Interstate electrical interconnection benefits and cost allocation:

Northeast Asia case analysis

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A few words about Skoltech

The **Skolkovo Institute of Science and Technology** is a new (since 2011) private institute located in Moscow, Russia

Established in collaboration with MIT

International, English-speaking, about 20% foreign faculty and students

Center for Energy Systems: advanced mathematical methods for energy systems and multidisciplinary approach

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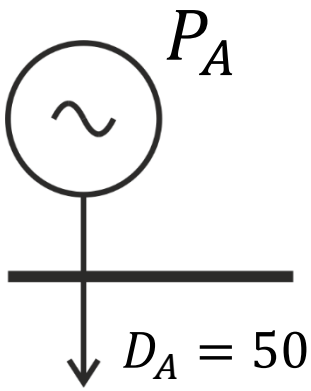
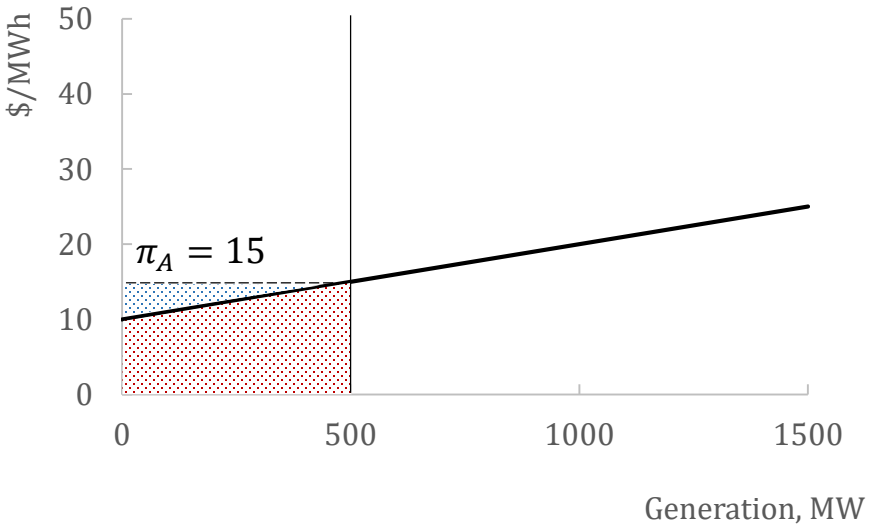
Report structure

- Fundamentals of power systems interconnection
  - Influence on power markets
  - Benefits estimation
- Cooperative game theory applied to power systems
  - Benefits and cost allocation
- Northeast Asia case analysis
  - Optimal routes of interconnection
  - Cost allocation
- Russian-Japanese electrical interconnection

Fundamentals of power systems interconnection



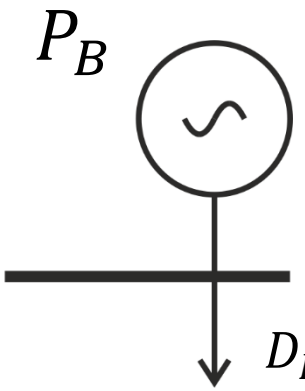
$\pi_A = 10 + 0.01\ P_A$ [\$/MWh]



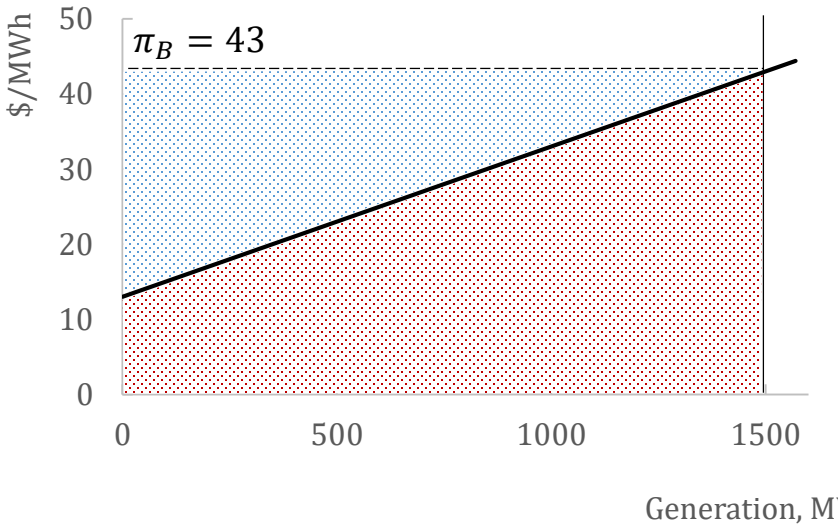
$C_A = 6\ 250$ \$/h

$S_A = 1\ 250$ \$/h

$P_A = 15 \cdot 500 = 7\ 500$ \$/h



$\pi_B = 13 + 0.02\ P_A$ [\$/MWh]



$C_B = 42\ 000$ \$/h

$S_B = 22\ 500$ \$/h

$P_B = 43 \cdot 1500 = 64\ 500$ \$/h

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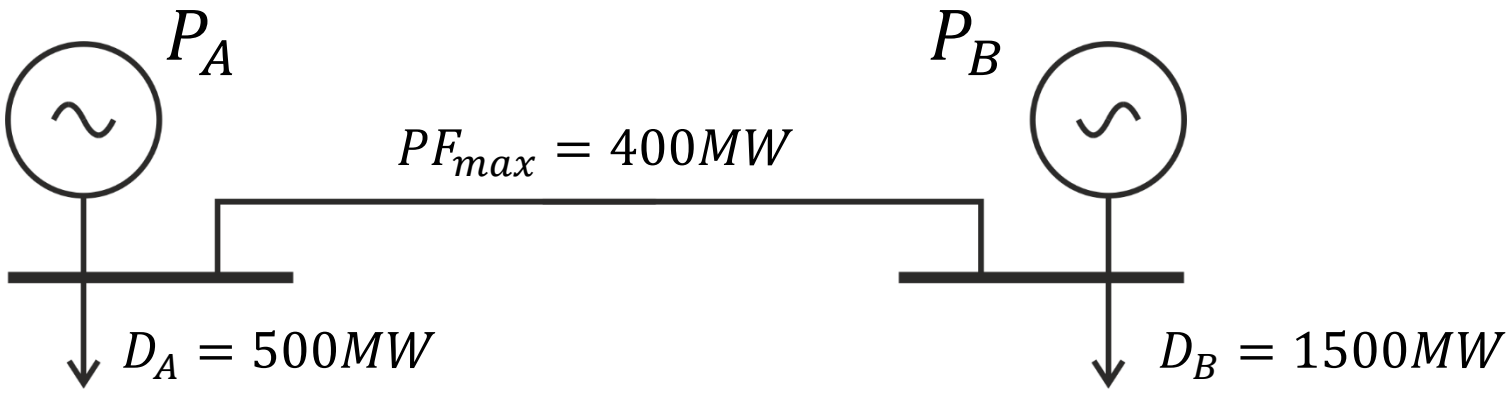
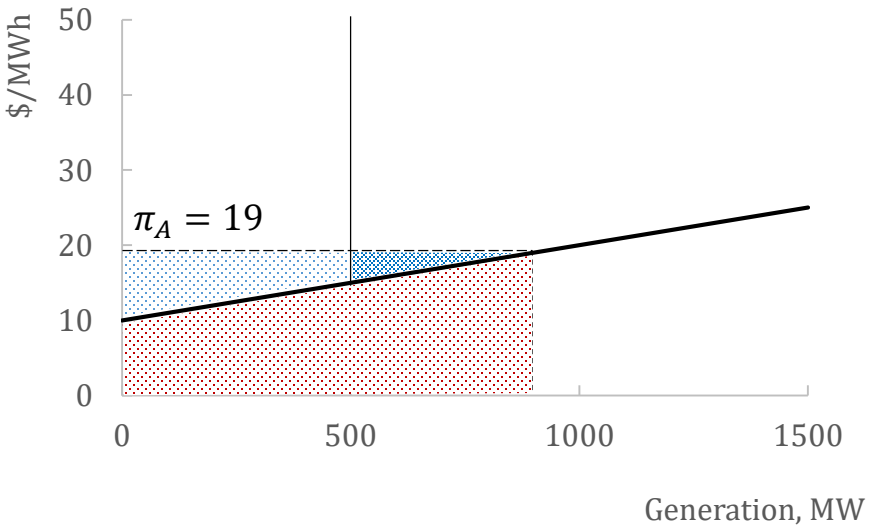
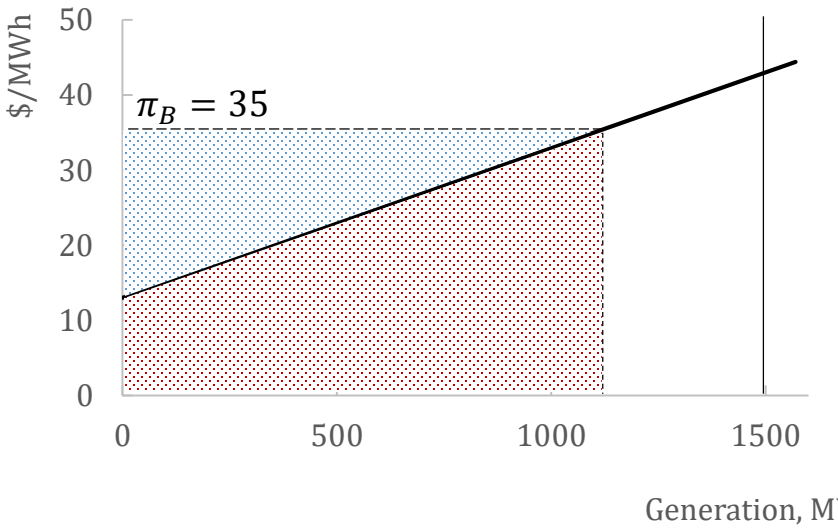
Fundamentals of power systems interconnection



$\pi_A = 10 + 0.01\ P_A$ [\$/MWh]

$\pi_B = 13 + 0.02\ P_A$ [\$/MWh]





$C_A = 13\ 050$ \$/h

$S_A = 4\ 050$ \$/h

$P_A = 19 \cdot 900 = 17\ 100$ \$/h

$C_B = 26\ 400$ \$/h

$S_B = 12\ 100$ \$/h

$P_B = 35 \cdot 1100 = 38\ 500$ \$/h

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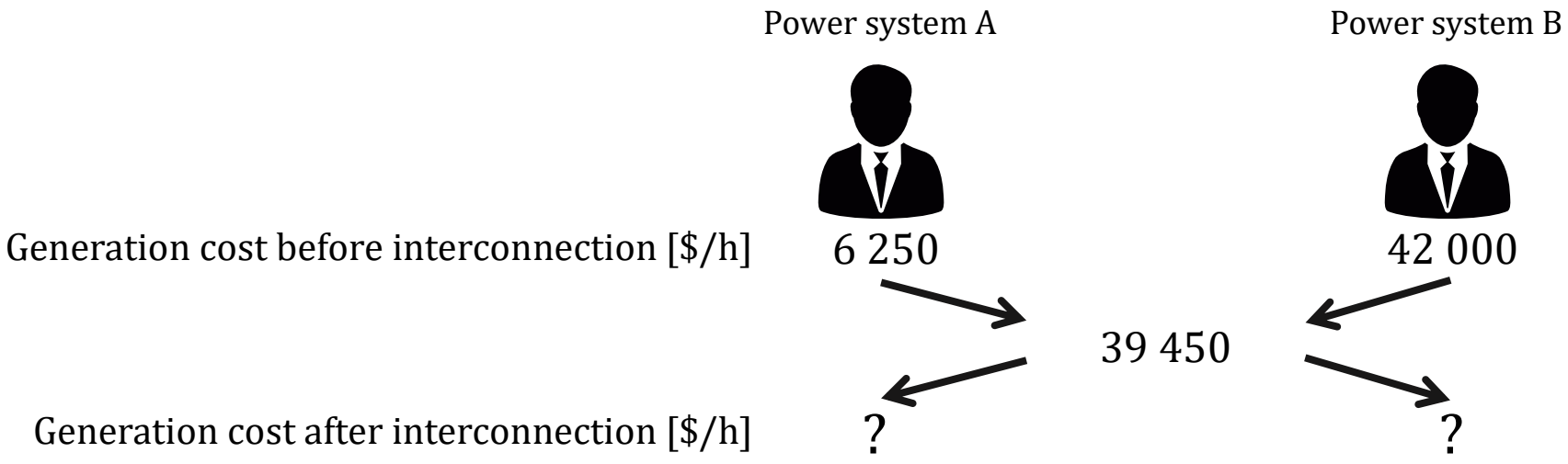
Cooperative game theory applied to power systems



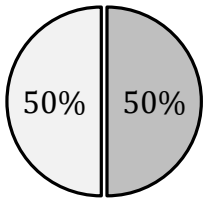
Shapley value solution concept:

$$Sh_i(v) = \sum_{S, i \in S} \frac{(|S|-1)! \cdot (|N|-|S|)!}{|N!|} \cdot [v(S) - v(S¥\{i\})]$$

$$Sh_1 = \frac{(|1|-1)! \cdot (|2|-|1|)!}{|2!|} \cdot [6250 - 0] + \frac{(|2|-1)! \cdot (|2|-|2|)!}{|2!|} \cdot [39450 - 42000] = 1\,850 \text{ [\$/h]}$$

$$Sh_2 = \frac{(|1|-1)! \cdot (|2|-|1|)!}{|2!|} \cdot [42000 - 0] + \frac{(|2|-1)! \cdot (|2|-|2|)!}{|2!|} \cdot [39450 - 6250] = 37\,600 \text{ [\$/h]}$$

Cost allocation [$/h]	1 850	37 600
Benefits [$/h]	4 400	4 400



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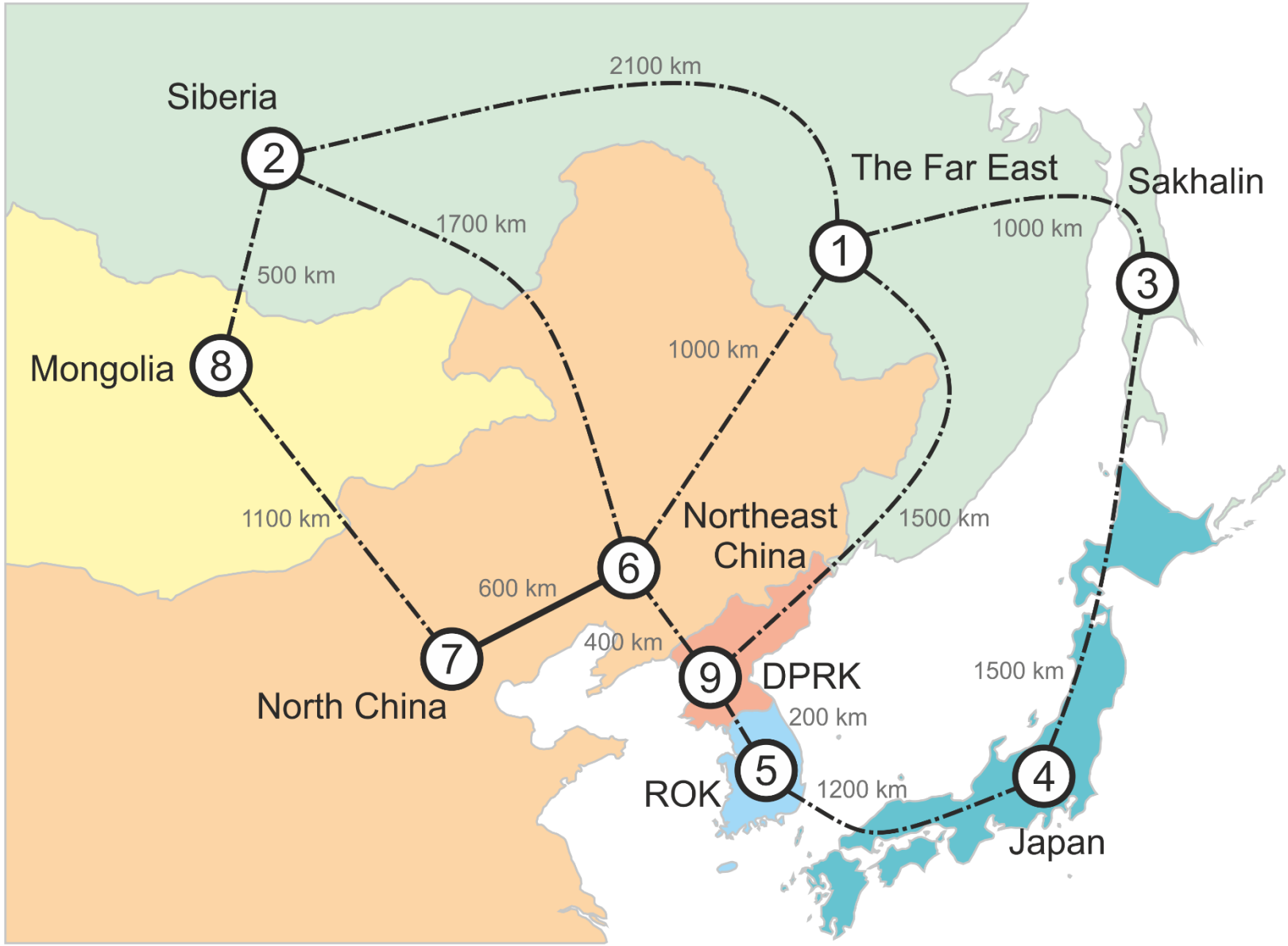
Northeast Asia case analysis



[APERC, IEEJ] T. Otsuki, A. Binti Mohd Isa, R. D. Samuelson, "Electric power grid interconnections in Northeast Asia: a quantitative analysis of opportunities and challenges", Energy Policy, vol. 89, 2016.

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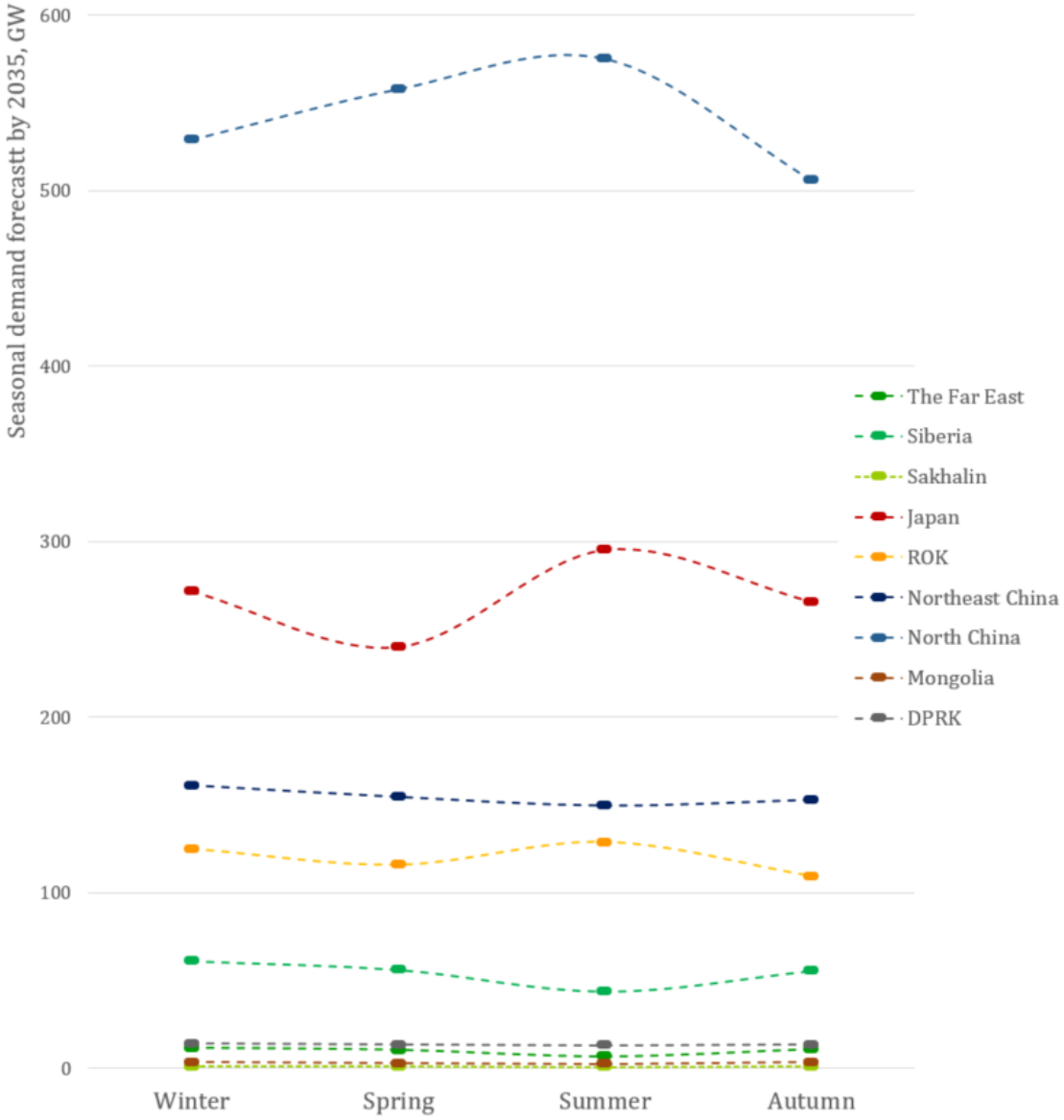

Seasonal demand curves of the countries forecast by 2035

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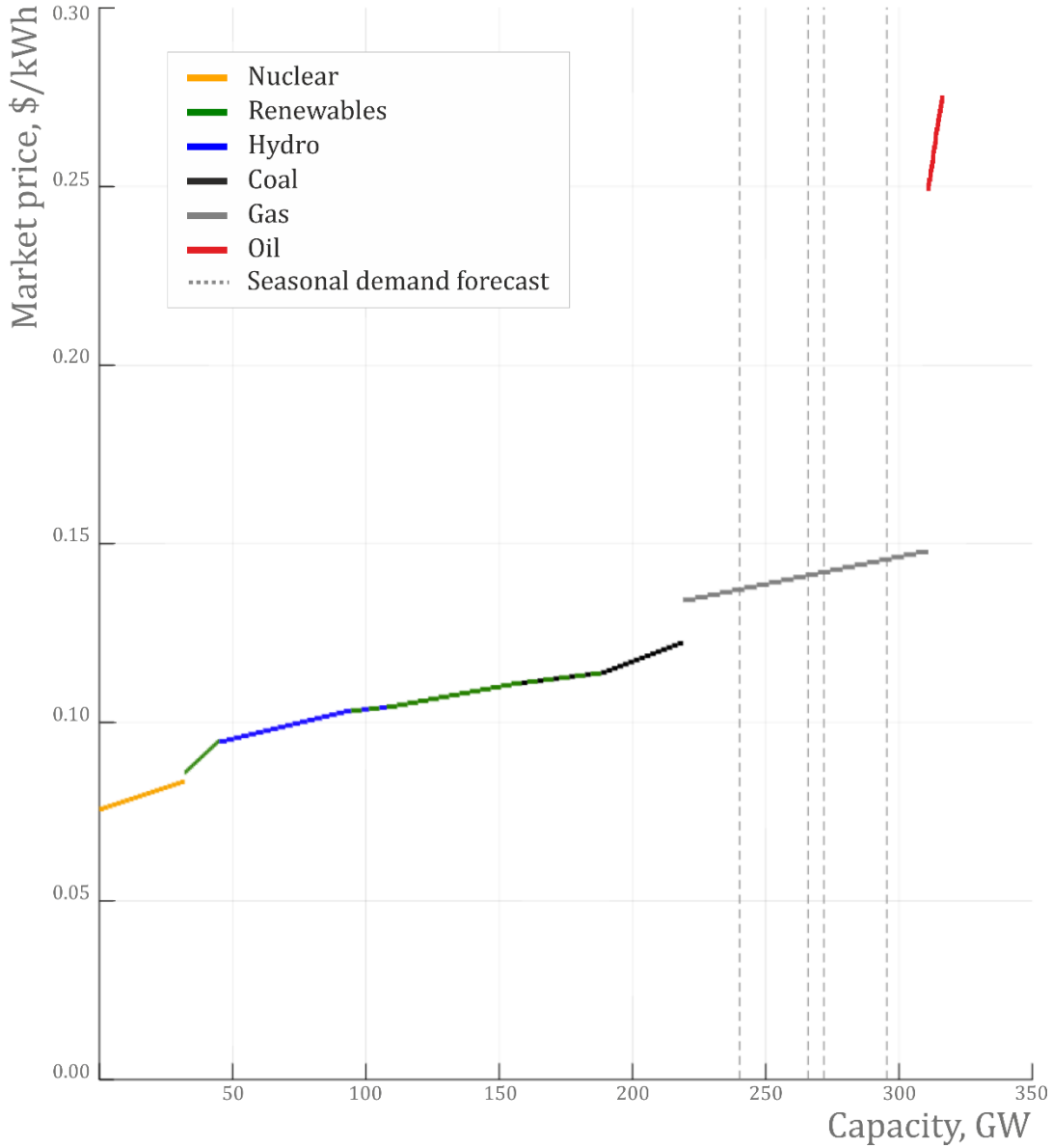
Northeast Asia case analysis



Japanese power market forecast

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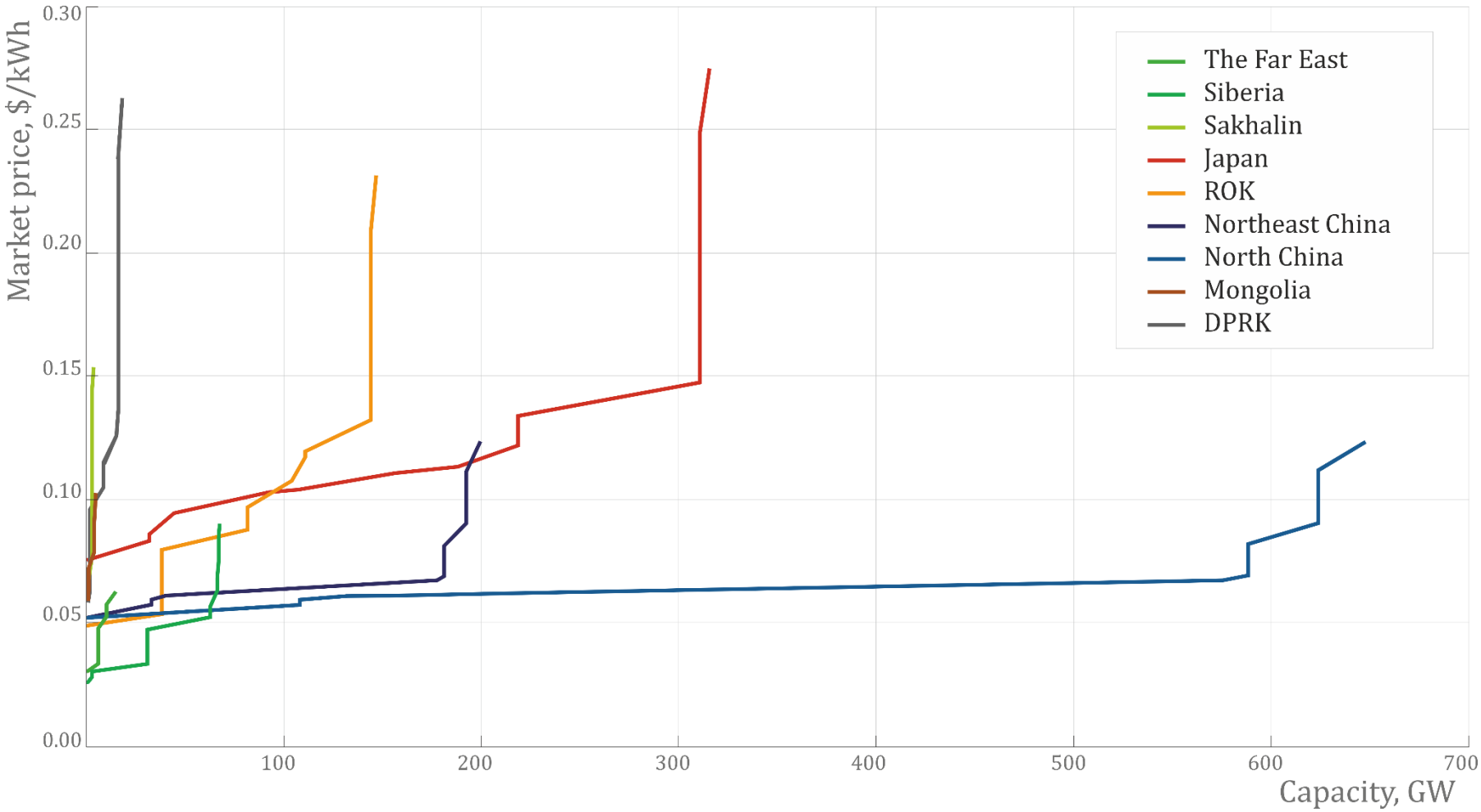
Northeast Asia case analysis



Northeast Asia power markets forecast

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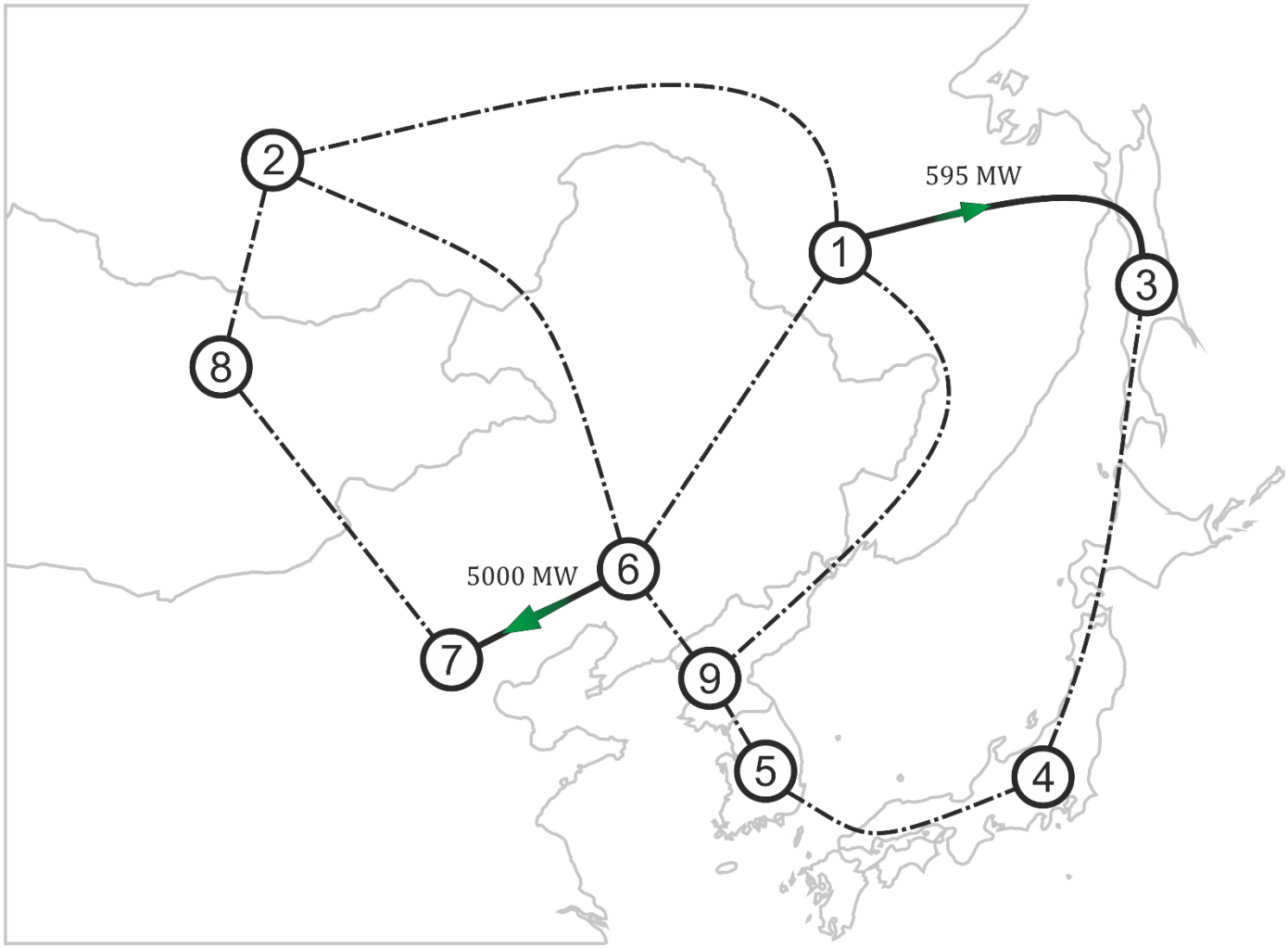
Northeast Asia case analysis



Optimal transmission capacities and power flow directions
in case of no interstate interconnections (a)

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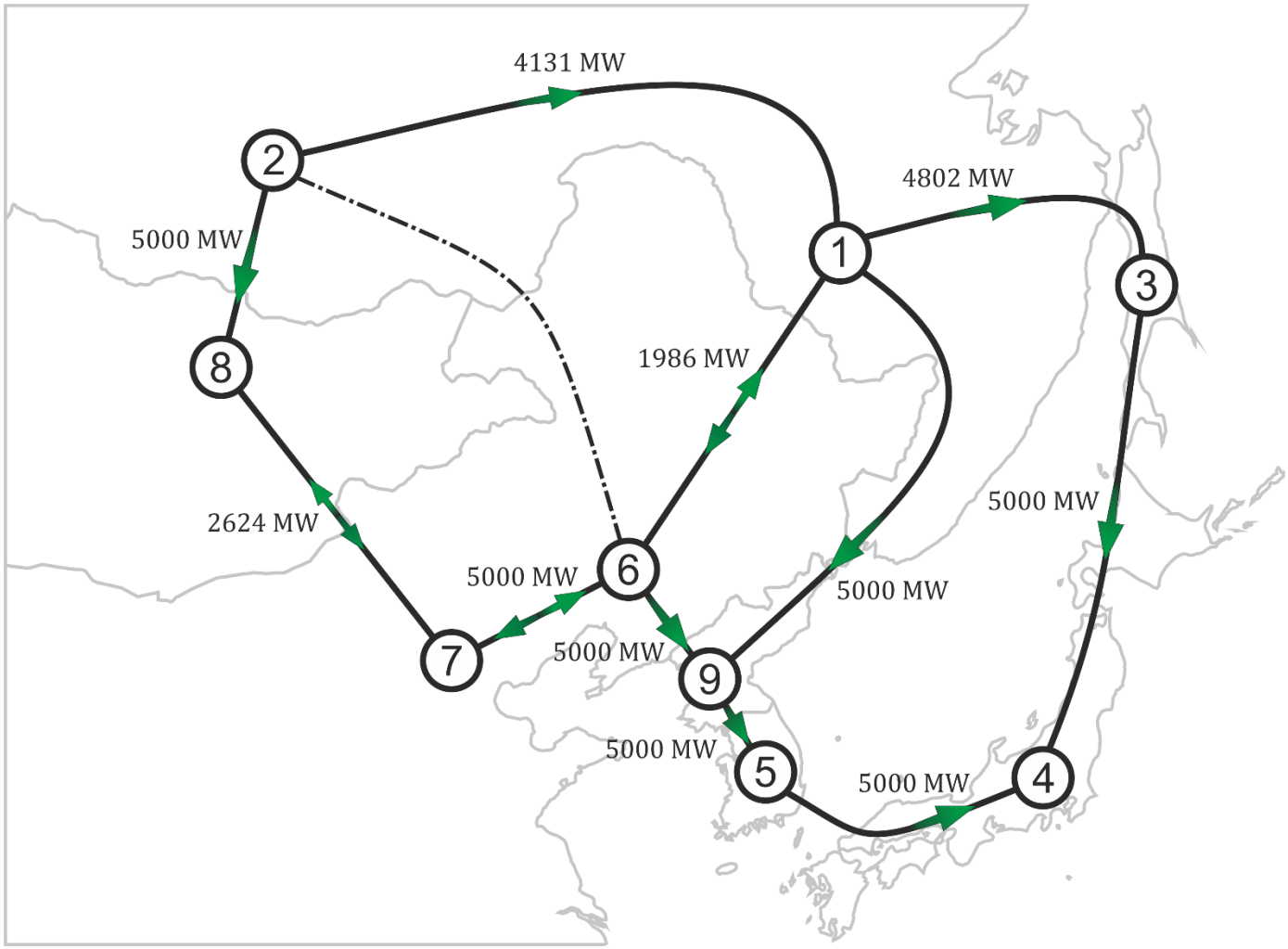
Northeast Asia case analysis



Optimal transmission capacities and power flow directions
in case of complete cooperation (b)

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Northeast Asia case analysis

	Separate development of the systems (no interstate lines can be built)	Complete energy cooperation (all the suggested lines can be built)
Total generation cost [million $ / year]	756 949.72	746 846.86
Annualized investment cost [million $ / year]	26.79	2 998.05

Total savings equal **7.1** billion dollars per year

How to share these benefits and allocate cost of the power lines?

Northeast Asia case analysis

Players: Russia 1, China 2, Japan 3, ROK 4, Mongolia 5, DPRK 6

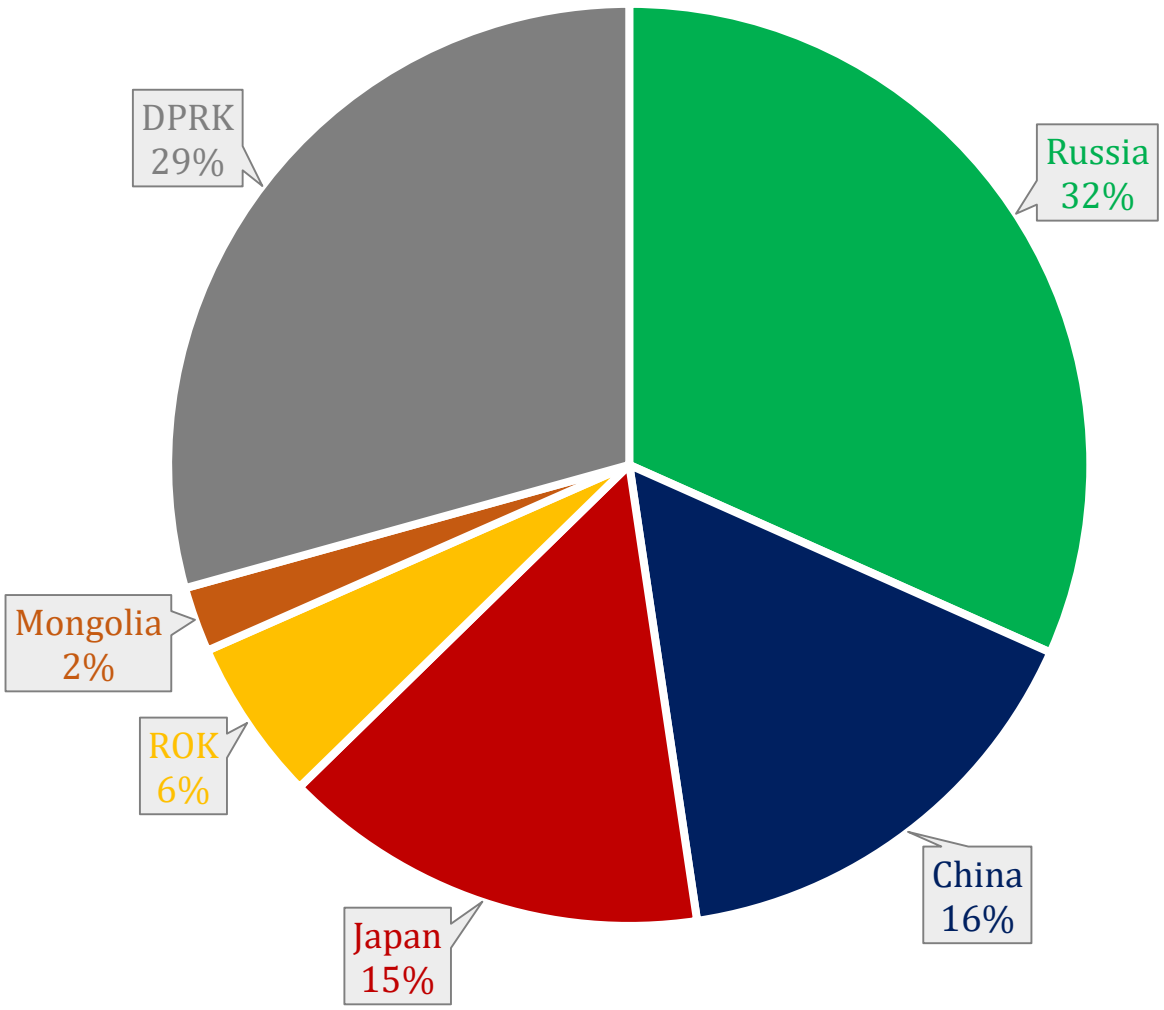
Scenario	Coalitions	Countries expenses, bln USD						V	
1	1 0 0 0 0 0	22.4581	378.509	256.260	85.6869	1.89956	12.1353	22.4849	
2	1 1 0 0 0 0	26.4634	373.692	256.260	85.6869	1.89956	12.1353	400.639	
3	1 1 1 0 0 0	27.3535	375.590	250.079	85.6869	1.89956	12.1353	654.962	
4	1 1 1 1 0 0	27.3535	375.590	243.931	91.1190	1.89956	12.1353	740.373	
5	1 1 1 1 1 0	28.3850	375.855	243.931	91.1190	0.25764	12.1353	741.948	
6	1 1 1 1 1 1	29.1117	380.866	243.931	85.6869	0.25764	6.99367	749.845	GC
7	1 1 1 1 0 1	28.5689	379.985	243.931	85.6869	1.89956	6.99367	748.214	
8	1 1 1 0 1 0	28.3850	375.855	250.079	85.6869	0.25764	12.1353	656.537	
9	1 1 1 0 1 1	29.1117	380.866	250.079	85.6869	0.25764	2.54639	665.379	
10	1 1 1 0 0 1	28.5689	379.985	250.079	85.6869	1.89956	2.54639	663.748	
⋮	⋮	⋮		⋮				⋮	
55	0 0 1 0 0 1	22.4581	378.509	256.26	85.6869	1.89956	12.1353	270.322	
56	0 0 0 1 0 0	22.4581	378.509	256.26	85.6869	1.89956	12.1353	268.423	
57	0 0 0 1 1 0	22.4581	378.509	256.26	85.6869	1.89956	12.1353	85.7137	
58	0 0 0 1 1 1	22.4581	378.509	256.26	85.6869	1.89956	12.1353	87.6133	
59	0 0 0 1 0 1	22.4581	378.509	256.26	85.6257	1.89956	12.1702	99.7341	
60	0 0 0 0 1 0	22.4581	378.509	256.26	85.6257	1.89956	12.1702	97.8345	
61	0 0 0 0 1 1	22.4581	378.509	256.26	85.6869	1.89956	12.1353	1.92636	
62	0 0 0 0 0 1	22.4581	378.509	256.26	85.6869	1.89956	12.1353	14.0617	
63	0 0 0 0 0 0	22.4581	378.509	256.26	85.6869	1.89956	12.1353	12.1621	

$$Sh = [20.2084 \quad 377.374 \quad 255.192 \quad 85.2808 \quad 1.73692 \quad 10.0533]$$

$$\sum Sh = 749.845$$

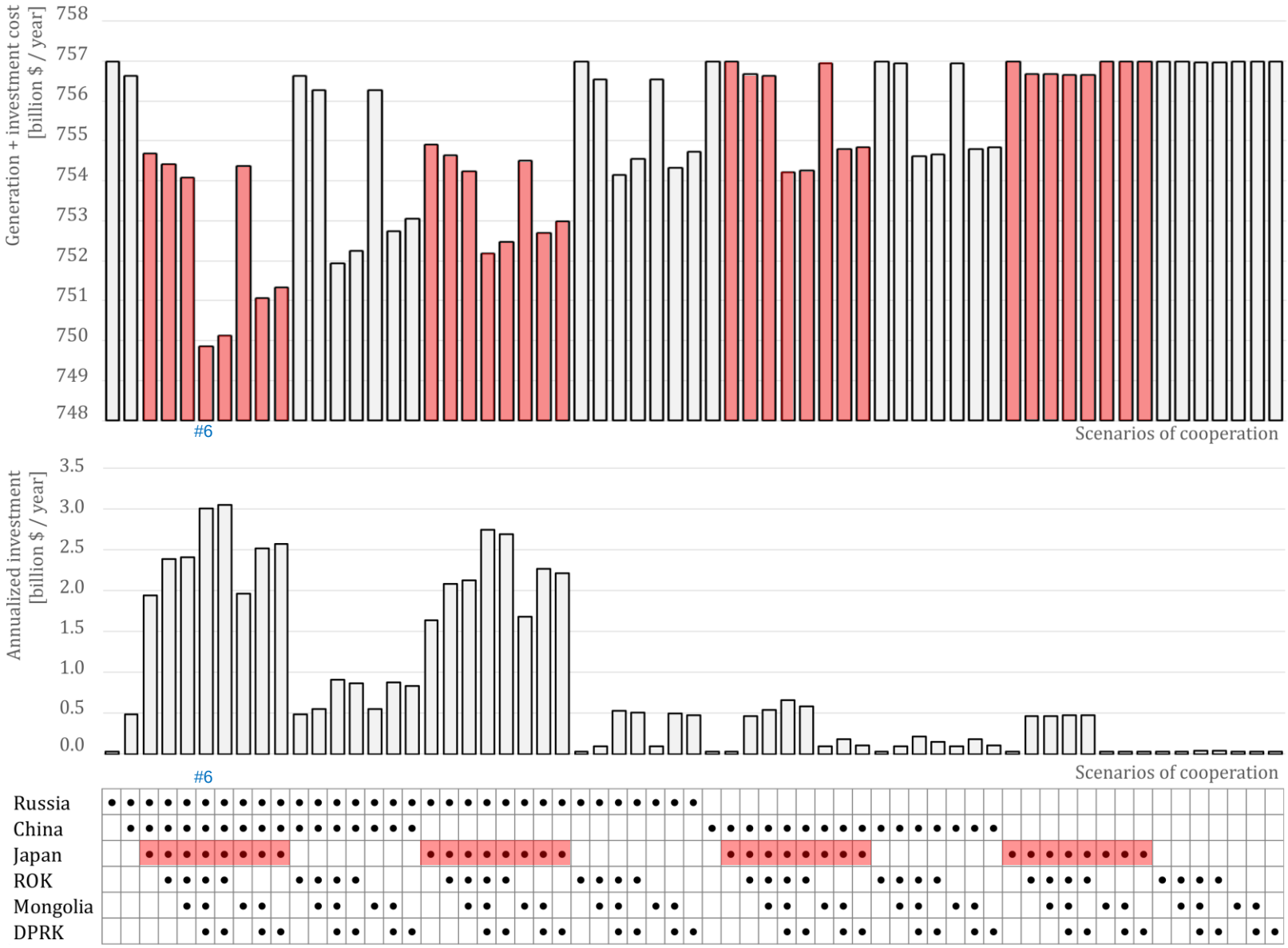
$$\text{Expenses - } Sh = [2.24 \quad 1.13 \quad 1.06 \quad 0.41 \quad 0.16 \quad 2.08\ ]$$

Northeast Asia case analysis



Benefits allocation among the countries according to Shapley value

Northeast Asia case analysis



Comparison of the scenarios

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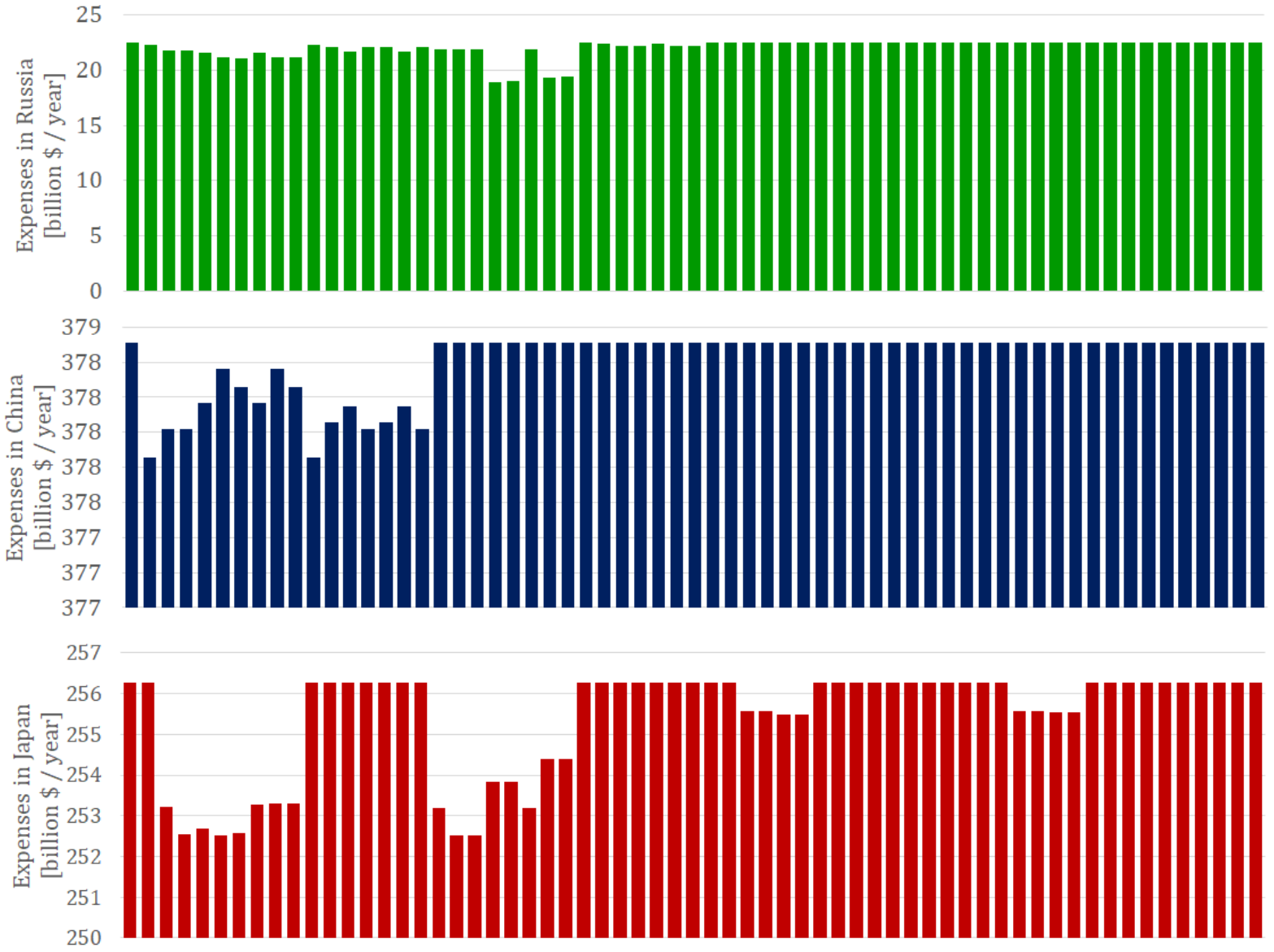

Stability issues of cost allocation

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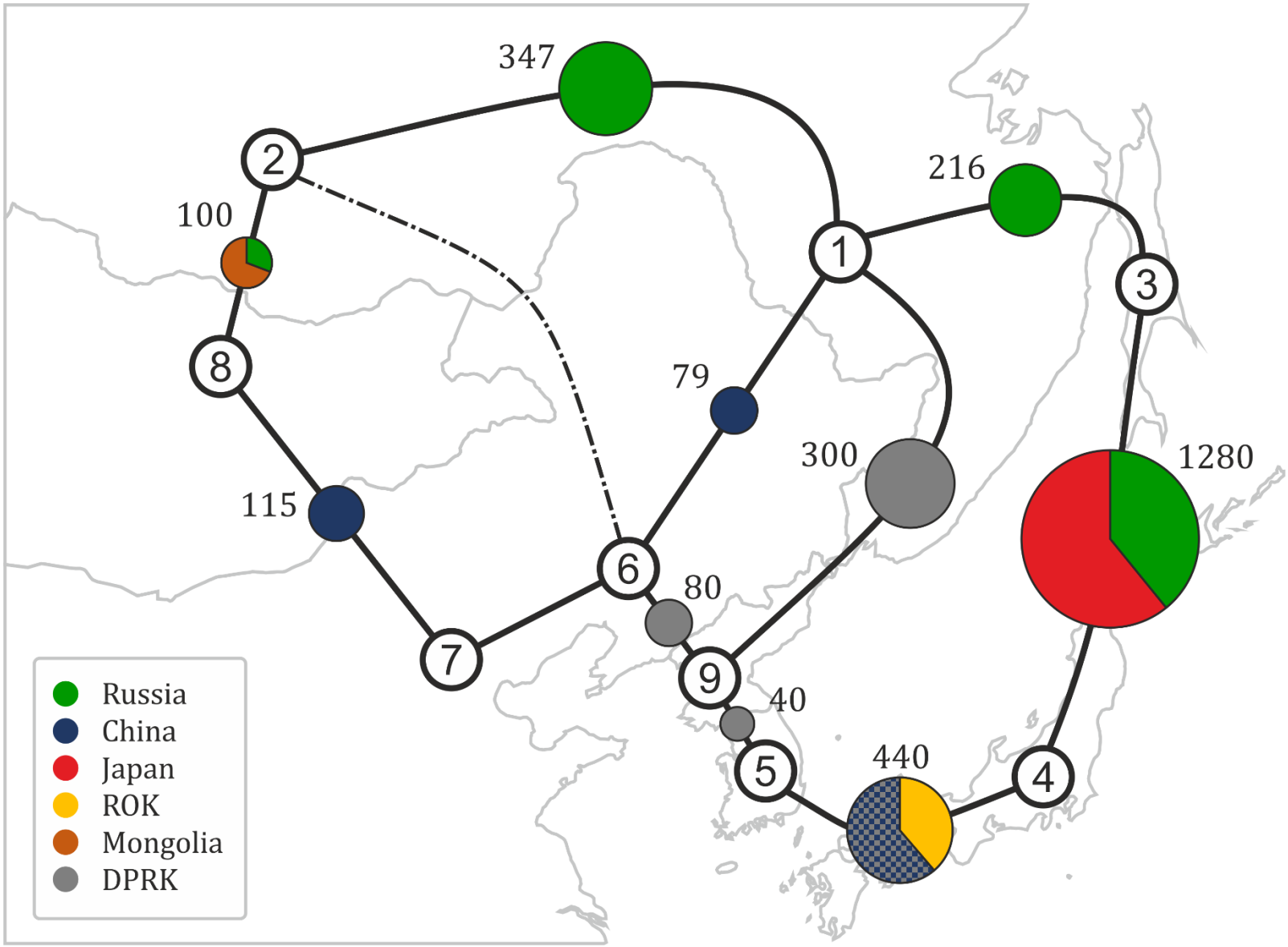

Power lines investment allocation scheme [million $ per year]

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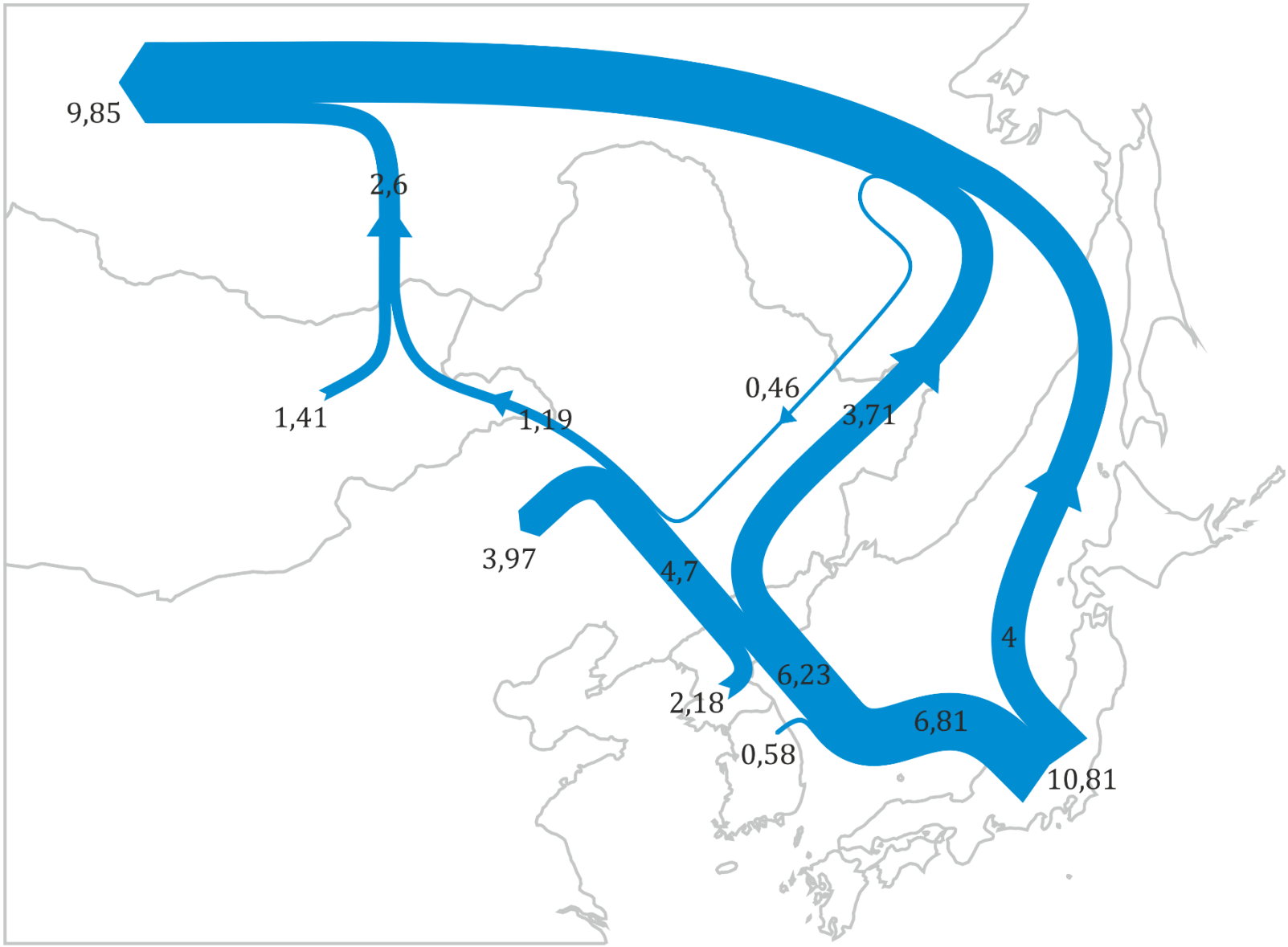

Scheme of the money flows between the countries [billion $ per year]

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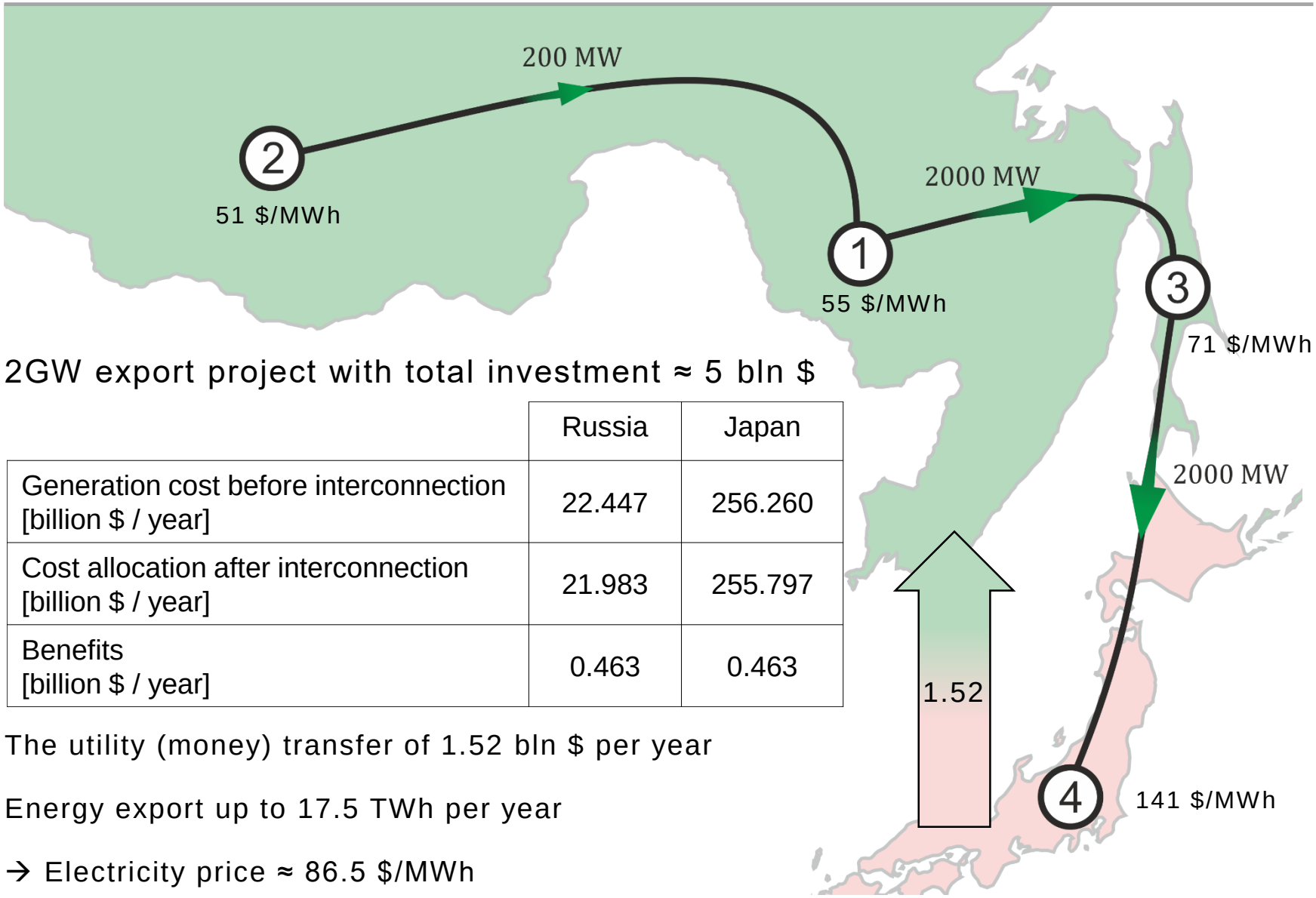
Russian-Japanese electrical interconnection



2GW export project with total investment ≈ 5 bln $

	Russia	Japan
Generation cost before interconnection [billion $ / year]	22.447	256.260
Cost allocation after interconnection [billion $ / year]	21.983	255.797
Benefits [billion $ / year]	0.463	0.463

The utility (money) transfer of 1.52 bln $ per year

Energy export up to 17.5 TWh per year

→ Electricity price ≈ 86.5 $/MWh

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Conclusions

I. There are prerequisites to create bilateral electrical interconnections in Northeast Asia. Examples: Russia-China, Russia-Japan.

II. However, development of the global interconnection in the region (such as Asian Super Grid) is even more profitable.

III. We suggest a solution concept how the cost of this capital-intensive project should be allocated among the countries.

Thank you for your attention

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