

Following complementary empirical and theoretical quantitative analyses in Chapter 2 and 3, respectively, an innovative qualitative analysis based on a survey of energy experts has been led and is presented in this chapter. The objective of this survey was to get a better understanding, beyond quantified estimates, of the impacts of international electrical interconnections on EPCOs' competitive business segments by collecting knowledge of experts in the field of energy, and particularly cross-border electricity trade and competition in the power sector. This qualitative analysis is thus complementary for the prior two previous quantitative analyses presented in Chapters 2 and 3.

Moreover, this qualitative analysis not only brings a new light on the impacts of cross-border electricity trade competition on EPCOs' competitive business segments by dedicating several questions on a Japan – South Korea electrical interconnection specifically, but also by trying to achieve this goal by leading a survey of energy experts – a methodology not found in previously published peer-reviewed research papers on this topic. Indeed, in [1-3], for examples, research rather considering a European framework has been led on the theoretical impacts of cross-border electricity trade on market participants, including prices, volumes, and strategy effects. Our topic of interest is also discussed referring to specific case studies such as Colombia-Ecuador and France – Great Britain in [4], Great Britain – Ireland in [5], Norway and Switzerland in [6], and Belgium in [7]. Furthermore, research papers surveying energy experts on the impacts of cross-border electricity trade have rarely been published. For instance, [8] focusing on opportunities and challenges for cross-border electricity trade for Bangladesh is the most relevant example that could be identified. This paper, however, does not go as far as trying to understand the impacts of international electrical interconnections on EPCOs' competitive business segments.

4.1.2 Related administrative procedures

To start with, the doctoral student participated in the ethics training course for research involving human subjects, and received a completion certificate (#19399) in February 2020. The student then submitted his human subjects research ethics review implementation application to the Human Subjects Research Ethics Review Committee of Tokyo Institute of Technology administration office, which was approved (#2020007) in April 2020 (see Appendix B on page 95).

4.2 Methodology

4.2.1 Organization, content and analysis of the survey

The survey entitled "Impacts of international electrical interconnections on power companies' competitive business segments" has been led from mid-June to mid-December 2020 essentially by submitting an online anonymous written questionnaire using the software Google Form (see Appendix C on page 96). All participants (described in the next sub-section) were asked to answer the seven following questions in this order:

- Question 1:

  Is the organization you work for an electrical power company? Yes/No

  If yes, is the electrical power company you work for participating in international electricity trade competition; at the generation and/or supply level (please specify)? And in which geographical market(s)?

- Question 2:

  Before international electricity trade competition took/take place in the markets where your expertise is prominent (please specify), what were/are the typical expectations for power companies; at the generation level? At the supply level?

  In the case international electricity trade competition already takes place in the markets where your expertise is prominent, were these expectations met in reality? Have there been additional benefits observed which were not originally expected (i.e., redundancy, disaster, resiliency…)?

- Question 3:

  Would you say that power companies are rather ambitious or cautious about international electricity trade competition? Does it depend on the considered business; generation/supply?

- Question 4:

  In Japan and South Korea, from a theoretical perspective, power companies engaged in the generation business seem more reluctant about international electricity trade competition than power companies engaged in the supply business. To your knowledge, are there empirical evidences in other geographical markets justifying these stances?

- Question 5:

  What could be the key strategies to be implemented at the generation and supply levels for power companies in Japan and South Korea to improve their business situations in a framework of international electricity trade competition?

- Question 6:

  What are your thoughts on why such interconnection Japan – South Korea has not been realized to date? Are the stances of power companies in Japan and South Korea playing an important role?

- Question 7:

  Related to the environment, has your organization accessed the environmental impact of its international power exchange activities and does it result in CO_2 reduction or less air pollution?

These seven questions have also been asked in a couple of online (either due to the COVID-19 pandemic or because of logistical matter) interviews to energy experts who declined the invitation to participate in a written questionnaire, but welcomed offering oral participation.

Given the fact that the energy experts selected and invited to participate in the survey are all quite occupied senior professionals the questionnaire stated that: "Concise answers are welcomed" and that "This survey should not take more than 20 minutes to complete."

Survey responses have been analyzed by the doctoral student in a two-step process. First, by reading replies several times and trying to identify key similarities and differences among them, so that answers could be categorized and put into perspective. Second, by using the software KH coder, a free software for quantitative content analysis or text mining [9], to fairly correct and strengthen the first step of the analysis, which despite great care remained subject to possible implicit biases and omissions. In particular, the "word frequency list" and "key word in context concordance" functions of KH coder have been used to ensure which concepts were mainly developed by participants in the survey and how.

4.2.2 Population of the survey

A total of 30 energy experts were selected and invited to participate in the survey. These experts were selected based on their deep knowledge of cross-border electricity trade and competition in the power sector limiting the population size. The latter is not considered problematic in the framework of this survey since quality responses, rather than quantity, were sought.

Table 4-1 lists by organization alphabetical order all the organizations selected and invited to participate in this survey, indicating their geographical area and their type.

Table 4-1 Selected and invited organizations to take part in the survey, geographical area and type specified.

#	Organization	Geographical area	Type
1	Agora Energiewende	Europe – Germany	Think tank/Research
2	Asian Development Bank Institute	Asia-Pacific	Think tank/Research
3	Australian National University	Asia-Pacific – Australia	Academia
4	BloombergNEF	North America – United States	Think tank/Research
5	Électricité de France	Europe – France	Power company
6	Enel Green Power	Europe – Italy	Power company
7	French Institute of Petroleum New Energies	Europe – France	Think tank/Research
8	Institute for Energy Economics and Financial Analysis	North America – United States	Think tank/Research
9	Institute of Energy Economics, Japan	Asia-Pacific – Japan	Think tank/Research
10	International Energy Agency	World	Intergovernmental
11	International Renewable Energy Agency	World	Intergovernmental
12	Korea Electric Power Corporation	Asia-Pacific – South Korea	Power company
13	Korea Electrotechnology Research Institute	Asia-Pacific – South Korea	Think tank/Research
14	Korea Energy Agency	Asia-Pacific – South Korea	Governmental
15	Korea Energy Economics Institute	Asia-Pacific – South Korea	Think tank/Research
16	National Renewable Energy Laboratory	North America – United States	Governmental
17	Nord Pool Consulting	Europe – Norway	Other (power exchange)
18	Paris Dauphine University	Europe – France	Academia
19	Renewable Energy Institute	Asia-Pacific – Japan	Think tank/Research
20	Renewable Energy Policy Network for the 21st Century	World	Think tank/Research
21	Rocky Mountain Institute	North America – United States	Think tank/Research
22	SB Energy	Asia-Pacific – Japan	Power company
23	Soladvent	Europe – France	Other (hydrogen company)
24	Svenska kraftnät	Europe – Sweden	Power company
25	Tokyo Electric Power Company	Asia-Pacific – Japan	Power company
26	Tokyo Institute of Technology	Asia-Pacific – Japan	Academia
27	United Nations Economic and Social Commission for Asia and the Pacific	Asia-Pacific	Intergovernmental
28	University of Tokyo	Asia-Pacific – Japan	Academia
29	Vattenfall	Europe – Sweden	Power company
30	Yokohama National University	Asia-Pacific – Japan	Academia

Note: For the geographical area a country is specified when relevant.

The energy experts selected and invited currently occupy professional positions in the following four geographical areas: Asia-Pacific, Europe, North America, and World (i.e., global intergovernmental organizations or networks). Because the possible international electrical interconnection studied in this dissertation is between Japan and South Korea, it was absolutely critical to invite energy experts of the Asia-Pacific region (Australia, Japan, and South Korea) to understand the local specific challenges and opportunities. Europe (France, Germany, Italy, Norway, and Sweden) and North America (United States) being regions quite advanced in cross-border electricity trade and competition in the power sector, it was also necessary to invite energy experts from these two geographical areas to learn from their valuable experiences. Energy experts from global intergovernmental organizations or networks were invited with the expectation that they would bring bird's-eye views thanks to their broader geographical scope of work.

Fig. 4-1 breaks down the selected and invited organizations to take part in the survey by geographical area. It shows that the targeted population for the survey was dominated by energy experts working for organizations of the Asia-Pacific region (largely Japan and South Korea), almost half of the population (47%). The second most targeted region to consult was Europe, with a little less than one-third of the study population (30%). Finally, the remaining of the targeted population was split roughly equally between North America (13%) and World (10%).

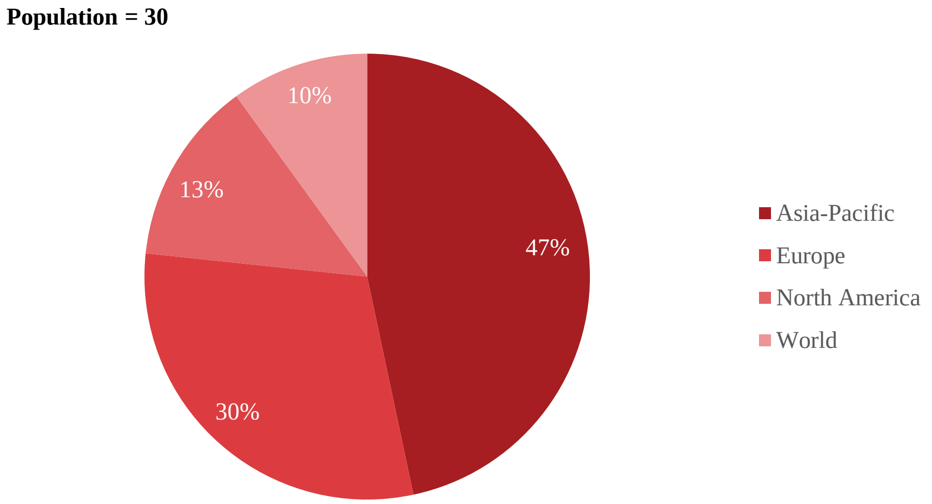


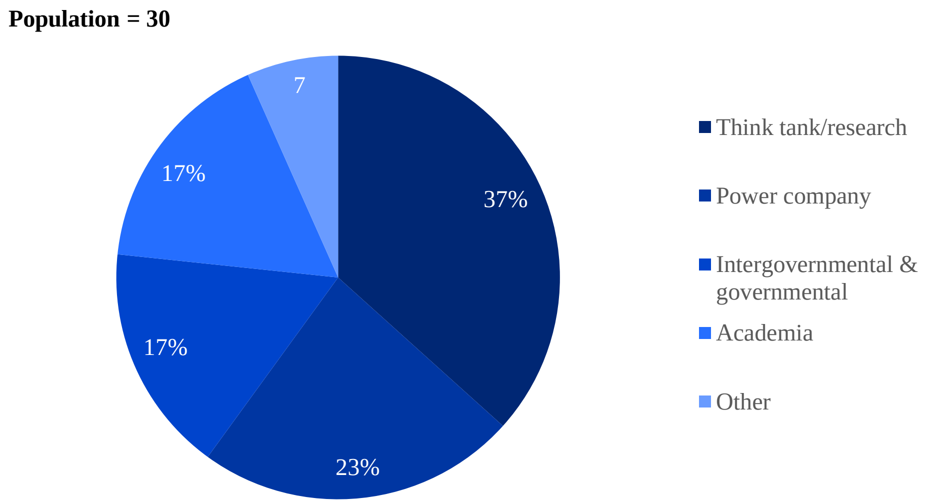
Fig. 4-1 Geographical area breakdown of the selected and invited organizations to take part in the survey.

To obtain various responses, energy experts from different types of organizations were selected. Thus, not only representatives of power companies (covering all business segments: generation, T&D, supply) were invited to participate in, but also representatives of intergovernmental and governmental organizations, as well as representatives of public or private organizations such as academia, think tanks/research, and other (i.e., a leading power exchange in cross-border electricity trade, and a hydrogen company which in the future could offer a commodity competing with electricity in international trade).

Regarding the representatives of power companies, in particular, they were selected based on the grounds that the organization they work for are: (1) established international power companies with long and strong experiences in international competition; Électricité de France (EDF), Enel Green Power, Svenska kraftnät, and Vattenfall, (2) incumbent dominant power companies in our markets of interest; TEPCO for Japan and KEPCO for South Korea, and (3) a new entrant in the Japanese power sector, dynamically expanding internationally and indirectly promoting international electrical interconnections; SB Energy (subsidiary of the SoftBank Group).

Into more details, French EDF is one of the world's largest power company active in and beyond Europe: Africa, the Americas, and Asia [10]. Italian Enel Green Power (RE subsidiary of the Enel Group) is also active in and beyond Europe: Africa, the Americas, and Asia [11]. Swedish Vattenfall is active in Europe in and beyond its country borders, especially in: Germany, the Netherlands, and the United Kingdom [12]. Svenska kraftnät is Sweden's state-owned electricity TSO [13], and the country is one of Europe's largest electricity exporters [14]. TEPCO is Japan's largest EPCO with activities not only in the country, but also overseas, especially in: Southeast Asia and the United States [15]. KEPCO is South Korea's main EPCO with activities not only in the country, but also abroad, especially in the Middle East and Southeast Asia: [16]. Finally, SB Energy the newcomer of this group was established in 2011 and is particularly active in RE projects and Japan and overseas, in Mongolia notably [17].

Fig. 4-2 breaks down the selected and invited organizations to take part in the survey by type. It shows that the targeted population for the survey was dominated by energy experts working for think tank/research organizations (37%). The second most consulted group of energy experts were representatives of power companies (23%). Then, tied in third place were representatives of intergovernmental & governmental and academia organizations (17% each). Finally, the remaining of the targeted population were representatives of other organizations (7%).



Note: "Other" includes a power exchange and a hydrogen company.

Fig. 4-2 Type breakdown of the selected and invited organizations to take part in the survey.

To briefly summarize, among selected and invited energy experts to participate in the survey most were representatives of organizations of the Asia-Pacific area (47%) and of think-tank/research type (37%).

All energy experts selected have been contacted via individual emails. They were first informed of the goal and content of the survey; at this occasion, a dedicated research description form providing all necessary details was shared with them. They were also invited to express their interest in participating in the survey. Upon receiving formal agreements to participate in, individual electronic invitations to submit written answers were sent or interviews were scheduled and conducted (the latter being organized to accommodate energy experts who were willing to provide oral answers instead of written ones).

4.3 Results and discussion

4.3.1 Participation

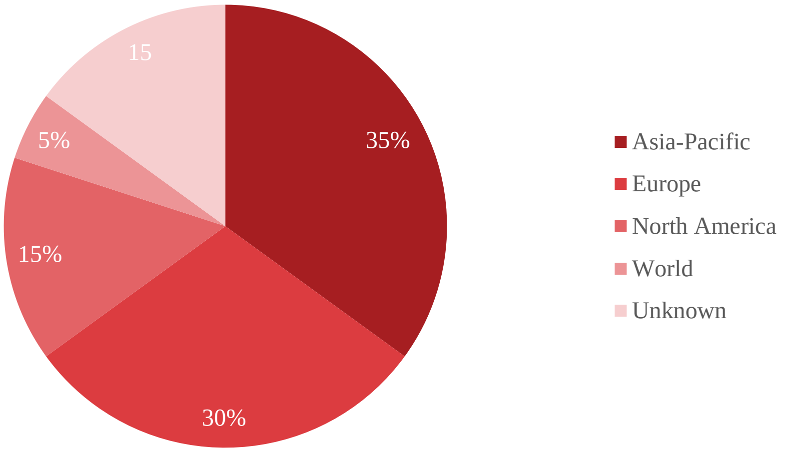
The participation rate was rather satisfactory: 20 energy experts, or two-thirds of the selected and invited population completed the survey. Participation essentially took place online with 18 of the 20 contributions (90%) being written answers.

Among these 20 energy experts, 14 have authorized the doctoral student to quote their name and affiliation for acknowledgement purpose. In the next paragraph this information is provided to express the doctoral student's deep gratitude towards these energy experts who have on a voluntary basis participated in this survey providing invaluable insights to its content. Naturally, this expression of gratitude is extended to the energy experts who wished to keep anonymity.

For their participation in the survey "Impacts of electrical interconnections on power companies' competitive business segments" the doctoral student Romain Zissler, Tokyo Institute of Technology would like to warmly thank the energy experts (by surname alphabetical order): Douglas J. Arent (National Renewable Energy Laboratory), Tim Buckley (Institute for Energy Economics and Financial Analysis), Sumin Chae (Korea Electric Power Corporation), Patrice Geoffron (Paris Dauphine University), Llewelyn Hughes (Australian National University), Seiichiro Kimura (Renewable Energy Institute), Sidney Lambert-Lalitte (French Institute of Petroleum New Energies), Thierry Lepercq (Soladvent), Amory B. Lovins (Rocky Mountain Institute), Dimitri Pescia (Agora Energiewende), Takashi Otsuki (Institute of Energy Economics, Japan), Koji Tokimatsu (Tokyo Institute of Technology), Matthew Wittenstein (United Nations Economic and Social Commission for Asia and the Pacific), and Jae Young Yoon (Korea Electrotechnology Research Institute).

On next page, **Fig. 4-3** breaks down the participants in the survey by geographical area. It shows that among participants most were representatives of organizations of Asia-Pacific (35%) and Europe (30%). Then, tied in third place were representatives of North America and unknown (i.e., participants who wished their affiliation to remain anonymous) (15% each). Finally, the remaining participant was a representative of World (5%).

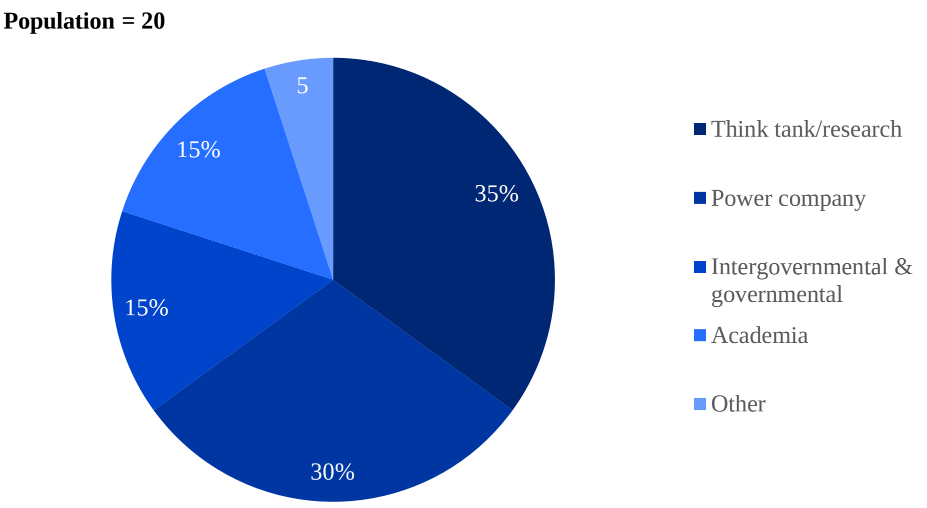
Population = 20



Notes: "Unknown" includes three participants who wished their name and affiliation to remain anonymous. Representatives of the European power companies EDF and Svenska kraftnät provided their affiliation, but not their name, which is the reason why they are not acknowledged personally, but the geographical area of the organization they represent identified. This also applies to a participant who represents a global intergovernmental organization which name has not been indicated.

Fig. 4-3 Geographical area breakdown of the participants in the survey.

On next page, **Fig. 4-4** breaks down the participants in the survey by organization type. It shows that most participants in the survey were representatives of think tank/research organizations (35%). In second place were representatives of power companies (30%). Tied in third place were representatives of intergovernmental & governmental and academia organizations (15% each). Finally, the remaining participant was a representative of other organizations (i.e., a hydrogen company) (5%).



Notes: "Other" includes a hydrogen company. Unlike in Fig. 4-3 there is no "Unknown" category in Fig. 4-4 this can be explained by the fact that among the 20 participants, 17 participants have directly either provided their name, affiliation, or company type, including three power company representatives, and that among the 20 participants, six have reported being representatives of power companies (see answers to question 1 on next page). This means the three participants who wished their name and affiliation to be remain anonymous are representative of power companies (which does not bring accurate additional information, neither about their affiliation nor their geographical area).

Fig. 4-4 Type breakdown of the participants in the survey.

Similarly, as the selected and invited energy experts to participate in the survey, most respondents in this survey were representatives of organizations of the Asia-Pacific area (35%) and of think-tank/research type (35%). This is unsurprising given the predominance of these two categories as selected and invited energy experts to participate in the survey.

4.3.2 Survey responses

In this sub-section, the questions introduced as a single block on pages 63-64 to present the content of the survey are repeated separately as reminders for practical purpose. Each question is followed by a dedicated summary based on the answers received from the participants.

To guarantee the granted complete anonymity to the participants in the survey, answers are never attributed, neither to their name nor the organization they represent.

Question 1:

Is the organization you work for an electrical power company? Yes/No

If yes, is the electrical power company you work for participating in international electricity trade competition; at the generation and/or supply level (please specify)? And in which geographical market(s)?

To the first question of this survey six participants answered they work for an electrical power company. Among these six participants, half positively replied to the question about the participation of the company they represent in international electricity trade competition. One of the companies in question was described as "a global company with interest and activities worldwide on the following domains: generation, supply, trading and distribution of energy, mainly electricity." Another company was described as mainly a European market player, but also outside of Europe for RE. The last company was essentially described as a European market player. The other half the participants responded that the companies they represent do not participate in international electricity trade competition, and one answer specified the organization the participant represents is a national TSO (and member of the European Network of Transmission System Operators for Electricity).

It may be added that a participant indicated having formerly worked for ENGIE, which was described as "a company active in power markets in Europe, Latin America, the United States, Asia, Australasia, and Africa."

Given the fact that seven power companies were invited to participate in the survey, having six of them – almost all – participating in it is quite satisfying. First, because this dissertation focuses on the impacts of cross-border electricity trade on the activities of these key actors, and second because it is a guarantee to obtain various insights depending on the companies' different experiences and situations regarding international electrical interconnections. Also, the participation of a former power company representative may be seen as a valuable bonus.

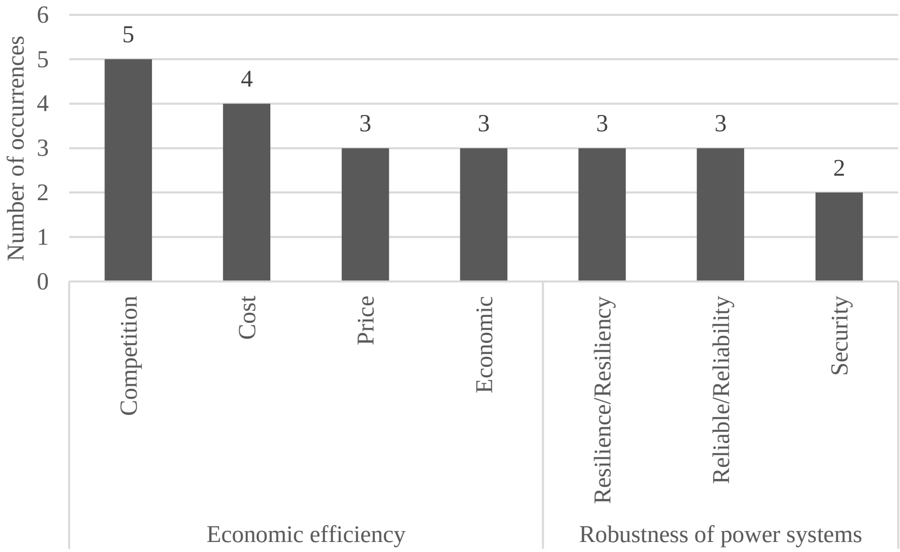
<u>Question 2</u>:

Before international electricity trade competition took/take place in the markets where your expertise is prominent (please specify), what were/are the typical expectations for power companies; at the generation level? At the supply level?

In the case international electricity trade competition already takes place in the markets where your expertise is prominent, were these expectations met in reality? Have there been additional benefits observed which were not originally expected (i.e., redundancy, disaster, resiliency…)?

The first two common expectations of international electrical interconnections are benefits in terms of economic efficiency and robustness of power systems by stimulating competition, combining diverse resources and sharing reserve capacity.

On next page, **Fig. 4-5** indicates the number of relevant occurrences of the keywords which terminologies are either related to economic efficiency or robustness of power systems in the answers to question 2. This analysis was conducted by using the software KH coder.



Notes: Word occurrences are counted only once per reply. Minimum threshold set at two occurrences.

Fig. 4-5 Keywords number of occurrences in replies to question 2.

Regarding economic efficiency, references to "competition" were the most numerous (five occurrences). The competitive framework of international electrical interconnection was expected to contribute to "cost savings" or "low cost" (four occurrences), and "price optimization" or "price transparency" (three occurrences). Direct references to "economic efficiency" or "economic mutual benefits" (three occurrences) were also made. As for robustness of power systems, references to grid "resilience/resiliency" and "reliable/reliability" (e.g., of the system) were the most numerous (three occurrences each), followed by references to "security" (e.g., of supply) (two occurrences).

Cost savings are expected both from investment and operational perspectives, and price volatility is expected to be reduced. Improvement in the management of peak demand events has been raised several times as an example of power system reliability thanks to cross-border electricity trade. These two benefits are expected in all the geographical areas the participants in the survey have reported to have relevant experience in: the Americas, Asia, Europe, and the Cooperation Council for the Arab States of the Gulf (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates). In the case of Europe, a participant provided an additional and deeper perspective. Cross-border electricity trade was one of the several aspects of the liberalization process which primary goal was to create a single competitive European Union-wide electricity market. The ongoing realization of this wide-market needs sufficient international electrical interconnection capacity, among other key factors (including: unbundling, introduction of competition in the generation and supply business segments in national electricity markets, third party access to electrical grid infrastructure, and enabling regulations), to stimulate competition across the continent.

More recently, cross-border electricity trade has been expected to facilitate the adoption of cleaner generating technologies into power systems, and particularly variable renewable energy thereby contributing to climate change mitigation, which is a third benefit. For instance, larger balancing areas help integrating large shares of solar and wind power by providing greater access to the most-cost effective flexible capacity. This point was especially raised by the participants from Europe and the United States.

On a less positive note, a participant expressed concerns about the possibilities that cross-border electricity trade "may also need new transmission capacity that can be slow, costly, and difficult to arrange, and adds some degree of vulnerability to disruption by accident, malice, or political intent, raising security-related risks to varying degrees."

In the case cross-border electricity trade already takes place there was a consensus among the participants that the first three expectations mentioned above were met in reality. A participant stated: "International competition does tend, as hoped, to improve cost discipline, make pricing more transparent, greatly improve operational efficiency and thus reduce emissions, and also improve redundancy and resilience." Another one affirmed: "It is clear that these objectives have been met and the Nordic region[j] today has the lowest cost and the cleanest power system in Europe." Another one described cross-border electricity trade as "working fine since decades and very profitable."

Regarding power companies more specifically, expectations differ depending on whether their business activities are facing competition from cross-border electricity trade or not, and in the case their business activities face competition from it, depending on their strategic behavior towards competition.

For power system operators – not facing competition, an overall more cost efficient and reliable power system is definitely a goal to aim for. However, there may an expectation that cross-border electricity trade can increase risk by exposing system operators to events outside of their control area (e.g., system outages in the area of the trading partner).

For power companies facing competition, cross-border electricity trade is more divisive and their stance towards it varies depending on national contexts. For example, a participant reported that in France "prior to the opening to international competition, security of supply had been the driving force behind the nuclear-oriented power generation program. Since then, international trade has provided an external outlet due to excess generation capacity." In this case, cross-border electricity trade is seen as an export opportunity for generators. Offering a different and complementary point of view another participant responded that through increased competition: "[…] domestic/local generation may not run as often if they are exposed to competition from lower cost generation in other service territories […]." In this case, cross-border electricity trade is seen as a threat for generators.

Considering national contexts further, two participants stressed the importance of expectations towards power companies. One of them replied that in the United States the priority is given to consumer choice over the interests of electric utilities, meaning that for example a cross-border electricity trade project to import power may be advanced to reduce supply prices to customers to the detriment of domestic cost inefficient generators. In reality this happens with the United States being a net importer of Canada's cheap hydroelectricity [18]. In Europe, also, the United

[j] The Nordic region (including Denmark, Finland, Norway, and Sweden, notably) is a world leader in cross-border electricity trade.

Kingdom is a net importer of France's nuclear electricity for the same reason [4]. This respondent made a comparison with Japan where despite the ongoing electricity system reform the EPCOs' influence still outweighs that of consumers, and added that these companies are reluctant to competition, and therefore to cross-border electricity trade. The other participant stated: "I have advised electricity providers all over the world. They are generally expected to generate power reliably and sell it at competitive prices, except in places (like Japan) where they unduly influence price formation and can block competition." This answer also emphasizes Japanese EPCOs defensive stance towards competition.

Question 3:

Would you say that power companies are rather ambitious or cautious about international electricity trade competition? Does it depend on the considered business; generation/supply?

Among answers to this question no clear consensus emerged, which was relatively expectable because as a participant in this survey stated it: "[…] the benefit of electricity trade is asymmetric".

Fig. 4-6 shows that in the majority of answers, however, "cautious" rather than "ambitious" was selected by the participants to qualify the approach of power companies towards cross-border electricity trade. Interestingly, "both" ("cautious" and "ambitious") was relatively frequently chosen underlining indecisiveness. Also, from the answers received, it is clear that the choice of these adjectives usually depends more on domestic contexts rather than the considered business segment types.

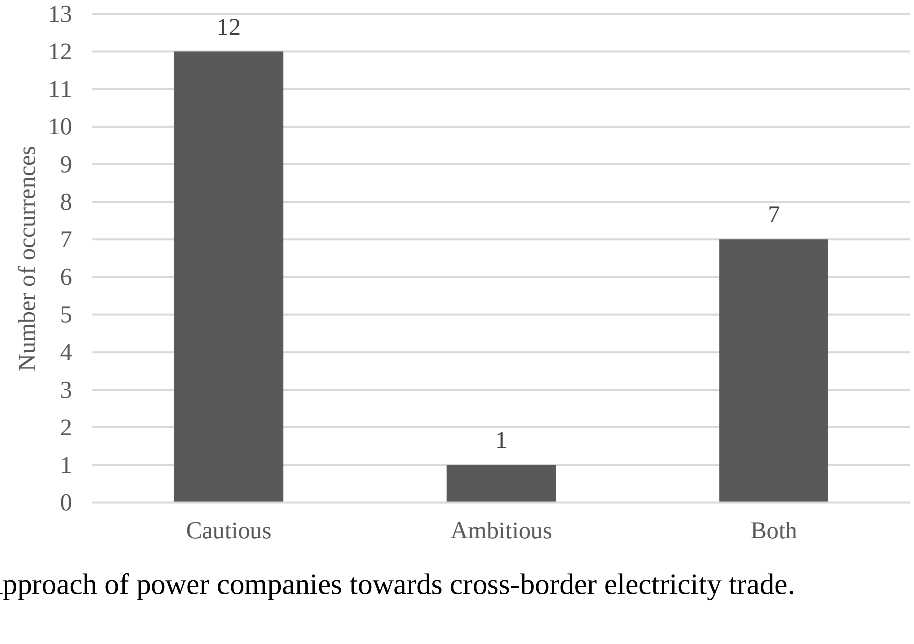


Fig. 4-6 Approach of power companies towards cross-border electricity trade.

To justify why power companies are cautious towards international electricity trade various arguments were advanced, mainly economic, but not only. Risks and opportunities behind cautious approaches may apply to all business segments. Though the question was limited to the competitive segments of generation and supply, a few participants mentioned risks and opportunities for the non-competitive segment of transmission. Since these contributions are also instructive, some of the key points received in this regard are disclosed as well for information purpose.

Because of increased economic competition generators and suppliers may be cautious towards cross-border electricity trade.

In the case of (cost inefficient) generators in potential importing countries, such trade may be seen as a threat to “captive” sales and profits. For example, a participant considered that: “[…] international trade may result in more competition and loss of customers for existing players in Japan. They have already invested in power plants; international power trade may result in lowering capacity factor and profitability of existing plants.” Another participant shared this point of view, in a broader context apparently (i.e., without explicitly referring to Japan), by replying that power companies: “[…] tend to be cautious because they may want the operational benefits but not the competition that comes with it. This is especially true for generators seeking to shield legacy assets from modern competitors’ price competition.” On the other hand, it was also reported that in France and the Nordic countries where plenty of low-cost electricity is generated, international competition was rather ambitiously pursued by generators. These different answers show well that generators’ stances towards cross-border electricity trade depend more on their domestic contexts rather than their business segment type. Finally, a participant emphasized that Japanese EPCOs should be more concerned about the competition from the domestic expansion of RE, and particularly solar PV, in which they are slow to take part in rather than that from foreign power plants.

In the case of suppliers in potential exporting countries, such trade may be seen as a threat to access domestic cheap electricity, and domestic customers may be supportive of suppliers in objecting to it. Regarding the latter, a participant well-illustrated this point by stating that in the Nordic countries in the past: “The resistance towards building interconnections has rather been among the industries that wanted to “keep” the low-cost energy.” (a position which has since then evolved as they have realized that in the long-term an interconnected system is more efficient with lower costs and a higher resilience). On the other hand, it was also replied that: “Typically […] consumers/retailers in the European Union importing countries are more favorable to electricity trade, as they both benefit most from it,” and that “[…] suppliers appreciate diversification of procurement and lower wholesale prices” resulting from cross-border electricity trade competition. These different answers show well that suppliers’ stances towards cross-border electricity trade also depend more on their domestic contexts rather than their business segment type.

In the case of system operators, technical risks were advanced as a reason to be cautious. Exposure to outages outside of their control area was identified as the main concern. A participant, answered that in Japan there are worries that: “[…] sudden disruption and subsequent blackout would bring significant economic damages.” Also, despite a rather positive historical track record for undersea transmission cables, A participant raised the point that the potential occurrence of technical issues and their negative economic consequences should not be ignored: “Australia's experience with subsea cables for Victoria-Tasmania

(Basslink) has been extensive, going on two decades, but there have been major engineering issues requiring downtime for repairs, and the economics have not been disclosed, and my understanding is the project has never delivered the expected rates of return predicted." On a more positive note, another participant affirmed: "TSOs are obviously the main supporters of the market and system interconnection process (since they benefit from congestion rents, and since interconnections increase the reliability of the overall system)."

Other arguments advanced to justify a cautious stance of power companies towards international electricity trade were political, regulatory, and cultural barriers, as well as a fear of uncertainty (the latter was specifically attributed to Japanese EPCOs).

Question 4:

In Japan and South Korea, from a theoretical perspective, power companies engaged in the generation business seem more reluctant about international electricity trade competition than power companies engaged in the supply business. To your knowledge, are there empirical evidences in other geographical markets justifying these stances?

To this question participants provided answers supporting four main ideas: (1) The historical lack of competition in the Japanese and South Korean generation markets has resulted in poor economic efficiency, (2) the recognition of poor economic efficiency leads to concerns over competition, (3) these concerns are legitimate, and (4) may trigger defensive strategies. Nevertheless, a few more positive views were also proposed.

Quantitatively analyzing answers received using KH coder, issues related to competition were directly mentioned with the words "competition," "competitive," and "compete" explicitly used in five replies. The poor economic efficiency of generators was referred to through references to "high prices" used in two replies. And the potential negative consequences of cross-border electricity trade associated with poor economic efficiency appeared through the use of the words "opposed," "reluctant", "threat," "worsen," and "weaken" in five replies.

Supporting the first idea, participants advanced the arguments that both in Japan and South Korea the generation segment of EPCOs enjoyed comfortable non-competitive monopoly situations for decades. According to a participant, monopolies tend to be "more national-centric," and "often consider as a first priority their contribution to security of supply within their domestic market." In this framework, it is understood that international expansion and economic competitiveness are not prioritized. Then, the fact that incumbents usually do not welcome increased competition – that is often at the heart of electricity system reform efforts – may be understood as ultimately counterproductive for economic efficiency, including their own. In this regard, a participant noted that in the two countries studied incumbents were opposed to electricity system reform: "[…] the skepticism of producers in Japan and South Korea may have rather to do with their general resistance against the liberalization agenda as a whole, since the liberalization process weaken their dominant position."

Supporting the second idea, several participants rightly stated that electricity prices in Japan and South Korea electricity prices are high. This fact may indeed be observed by comparing power exchange prices in these countries; on average JPY 8.4/kWh in Japan [19] and JPY 8.6/kWh in mainland South Korea [20] in the calendar year 2019, with those about 1.5 to 4.0 times lower in Europe (e.g., France and Germany [21], and the Nordic region [22]), and in most of the United States [23] in the same year. For example, a participant replied that the reason for power companies in the generation business segment to be reluctant to cross-border electricity trade: "[…] is probably that the power companies are acting on local markets with relatively high prices."

Supporting the third idea that poor economics leads to legitimate concerns about increased competition from cross-border electricity trade two participants made unequivocal statements. The first was: "When your home market has high wholesale prices as in Japan, competition is a threat." The other was: "Competition is a great advantage for the generators who are efficient and competent. Only if you know that you cannot achieve competitive generation it is obvious you should be reluctant, and even oppose open competition." In a broader scope, another participant provided the example of the impacts of competition from domestic and foreign RE on incumbent power companies: "Competition (and its prospect) with both domestic and foreign renewables roughly halved German utilities' market cap in a few years, and is currently speeding the retirement of old and even rather new thermal plants in the Nordic and United States power pools (and in principle in France). Increasingly around the world, thermal plants' operating costs alone can no longer compete with new renewables. Incumbents, seeing their legacy thermal plants inexorably pushed up the load-duration curve and toward insolvency, are therefore naturally reluctant to expose their balance sheets to that competition, or to allow competition that would forego politically enabled opportunities to keep earning profits from uncompetitive assets," echoing to some extent one of the contributions received for question 3 about the fact the Japanese EPCOs should be more concerned about the competition from the domestic expansion of RE rather than that from foreign power plants.

Supporting the fourth idea, it is understood that to avoid worsening profits from competition, as a participant simply put it: "Any generator would like a monopoly or oligopoly." Therefore, as another participant answered: "[…] the natural movement of insider operators is to preserve their internal market." An empirical example of this type of strategy was provided by another participant again: "In France, EDF has opposed stronger grid connections to the renewable-rich Iberian grid – while encouraging them to the higher-priced British grid."

This description of competition for Japanese and South Korean generators is rather dark. However, a few participants also offered more positive perspectives. For instance, a participant stated that: "[…] most generators will survive and should be in favor of open international competition." Another one answered that suppliers benefit from competition at the generation level, as observed in Europe. This answer combined with that of another participant: "[…] integrated companies can play both games at the same time" indicate that for EPCOs active in the generation and supply segments there are not only threats from competition, but also opportunities.

Finally, two participants offered additional points of views. The first, suggesting to strengthen electrical interconnections within Japan to spur domestic competition in priority, then to pursue international interconnections as a next step. The second, stressing the importance of cross-border electricity trade to deliver competitive electricity prices which are necessary for energy intensive industries to compete in global manufacturing markets. This participant expects that: "[…] in Japan and South Korea the industry would be the ones pushing for an opening of the market with an interconnection. All actors also need to see that in the long-term an interconnected system offers lower cost. As one example, a modern battery factory requires large amounts of electricity and here Japan today has no chance to compete with the Nordic countries."

Question 5:

What could be the key strategies to be implemented at the generation and supply levels for power companies in Japan and South Korea to improve their business situations in a framework of international electricity trade competition?

To this question the participants in the survey provided multiple answers, indicating there are many possible strategies that could be implemented to improve the situation of the competitive business segments of power companies in Japan and South Korea in a framework of cross-border electricity trade competition. The suggestions received were not limited to what power companies could do within their scope, they also included proposals for an overall more enabling framework. In the following paragraphs these suggestions are presented separately depending on whether they are to be implemented by power companies or not. There is no hierarchy made among the strategies proposed.

Among the strategies which could be implemented by power companies, the participants advanced six main ideas: (1) Seeking new opportunities, (2) starting small, (3) developing jointly, (4) opting for bidirectional trade, (5) differentiating generating and flexibility assets, and (6) reshuffling human resources.

Regarding the first idea of seeking new opportunities, two quotes from two different participants providing specific examples are used to illustrate this point: "Convince their financiers and Boards that incremental decay of business prospects, and losing customers, is inferior to boldly grasping new opportunities in cheaper efficiency and renewables." And: "Access to new markets. Risk diversification. Leading the sector transformation in the context of the liberalization (and the development of renewables)." As for the second idea of starting small (i.e., limiting the size of the initial interconnection), participants noted that it would enable power companies to experience the benefits from international electricity trade while being exposed to limited competition only. A participant answered: "Start relatively small and learn by doing with realistic shared goals, including acknowledging and valuing the energy security benefits of diversification, and load balancing." Another one that: "This limits the potential for competition, and therefore the potential price impact […]." The third idea about developing (the interconnection) jointly supports the point of view of sharing benefits and risks associated with interconnecting. A participant developed this idea further by answering that not only an interconnection could be developed between the two countries, but also RE projects: "Japan should also leverage the benefits of jointly developing offshore wind and subsea cable connectivity with South Korea, sharing the capital cost of development […]." The fourth idea is that cross-border electricity trade would preferably take place on a bidirectional basis as a participant stated it: "[…] trade can (and should) be bidirectional. That is, some generators on both sides may end up exporters at different times." This means that the door is fully opened to competition and this should avoid the establishment of dependence relationships between an exporter and an importer. The fifth idea highlights the importance of differentiating generating and flexibility assets. To start with, obsolete assets should be retired. Then, domestic RE resources aiming for comparative advantage should be developed as well as flexibility assets for integration purposes. In this framework, complementarities may be reached by differentiating and focusing on each participant's strengths. Regarding flexibility assets in particular, a participant referred to the increasing role of: "[…] digital analytics to forecast both supply and demand for electricity […]" and also mentioned "storage" and "demand side management" as solutions. Finally, the sixth and last idea supported by one of the participants was to reshuffle human resources targeting obstructive top decision makers when necessary: "Retire executives who keep trying to protect the old system rather than enable the new."

Among the strategies which could be implemented by other stakeholders to stimulate power companies to take part in international electricity trade competition, the participants advanced five ideas: (1) resolving historical and political issues to build trust, (2) establishing a fair and transparent legal and regulatory framework, (3) defining a clear and simple price setting mechanism, (4) encouraging customer choice for cleaner and cheaper power, and (5) lightening cumbersome administrative procedures (in Japan).

As for the first idea, without resolving historical and political issues and thus building mutual trust between the two countries, it is probably exaggeratedly complicated for power companies on each side of the border to commit to an international interconnection project. In this regard, a participant suggested top level cooperation including both national governments and power companies to move forward with a technical feasibility study of power transmission: "It is necessary to start the inter-governmental talks with both country's utility and co-work the detailed feasibility study." The second idea was to establish a fair and transparent legal and regulatory framework. Supporting this idea, a participant stressed the necessity of ensuring: "[…] a strong and independent regulator," without further details. As for the third idea, defining a clear and simple price setting mechanism, several suggestions were made in this direction, sometimes including GHG emissions considerations. For example, a participant replied that a: "Starting point would have to be to take an independent look at the most efficient way to build a fossil-free electricity system for the region rather than the countries. Experiences from the Nordics but increasingly also from Europe is that a regional approach taking in account the regional benefits e.g., where the lowest cost renewable production can be built will result in the lowest cost and the most competitive system." This participant also added that any non-price-based dispatch rules should be removed (as it currently exists in Japan [24]). Another participant answered: "Price transparently across time and space. Allow all demand- and supply-side resources to compete fairly at honest prices. Seek comprehensive energy de-subsidization." (an evidence of the latter is the fact that retail electricity prices [25] are sometimes below power exchange prices [26] in South Korea). A third participant hinted to a power exchange as the appropriate platform for such cross-border electricity trade. The fourth idea is based on encouraging customer choice for greener and cheaper power "possibly sourced from abroad" as a way "to put pressure on reluctant power generators." Finally, the fifth and last idea was to lighten cumbersome administrative procedures for Japanese power companies.

Though the expression/terminology of “red tape” was not directly expressed by the participant, it was heavily insisted that institutional issues are quite problematic for power companies in Japan to take action in interconnection projects, domestically and even more internationally.

Question 6:

What are your thoughts on why such interconnection Japan – South Korea has not been realized to date? Are the stances of power companies in Japan and South Korea playing an important role?

From the answers received to this question a quasi-consensus emerged that geopolitics has been the main issue that has prevented the realization of a Japan – South Korea electrical interconnection to date. Some participants stressed the importance of the stances of power companies, especially in Japan, with slow national electricity system reform processes in the background, while other participants recognized this issue as secondary. A few participants additionally pointed out the possible lacks of complementarities between the two countries' power systems and of potential economic benefits (these considerations are rather in contradiction with the facts and findings presented in Chapters 1 to 3 of this dissertation).

Fig. 4-7 visually summarizes the answers of the participants described in the previous paragraph.

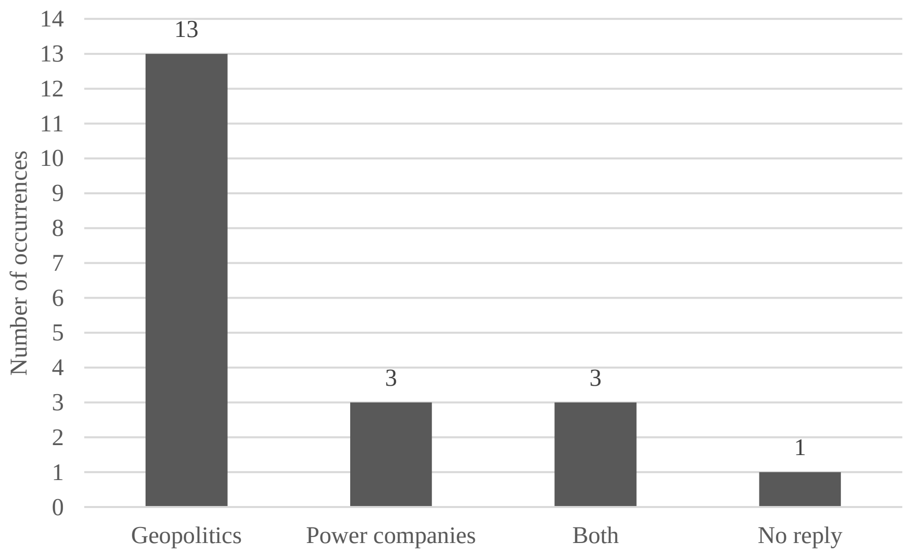


Fig. 4-7 Identified barriers to a Japan-South Korea electrical interconnection.

Damaged and not fully repaired historical relationships and current lack of mutual trust appear to be the key factors behind geopolitical issues between Japan and South Korea. Starting from this point, each country has rather taken a national-centric approach to ensure its energy security, i.e., which is the opposite of interdependency crystalized by interconnections. In this regard, four examples of participants' explicit answers are provided for illustrative purposes: a first participant stated: “I believe that there is no history of trust between the countries […].” A second one: “Frankly speaking, I think it is necessary to recover their political confidence. That is the prerequisite to realize the power trading between Korea and Japan.” A third one: “[…] the political mood between the countries is key in the first place and prerequisite for stepping forward business dialogue among private companies.” And a fourth one: “The relationship between Japan and Korea is a very sensitive issue. It is clearly difficult to think in Japan and Korea in terms of mutual interdependency which is structurally, what an interconnection is. It is not a surprise that interconnections have been progressing in Europe at the same time the European market became more integrated.” Interestingly another participant not only raised the geopolitical issue, but also the lack of interest from the Japanese Government itself: “It seems the Japanese government's trust for the South Korean side has not been built sufficiently. The South Korean government and Korea Electric Power Corporation have expressed their interest for more than ten years, yet power trade does not have any progress. Both governments even do not have any official discussions on this matter--this implies Japanese government does not have any interest at this point.” On a more positive note, another participant saw in an interconnection project a “part of an international reconciliation.”

Furthermore, some participants identified the importance of the power companies’ stances as a key hurdle towards the realization of electric interconnection projects. Slow electricity system reform being a reason of the behaviors of power companies, especially in Japan. A participant affirmed: “Yes—they are the main obstacle. Incumbent utilities' undue policy influence, opaque pricing and operations, and aversion to price competition create potent obstacles. Historic enmities and diplomatic frictions are also exploited by politicians and interest groups to create a diplomatic background unhelpful to collaboration.” Another one contributed: “The position of domestic power companies is certainly a key point. Within Japan, for example, there is already a relative lack of integration between EPCOs, the result of a general preference toward locally developed and controlled generation and transmission systems.” And a last one replied: “The case for international supergrids in Asia and elsewhere depends on many complex factors. The most obvious questions are around cost and security (which cannot be similarly monetized and may be incommensurable). However, opening up recalcitrant incumbents to full and fair competition could certainly be a very important side-benefit of such engagement by Japan and South Korea.”[k]

Finally, a few participants pointed out the possible lacks of complementarities between Japan and South Korea’s power systems, and of potential economic benefits. For instance, a participant comprehensively developed: “Mostly a lack of geopolitical support and low economic benefit. I think indeed that the benefit of power system integration between Japan and South Korea is minimum today, and therefore politically not very attractive (especially because there is other strong geopolitical resistance against such an integration process between the two countries). From an energy policy point of view, it seems to me normal that the priority is given to the national market liberalization processes and system integration challenges in both countries, as their impact is much more important. I would also favor such an approach,

[k] Exceptionally, because of its relevance to this question this quote has been transcribed here from the “Thank you very much for your participation! Please feel free to ask a question, or leave a comment!” dedicated field at the end of the survey.

as it would bring more immediate benefits when it comes to integration of renewables. Given their historic structure and function within the economies, in both Japan and South Korea, I expect power companies to simply align themselves on the high-level geopolitical priorities from their respective countries." And another one answered: "Japan and South Korea have similar power generation profiles based on expensive fossil-fuel imports and nuclear. They are not as complementary as for instance Spain (with abundant cheap solar resource) and France (with aging and more expensive nuclear)."

Question 7:

Related to the environment, has your organization accessed the environmental impact of its international power exchange activities and does it result in CO_2 reduction or less air pollution?

In response to the first part of this question, five participants clearly indicated that the organization they represent accessed the environmental impact of their international power exchange activities, and five replied negatively. The other participants did not provide clear answers to the first part of this question and rather focused on its second part. Regarding the latter, the participants' contributions provided two key points: (1) The impact of cross-border electricity trade on GHG emissions depends on the electricity generation mixes of the countries taking part in such exchanges, and (2) international interconnections help the integration of RE into power systems, which should ultimately result in the reduction of GHG emissions.

The participants who raised the first point above explained that it depends on the carbon intensity of the electricity imported that replaces domestic generation. Before quoting answers from some of the participants, an illustrative example is given to facilitate readers' understanding. This example is centered on electricity generated from heavily polluting coal, which has higher marginal costs than some clean RE (e.g., solar and wind…), but often lower than moderately polluting gas. At the wholesale level, the price of electricity is set by the marginal cost of the marginal power plant dispatched (merit order principle). It is thus understood that a country generating a lot of its electricity from coal may be interested in importing electricity generated from solar and wind for economic reasons, which would benefit the environment. At the same time, a country generating a lot of its electricity from gas may be interested in importing electricity generated from coal for economic reasons, which would be detrimental to the environment. Echoing this rather simple demonstration, a participant replied: "[…] we have assessed CO_2 emissions impact due to international trade, and concluded that CO_2 benefits depend on power mix (power trade is not always environmentally friendly). For example, if Japan imports fossil fuel power (like cheap coal-fired power from neighboring countries), it would result in worsening climate issues." Another one: "In Europe, […] there have been "paradoxical" periods over the last decade during which the market's operating rules have given priority to coal, to the detriment of European interests in terms of CO_2 and air pollution." And a last one: "International trade can result in lower emissions if you can import cheap renewables. This is the case in Europe with cheap Nordic wind and Mediterranean solar." An analysis is therefore required in each particular case. A participant suggested that this issue may be solved thanks to economically explicit environmental policies such as an emissions trading system that can be operated on a competitive international market.

As for the second point, several participants affirmed that international electrical interconnections help the integration of variable renewable energy into power systems because over larger areas generation profiles of solar and wind are more complementary and less volatile, hence contributing to the reduction of GHG emissions. For instance, a participant illustrated: "Today's very high penetration of renewables particularly in Northern Europe would never have been possible without interconnections. The first example of this was the large expansion of wind power in Denmark that was entirely relying on balancing power from the Nordic neighbors. This is now repeated on a larger scale particularly in Northern Europe where interconnections between the Nordic System and the mainland Europe, but also between the countries is instrumental for expansion of the renewable production system. This is also the reason that there exist concrete plans on European level to expand the interconnections and harmonize the markets." And another one: "[…] international power exchange should assist grid balancing of intermittent renewable energy and drive a progressive decarbonization, as it has done in the United Kingdom. For India, there is huge opportunity for the country to progressively build zero emissions green electricity exports, and to assist in evening load balancing by importing solar from Oman 1,500 km in the west (i.e., the time difference means it is still afternoon there into India's evening peak)."

4.4 Conclusion

In this chapter a qualitative analysis complementary of the empirical and theoretical quantitative analyses of Chapter 2 and Chapter 3, respectively, has been led. This analysis has been based on a novel survey of energy experts on the impacts of cross-border electricity trade on power companies in the framework of a Japan – South Korea interconnection, and consisted of seven questions.

Of the 30 energy experts, mainly from the Asia-Pacific region and Europe and principally representing think tank & research organizations and power companies, invited, 20 completed the survey. The overall participation rate was deemed satisfactory, so was that of representatives of power companies, which was critical since the topic focused on the impacts of international electrical interconnection on the activities of these latter ones.

It has been found that in the case of the competitive business segments of generation and supply expectations towards cross-border electricity trade were divisive with both opportunities and threats identified, and depend on national contexts. Power companies were seen as rather cautious than ambitious towards electricity trade, again depending on domestic situations. In the specific case of a Japan – South Korea electrical interconnection, participants pointed out that generators in these two countries tend to be reluctant to competition, leading to poor economic efficiency, and legitimate concerns about competition resulting from cross-border electricity trade. To address this issue, participants provided multiple suggestions for possible strategies that could be implemented to improve the business situation of the generation and supply segments of power companies in Japan and South Korea in a framework of cross-border electricity trade competition. These suggestions were not only limited to what power companies could do within their scope, but also included proposals for an overall more enabling framework highlighting the importance of other stakeholders. Moreover, even though a quasi-consensus emerged that geopolitics has been the main issue that has prevented the realization of a Japan – South Korea electrical interconnection so far, some participants also stressed the importance of the stances of power companies, especially in Japan, with slow national electricity system reform processes in the background. Finally, some participants clearly indicated that the organization they represent accessed the environmental impact of their international power exchange activities, some others replied negatively, and some did not provide clear answers. The participants also explained that the impact of cross-border electricity trade on GHG emissions depends on the electricity generation mixes of the countries taking part in such exchanges, and that international interconnections help the integration of RE into power systems, which should ultimately result in the reduction of GHG emissions.

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Chapter 5:
Conclusion

5.1 Dissertation summary and future research work

In the introductory Chapter 1, it has been observed that in many regions worldwide, international power system interconnections have been developed and cross-border electricity trade is the norm rather than the exception. Europe has been highlighted as the world's best example of interconnected power systems. In contrast, Northeast Asian countries, and especially Japan and South Korea which are still not interconnected with any of their neighbors, have been recognized as clearly lagging behind. Previous works have demonstrated that interconnecting Japan and South Korea should be technically feasible and economically profitable. With this background it has been understood that advancing such project would make sense and should raise the interest of EPCOs, and particularly their transmission arms. The doctoral student has identified that this has not been the case in Japan yet, partly because of energy security concerns related to possible geopolitical tensions, and partly because of the business structure of EPCOs and the fears about the impacts of international competition on their competitive generation and supply business segments. The latter being a critical scientific research unknown. Thus, the value of this dissertation has lied in its complementary creative attempts to bring answers to the fundamental question:

What will be the impacts of an international electrical power interconnect with South Korea on Japanese EPCOs' competitive business segments?

In Chapter 2, an innovative methodology based on an empirical comparison of power exchange prices has been advanced to assess the potential impacts of cross-border electricity trade between west Japan and mainland South Korea on EPCOs' competitive business segments. The key findings have been that: If an international electrical interconnection had existed between the two areas considered in the period 2018-2019, it would have benefited to Japanese EPCOs thanks to gains from lower procurement costs for suppliers, overcompensating the losses of generators due to increased competition. It has also been explained that despite its advantages, availability and transparency of accurate and detailed data, and its relative simplicity, this methodology proposed has been confronted to one major drawback that has been the impossibility to measure the impact of cross-border electricity trade on domestic prices.

In Chapter 3, a complementary theoretical quantitative analysis has been led by developing a computer simulation of Japan and South Korea interconnected power systems considering three different interconnection scenarios (Chugoku, Kansai, Kyushu), and also assessing the potential impacts of cross-border electricity trade between Japan and South Korea on EPCOs' competitive business segments. This analysis, though also imperfect (sophisticated and limited by input availability), has solved the main issue identified in the previous chapter. The key findings have differed a little from earlier results. Indeed, though in both analyses cross-border electricity trade would benefit to Japanese EPCOs, the new analysis conducted in this chapter has shown that in 2018 higher generators' sales would have overcompensated the losses of suppliers facing higher procurement costs due to increased electricity prices resulting from South Korea's net imports.

In Chapter 4, a qualitative analysis, complementary to the quantitative analyses of the two preceding chapters, based on a novel survey of energy experts has been realized. This survey has focused on the impacts of cross-border electricity trade on power companies in the framework of a Japan – South Korea interconnection, and has consisted of seven questions. Of the 30 energy experts, mainly from the Asia-Pacific region and Europe and principally representing think tank & research organizations and power companies, invited, 20 completed the survey. It has been found that in the case of competitive business segments, expectations towards cross-border electricity trade are divisive with both opportunities and threats identified, and depend on national contexts. Power companies have been seen as rather cautious than ambitious towards electricity trade, again depending on domestic situations. In the specific case of a Japan – South Korea electrical interconnection, participants have pointed out that generators in these two countries tend to be reluctant to competition, leading to poor economic efficiency, and legitimate concerns about competition. To address this issue, participants provided multiple suggestions. In addition, even though a quasi-consensus emerged that geopolitics has been the main issue that has prevented the realization of a Japan – South Korea electrical interconnection so far, some participants have also stressed the importance of the stances of power companies, especially in Japan. Finally, some participants have clearly indicated that the organization they represent assess the environmental impact of their international power exchange activities, some others have replied negatively, and some did not provide clear answers. They have also explained that the impact of cross-border electricity trade on GHG emissions depends on the electricity generation mixes of the countries taking part in such exchanges, and that international interconnections help the integration of RE into power systems.

To conclude, having extensively assessed the potential impacts of cross-border electricity trade between Japan and South Korea on EPCOs' competitive business segments, from all possible perspectives (empirical and theoretical quantitative analyses, as well as quantitative analysis), the doctoral student understands that it is in the interest of Japanese EPCOs to interconnect with South Korea under the current conditions, which should encourage them to adopt a more proactive stance. By definition, however, the future is uncertain, and power systems are constantly dynamically evolving. Recently, in October 2020, both Japan and South Korea announced targeting carbon neutrality by mid-century. At the time of writing this dissertation little is known on how each country will manage to reach this similar objective making it impossible to draw clear conclusions on the future potential impacts of the cross-border electricity trade proposed here. Once concrete plans and more information will be made available, which may take up to a few years, it will be possible to start calculating new meaningful projections for a Japan-South Korea interconnection, stimulating this research field again. At that time, it will be of utmost importance to evaluate the impacts of interconnecting these two countries both from economic and environmental perspectives. From an environmental point of view more specifically, this could include an environmental impact assessment of proposed interconnection projects, and analyses of decarbonization mechanisms such as carbon pricing or power plants GHG emissions standards. Also, thinking beyond the power sector, indirect effects of international electrical interconnections on the broader energy system of each country could be considered. This future work may be inspired by instructive lessons from Europe, the leading continent for both carbon neutrality and interconnection progresses.

Publication of Results

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Submitted to the Journal of Asian Energy Studies in August 2021; Zissler R, Cross JS. Japan's nuclear power 2030 projections unmet and replacement with international electrical interconnections.

Submitted to the 11th Solar & Storage Integration Workshop in August 2021; Zissler R, Wakeyama T, Cross JS. International electrical interconnection to unlock solar photovoltaic potential and accelerate progress towards carbon neutrality in Japan and South Korea [extended abstract accepted in June 2021].

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Thank you very much to you all again,

Romain

Appendices

Appendix A: Screenshot of the extended abstract (referred to in Chapter 3)

UKJEEL 2021 Virtual Workshop Abstract

Shaping Japan's Climate and Energy Future by Developing a National Dedicated Repository for Computer Simulation Research

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Keywords: Japan, energy future, repository, computer simulation.

I. Introduction

On October 26, 2020, new Prime Minister Yoshihide Suga announced that Japan will pursue the objective of carbon neutrality by 2050 [1]. This ambitious and necessary goal requires efficient climate and energy strategic planning. The future is by definition uncertain, but it is possible to explore it more or less accurately thanks to computer simulation. Computer simulation is a resource intensive engineering research work. Two main challenges are to be addressed in this enterprise: on the one hand data input, on the other hand data processing. This extended abstract focuses on the need to improve data input accessibility and transparency to enhance the quality of energy modelling, in particular of power systems, as a key tool to shape Japan's climate and energy future.

A. Key Observations

In Japan in 2019, the power sector accounted for 47% of the country's total carbon dioxide emissions, because of a heavy dependence on fossil fuels, especially coal and natural gas power which shares in electricity generation were 32% and 34%, respectively [2]. Thus, progressing towards carbon neutrality implies decarbonizing the power sector in priority.

This priority has been recognized in Japan for some time now. Indeed, before announcing pursuing carbon neutrality, the country in 2015 already advanced the 2030 commitments of reducing its greenhouse gas emissions by 26% (compared to 2013), notably by increasing the shares of renewable energy and nuclear in electricity generation to the detriments of fossils [3].

B. Roles of Computer Simulation and Validity Check Procedure

Computer simulation enables to explore decarbonization pathways by developing different scenarios to the discretion of researchers. Before reaching this advanced stage, it is, however, necessary to ensure correctness of data input & processing and model output. In this regard, proceeding to tests under the current situation is a critical starting point.

Tests under the current situation is a critical starting point because it allows to check the validity of computer simulation input and output. For example, in the case of the modelling of power systems in Japan, such validity check procedure may consist in comparing theoretical power system prices with those empirical provided by the Japan Electric Power Exchange.

II. Findings

A. Main Results

The validity check procedure is an energy and time-consuming effort especially when an issue occurs and it is not straightforward to identify. It may be caused either by an incorrect data input or data processing. Data processing is related to engineering science and there is no quick fix for issues occurring on this side of the computer simulation. In contrast, data input may be greatly improved.

Data input may require some knowledge, but does not require specific technical skills compared to data processing elaboration. Yet, it is equally important to deliver meaningful research results. When modelling Japan power system, one of the major issues researchers face is initial data collection. Indeed, it is necessary to dig into multiple resources to find relevant information for power plants, regional electricity consumption profiles, fuel costs, or electrical grids. Also, there is no guarantee that information found is consistently presented.

This hurdle may be cleared by developing and keeping up-to-date a national repository for power system computer simulation research. This repository could be made available for free and may be developed at an academic level with partnerships between universities, public and private research institutes, and stakeholders of the power industry. Once operational it could ease and accelerate research in this field by avoiding the repetition of isolated efforts without significant added value.

B. Discussions and Future Work

Organizing the creation of the suggested repository would require a substantial initial effort, and continuous efforts to keep it up-to-date afterwards. Identifying interested in participants is another challenge.

Based on feedback received this proposal may be strengthened, including other energy sectors, and more actively promoted.

References

[1] Prime Minister of Japan and His Cabinet, Policy Speech by the Prime Minister to the 203rd Session of the Diet (October 26, 2020).

[2] International Energy Agency. World Energy Outlook 2020 (October 2020).

[3] Ministry of Economy, Trade and Industry, Long-term Energy Supply and Demand Outlook (July 2015).

Appendix B: Human subjects research ethics review implementation application approved (referred to in Chapter 4)

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審査結果通知書

令和2年4月8日

研究責任者
所　　属　環境・社会理工学院
職・氏名　教授　Jeffrey S. Cross　殿

課題名：Impacts of Interconnecting with South Korea On Japan Electric Power Comnpanies' Competitive Business Segments
研究終了日:令和3年3月31日

上記課題の人を対象とする研究実施計画を令和2年4月2日の委員会で審査し、東京工業大学人を対象とする研究倫理審査委員会規則第9条に基づき、下記のとおり判定しましたので、通知します。

記

委員会記入欄	審査終了：令和2年4月8日 修正意見等 ■承認　□条件付承認　□不可　□非該当
条件又は変更勧告の内容及び理由等	
学長記入欄	承認：令和2年4月8日 東京工業大学人を対象とする研究倫理審査委員会の結果を受けて、本計画を承認します。 **承認番号：第2020007号** 東京工業大学長 益　一　哉

Appendix C: Screenshots of the survey (referred to in Chapter 4)

Question Reply 18

Impacts of electrical interconnections on power companies' competitive business segments

This questionnaire has been created by Romain Zissler, doctoral student at Tokyo Institute of Technology, school of environment and society – department of transdisciplinary science and engineering, under the supervision of professor Jeffrey S. Cross.

Following quantitative analyses on the potential impacts of a Japan-South Korea electrical interconnection on power companies' competitive business segments (generation and supply) in these two countries, this questionnaire aims at enhancing the qualitative analysis of the student's thesis by collecting valuable information from various experts engaged in this field.

If provided, the respondent's name, organization, and position will be made available in the doctoral student's thesis for acknowledgement purpose essentially. When quoted, in the case of a publication in a peer-reviewed journal and/or the doctoral student's thesis, only the continent of the organization will be referred to as for example; Tokyo Electric Power Company → Asian power company. Respondent's answer will never be attributed to the respondent's name.
More specifically, in the case of a publication in an international peer-reviewed journal, for transparency purpose, open access to the answers may be granted under complete anonymity (i.e. answers may be accessed, but neither the name of the respondent, nor its affiliation will be disclosed).

List of seven questions below. Concise answers are welcomed. This survey should not take more than 20 minutes to complete.

Consent form: I have been adequately informed about the goals and methods of "Impacts of Interconnecting with South Korea on Japan Electric Power Companies' Competitive Business Segments" by Romain Zissler who is an Investigator with responsibility for this project. I have read the research description form, or it has been read to me. All of the points listed below have been adequately explained to me. I have had the opportunity to ask questions about these issues, and any questions that I have asked have been answered to my satisfaction.

Descriptive text (long answer)

I feel confident that I understand the following aspects of the study/trial: *

- [ ] The goals and methods of the research;
- [ ] The potentially dangerous aspects or consequences of this research, and how these will be managed, prev...
- [ ] The fact that I may withdraw from this research project at any time at will;
- [ ] The fact that if I choose not to participate in this research, I will not be penalized in any way;
- [ ] The fact that my personal information will be strictly controlled to prevent leaks or misuse;
- [ ] The fact that my personal information will not be used for any purpose other than re-testing or inquiring in ...
- [ ] The fact that I may get compensation from the Tokyo Institute of Technology if I am harmed in the course ...

By selecting the "I agree" option below, I consent voluntarily to participate as a research subject in "Impacts of electrical interconnections on power companies' competitive business segments" *

- I agree
- I disagree

Before you start: Respondent Information (do not fill in if you wish to keep anonymity). Name/Organization/Position *

Descriptive text (long answer)

Question 1: Is the organization you work for an electrical power company? Y/N If yes, is the electrical power company you work for participating in international electricity trade competition; at the generation and/or supply level (please specify)? And in which geographical market(s)? *

Descriptive text (long answer)

Question 2: Before international electricity trade competition took/take place in the markets where your expertise is prominent (please specify), what were/are the typical expectations for power companies; at the generation level? At the supply level?In the case international electricity trade competition already takes place in the markets where your expertise is prominent, were these expectations met in reality? Have there been additional benefits observed which were not originally expected (i.e. redundancy, disaster, resiliency...)? *

Descriptive text (long answer)

Question 3: Would you say that power companies are rather ambitious or cautious about international electricity trade competition? Does it depend on the considered business; generation/supply? *

Descriptive text (long answer)

Question 4: In Japan and South Korea, from a theoretical perspective, power companies engaged in the generation business seem more reluctant about international electricity trade competition than power companies engaged in the supply business. To your knowledge are there empirical evidences in other geographical markets justifying these stances? *

Descriptive text (long answer)

Question 5: What could be the key strategies to be implemented at the generation and supply levels for power companies in Japan and South Korea to improve their business situations in a framework of international electricity trade competition? *

Descriptive text (long answer)

Question 6: What are your thoughts on why such interconnection Japan-South Korea has not been realized to date? Are the stances of power companies in Japan and South Korea playing an important role? *

Descriptive text (long answer)

Question 7: Related to the environment, has your organization assessed the environmental impact of its international power exchange activities and does it result in CO2 reduction or less air pollution? *

Descriptive text (long answer)

Thank you very much for your participation! Please feel free to ask a question, or leave a comment!

Descriptive text (long answer)