Accelerating Renewable Transitions of Power Sectors: Options and Challenges

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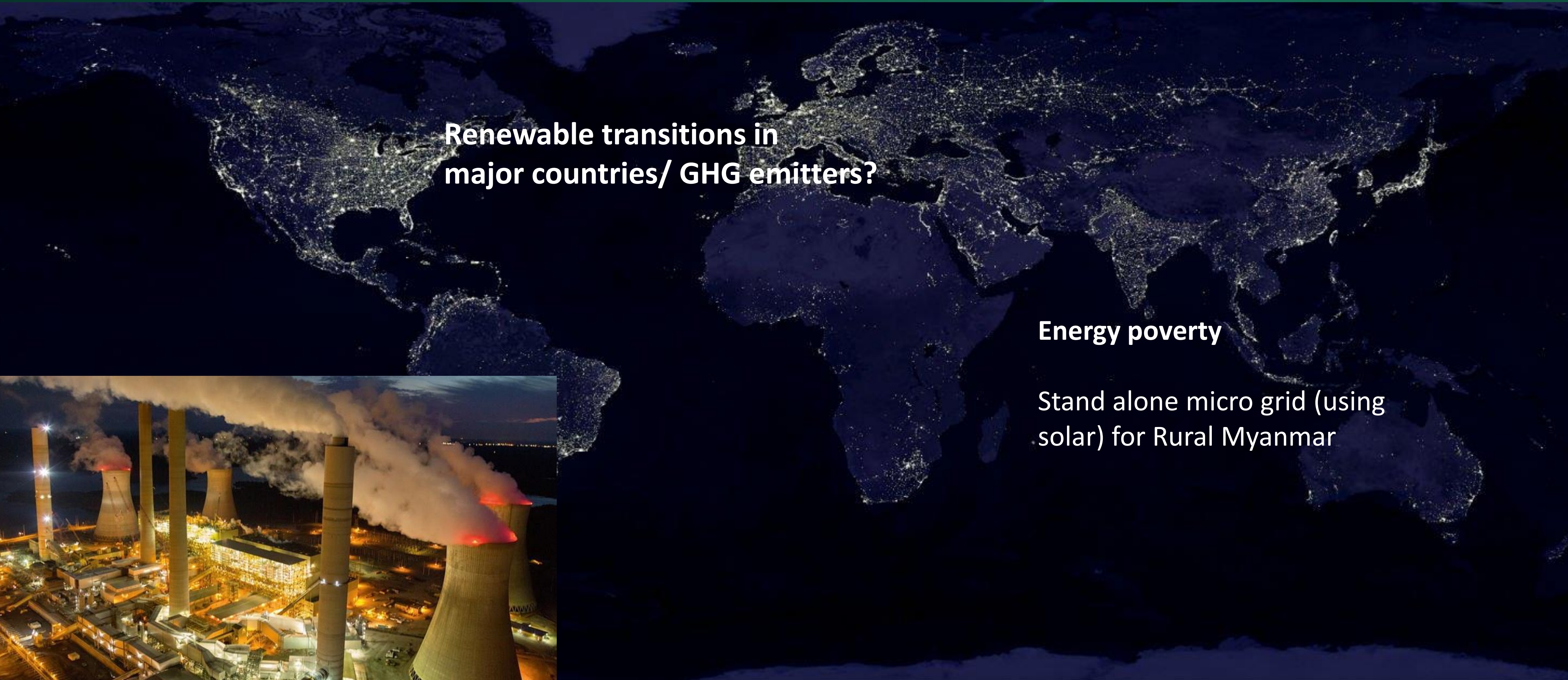
Outline

- Research motivation
- Acknowledgement
- Framework
- Chapter 1
- Chapter 2
- Chapter 3
- Q&A

Motivations: “Clean” Energy Access for All

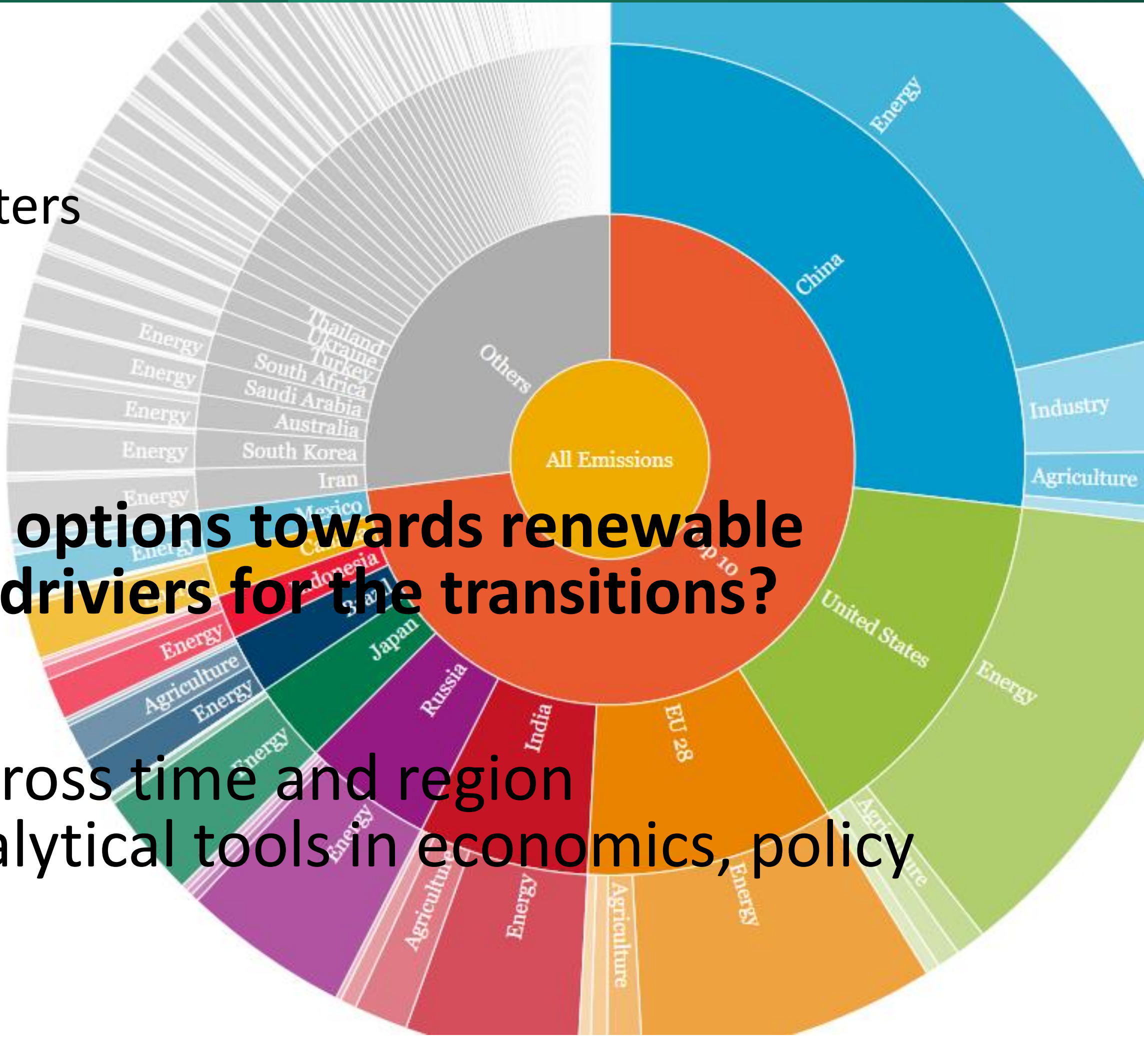


Renewable transitions in major countries/ GHG emitters?

Energy poverty

Stand alone micro grid (using solar) for Rural Myanmar

Driving Questions and Approaches



- Renewable transitions in major economies
  - Global GHG emissions driven by few large emitters
  - Energy sector is core
  - 40% of global electricity fueled by coal.

- **Interactions between different technology options towards renewable transitions of power sectors and what are driviers for the transitions?**

- Empirical study/energy system modeling across time and region encompassing various perspectives and analytical tools in economics, policy studies, and energy system engineering

Acknowledgement

Dr. Yong Gun Kim (Korea Environment Institute)

Essays on accelerating Renewable Transitions of Power Sectors: Options and Challenges

Chapters

1. The Role of Bioenergy in Decarbonization

Renewable Choices and Coal Phaseout: Past and Present in 21 OECD Countries

2. Asia Super Grid and Carbon Pricing

Grid interconnections for renewable transitions of Northeast Asia (NEA)

3. Asia Super grid for Carbon Neutrality

Technology pathways with trilateral power trade for carbon neutrality of NEA

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Accelerating Renewable Transitions of Power Sectors: Options and Challenges

Chapters

1. The Role of Bioenergy in Decarbonization

Renewable Choices and Coal Retirement in 21 OECD countries

2. Asia Super Grid and Carbon Pricing

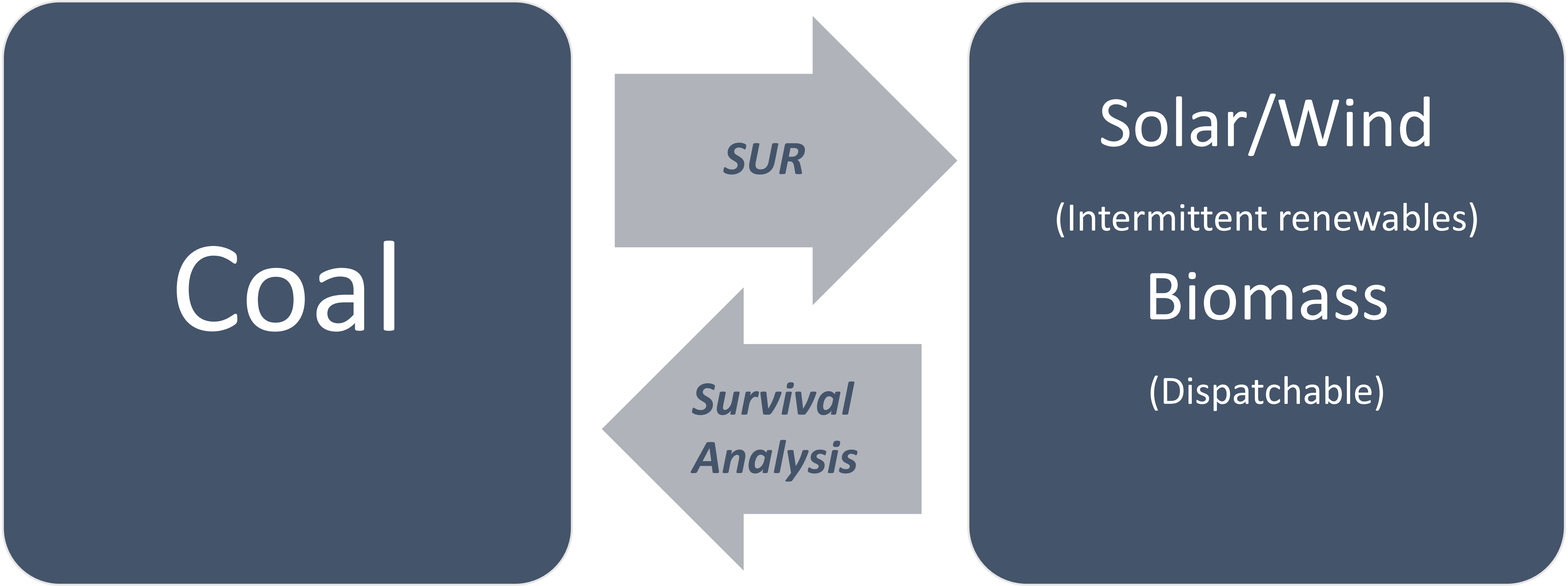
3. Asia Super grid for Carbon Neutrality

Background:

- Old coal capacities
- **Different characteristics of renewables**
  - **Solar/Wind energy reaching grid parity, but intermittency necessitates fossil fuels**
  - **Biomass energy as a non-intermittent and dispatchable renewable**

Objectives & Approaches

1. Identify interactions for existing coal capacities with new energy adoptions
2. Quantify the magnitude of factors affecting coal plant shutdowns



Coal

SUR

Survival Analysis

Solar/Wind

(Intermittent renewables)

Biomass

(Dispatchable)

Data

490 coal power plants in 21 OECD countries (1995-2015)

19 EU countries, South Korea, and Japan for leading renewable development

- Plant-level (Enerdata)
  - Capacity size
  - Commissioning year, Decommissioning year, age
- Country dummies indicating different energy paths
  - Aggregate plant capacity by technology and country
- Country-level
  - Environmental Policy Stringency Index (OECD): assigns countries a score 0-6
    ; Taxes (on CO_2, SOx and NOx), Feed in tariffs (solar and wind),
    Emission standards (PM, SOx and NOx), CO2 Trading schemes
  - GDP per capita (World Bank Development Index)
  - Electricity Consumption per capita (World Bank Development Index)

Methodology : Two approaches

1. Panel SUR(Seemingly Unrelated Regression)

- Examines impact of recent/traditional coal capacities and policy factors after controlling for country specific factors on biomass and solar/wind expansions in 21 countries
- Correlations of error terms reduced through SUR

$$\boldsymbol{b_{it} = \beta_{c1}c_{i,t-1} + \beta_{c2}c_{i,t-2} + \beta_{p}p_{it-1} + +\beta_{g}g_{it-1} + \beta_{e}e_{it-1} + \epsilon_{b}}$$
$$\boldsymbol{r_{it} = \beta_{c1}c_{i,t-1} + \beta_{c2}c_{i,t-2} + \beta_{p}p_{it-1} + +\beta_{g}g_{it-1} + \beta_{e}e_{it-1} + \epsilon_{r}}$$

$c_{i,t-1}$: Country i's coal capacity share at $t-1$
(β_{c1} : substitution effect)
$c_{i,t-2}$: Country i's coal capacity share at $t-2$
(β_{c2} : endowment effect)
p_{it-1} : Vector of policy variables; environmental tax, trading schemes, Feed in Tariff (FIT), and emission standards
g_{it-1}: GDP per capita
e_{it-1}: Electricity consumption per capita

Methodology : Two approaches (cont.)

2. Survival analysis

- Nelson-Aalen cumulative hazard estimates depicts distinctive coal retirement patterns among groups
- Cox Regression: focuses on shutdown risks with changing covariates
  - No assumption on the base line hazard (when all covariates are zeros)
  - Returns a relative risk (Hazard Ratio: HR) with a unit increase in the covariate

$$h(t) = \lim_{dt \to 0} \frac{\Pr\{t \leq T < t + dt | T \geq t\}}{dt} = \frac{f(t)}{1 - F(t)}$$

$$\boldsymbol{h_i(t) = h_0(t)\, exp\left(r_s s_{it} + r_{sa} s_{it} * a_{it} + r_g g_{it} + r_e e_{it} + r_p p_{it} + r_d d_{it}\right)}$$

s_{it} : Plant capacity size

a_{it} : Plant age

g_{it} : Country-level per capita GDP

e_{it} : Country-level per capita electricity consumption

d_{it} : Dummy variables to denote country groups with different energy transition paths

Approach 1. Panel SUR

Explanatory Variables

	DVs in SUR model 1		DVs in SUR model 2	
	Biomass Share	Solar/Wind Share	Biomass Share	Solar/Wind Share
Coal share t-1	**-0.106***** (.032)	**-0.379***** (.098)	**-.087***** (.023)	**-0.471***** (.063)
Coal share t-2	**0.071**** (.032)	0.035 (.097)		
Coal share t-5			**0.044**** (.019)	0.033 (.053)
Hydro share t-1			.008 (.018)	**-.363***** (.051)
Nuclear share t-1			**-.045***** (.017)	**-.226***** (.048)
Taxes t-1	**0.0035**** (.0009)	-0.002 (.002)	**0.004***** (.001)	**0.006**** (.003)
Trading Schemes t-1	**0.0013*** (.0007)	-0.003 (.002)	**0.0018***** (.0005)	-0.0002 (.001)
FIT t-1	**-0.0012***** (.0003)	-.0004	**-0.0009***** (.0003)	**.0014*** (.0008)
Standards t-1	.0001 (.0006)	0.0025 (.002)	.0002 (.0006)	<0.0001 (.001)
GDP	**0.0006***** (.0001)	.0004 (.0005)	**0.0007***** (.0002)	**.0017***** (.0006)
Electricity consumption	-.00051 (.0007)	**-.003*** (.002)	**-.002*** (.0008)	**-.007***** (.002)
obs	456	456	397	397
R2	0.927	0.745	0.934	0.812

Notes: *, ** and *** indicate p-values of <.1, <.05 and <.01, respectively. All models include year dummies and country dummies.

- Substitution effects of recent coal capacities on both biomass & intermittent renewables
- Endowment effects of traditional coal legacies on biomass
- Environmental taxes and trading schemes accelerate biomass expansions

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Result 1. SUR – Summary

	Solar/Wind	**Biomass**
Recent coal	Replacing recent coal capacities (substitution effect)	Replacing recent coal capacities (substitution effect)
Traditional coal		Old coal adopts more biomass (endowment effect)
Policy intervention	Time effects strong	Stringent environmental policies effective

Result 2. Cox Regression – Summary

Shutdown Delaying	Shutdown Accelerating
Past coal dependence Solar/ Wind leading	Biomass focused renewable development
	GDP
Environmental Taxes	Emission standards
Big and Young plants	Big and Old plants

Conclusion and Implications

- Confirmed endowment effects of traditional coal development on biomass adoptions (countries with historical coal dependence more actively adopt biomass)
- The transition into biomass intensive pathway accelerate shutdowns of coal power plants possibly for retrofits and to cofire with biomass.
- The transition into solar/wind energy delays retirements of existing coal plants possibly due to intermittency issues.

➢ Diversification of renewable portifolio using biomass and in countries with large inherited coal capacity will further facilitate the global low-carbon transition by reducing dependence on fossil fuels for backup.

Updates on Chapter 1

- Presented at AAEA (Agricultural &Applied Economics Association) annual meeting 2018
- Under review of Energy Policy

Accelerating Renewable Transitions of Power Sectors: Options and Challenges

Chapters

1. The Role of Bioenergy in Coal Shutdowns

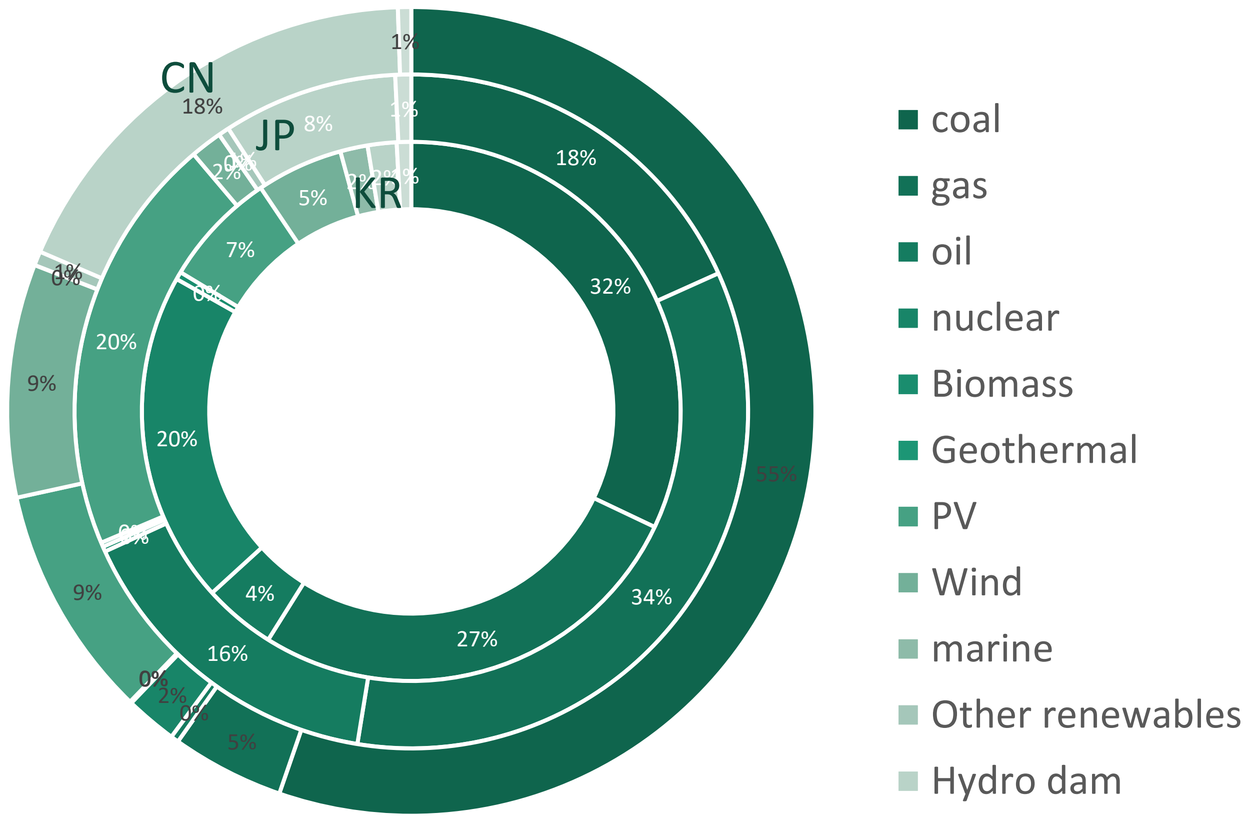
2. Asia Super Grid and Carbon Pricing

3. Asia Super grid for Carbon Neutrality

Chapter 2: Embarking on the Asia Supergrid : Carbon Pricing for equitable trade impacts

Background: Coal dependence in Northeast Asia (NEA)

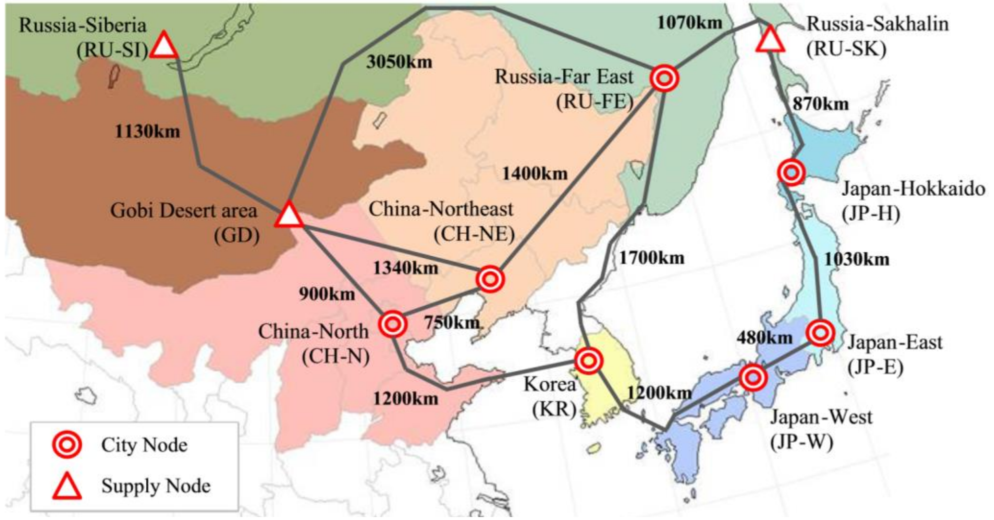
Generation mix of NEA



- China, South Korea, and Japan : World 1st, 6th, and 13th largest GHG emitters respectively as of 2017 (CAIT, 2018)
- Power sectors largely dependent on Fossil fuels and more fundamental actions required

Lit Review : Geographic Mismatch in Resource Availability and Power Demands

- Access to Gobi Desert and hydro resources in eastern Russia promotes sustainable generation mix with emission reduction of 5.4% (Otsuki et al. 2016)
- HVDC transmission grid leads to a cut-off storage utilization and significantly reduced generation capacities (Bogdanov &Breyer. 2016).
- Existing RE technologies can generate enough energy to cover all power demand for year 2030 on a lower price level compared to non-renewable options (Bogdanov, & Breyer. 2016).



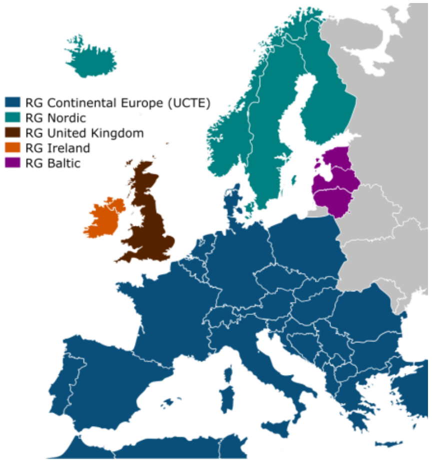
(Otsuki et al 2016)

(Bogdanov &Breyer, 2016)

Regional Cooperation of Power Sectors

EU

- Largest synchronous electrical grid (ENTSO-E)
- 660GW - as of 2008
- 400 M customers in 24 countries



Asia

- Currently no grid connections
- No cohesive political body
- Bigger gaps in economic wealth across countries
- Energy security concerns

Diplomatic and technical challenges?
***Power trade among demand centers** as the first and feasible step of the Asia super grid?*

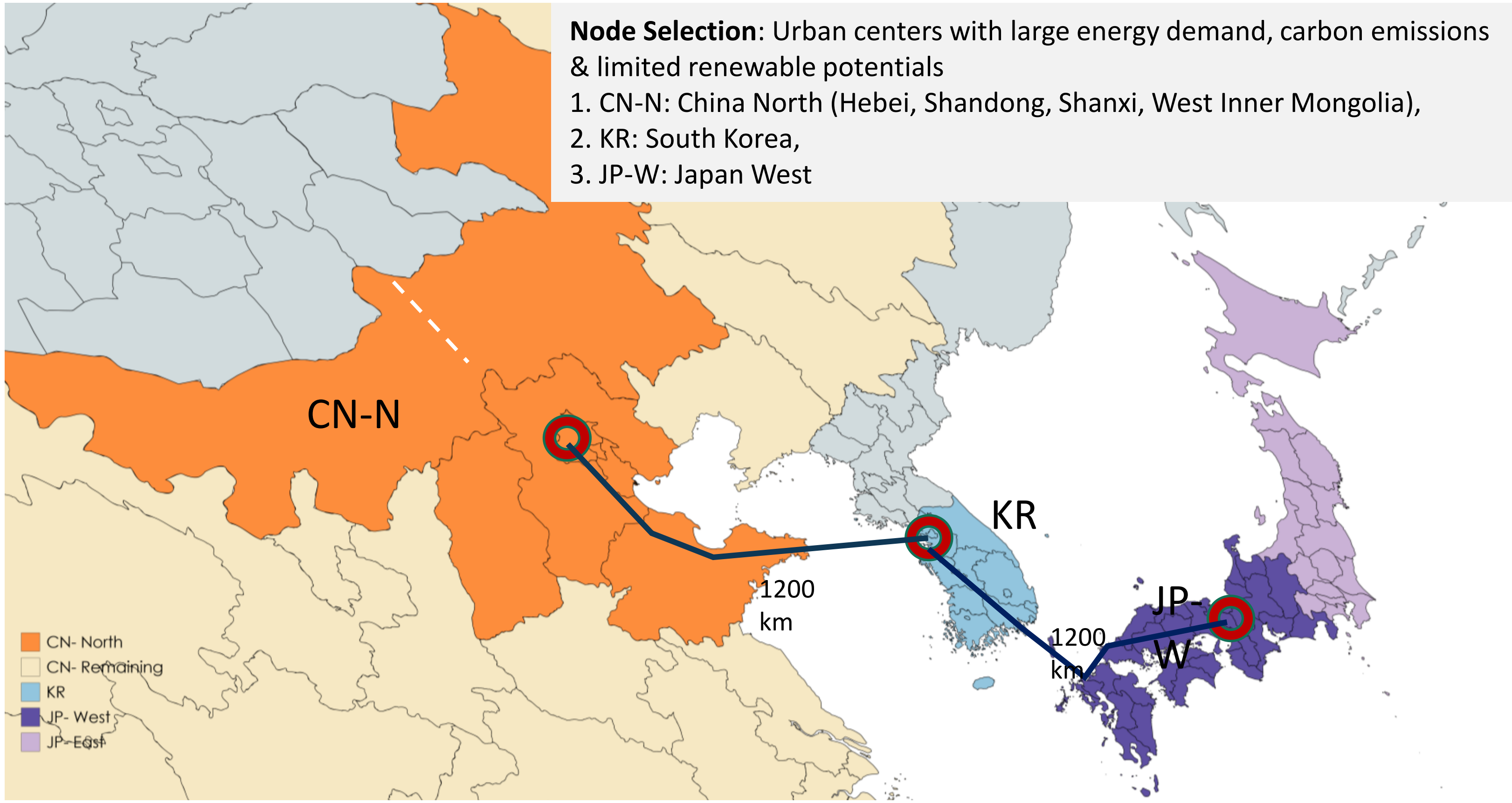
Research Gap and Questions

- Power trade **among *demand centers only***
  - renewable transitions ?
  - cost competitive ?

(Bogdanov &Breyer, 2016)

Research Questions

1. Does interstate power trade among demand centers help renewable transitions and still be cost competitive for 2050 ?

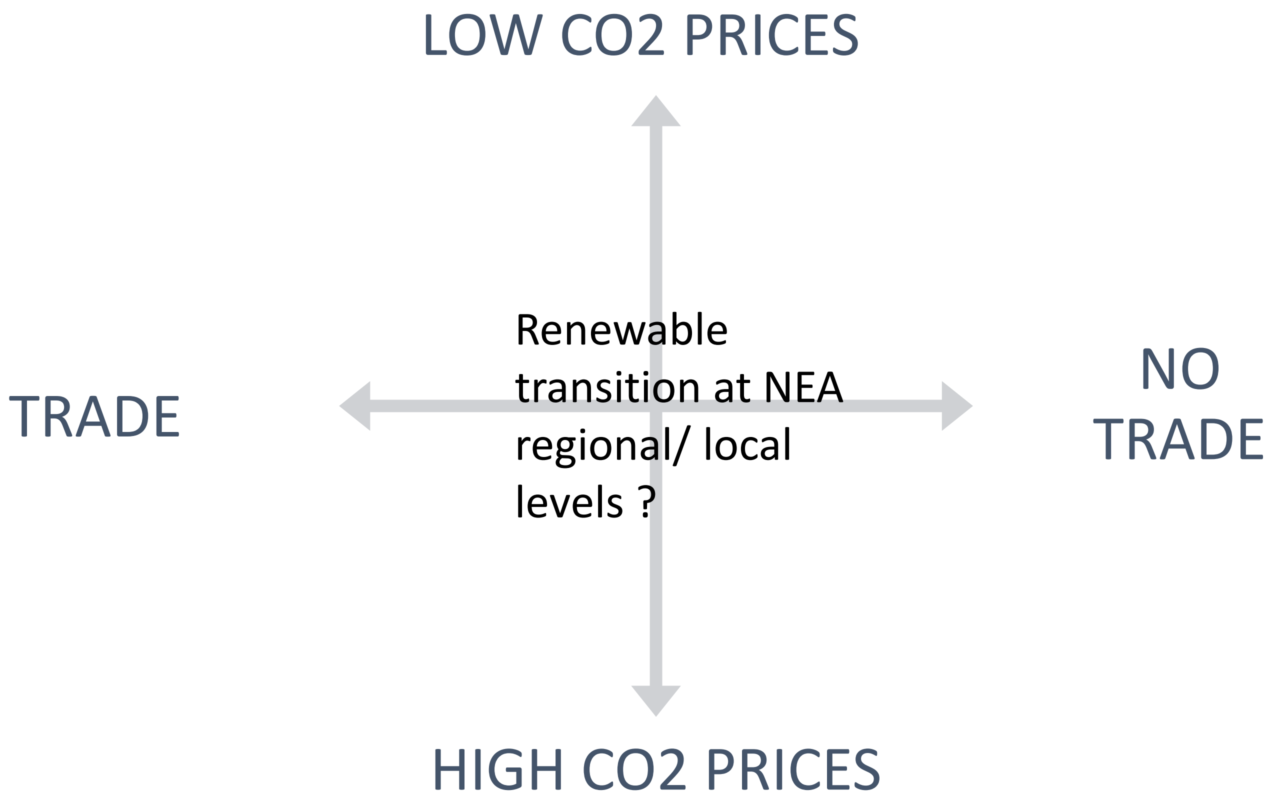


Node Selection: Urban centers with large energy demand, carbon emissions & limited renewable potentials

1. CN-N: China North (Hebei, Shandong, Shanxi, West Inner Mongolia),
2. KR: South Korea,
3. JP-W: Japan West

Research Questions

2. What are the roles of carbon price in trade impacts?



LOW CO2 PRICES

TRADE

Renewable transition at NEA regional/ local levels ?

NO TRADE

HIGH CO2 PRICES

Methodology

- A bottom-up partial equilibrium model for power sector
  - features a larger number of discrete technologies for generation/storage/carbon capture
- Objective function :Total cost to meet hourly power demand at 3 nodes in 2050 :

$$\min TC = CI + CO + CF + CE$$

- Constraints on
  - Supply-demand balance
  - Energy system operations specific to different types of technologies (generation , storage, CCS, transmission)
  - Trade assumptions
- Spatial resolution: 3 node (CN-N, KR, JP-W)
- Time resolution: 244 time slices for year 2050 (1 representative days/month* 12 months/year)

Methodology

Data

- Technology options: generation, storage (pumped hydro, ESS), CCS
  - Cost parameters (Otsuki 2018, Beyer 2016):
    - Capital cost, O&M cost for generation technologies, storage technologies, transmission lines, and CCS (annualized cost USD/kW)
    - Fuel cost for generating technologies (USD/kWh)
  - Availability : 1) maximum installable capacity, 2) hourly output for renewables

- Existing capacity
- 2050 Hourly Electricity Demand
- Emissions
  - CO2 Emission factors by generating technology (ton of co2/ kWh) (US DOE)
  - CO2 prices at C1: 0, C2:30, C3:60, C4: 90, C5: 120, C6: 150, C7: 180 (USD /metric ton of CO2 emitted)

Methodology. Data

Supply (Extant capacity):

2018 installed capacity in GW

- CN-N's coal capacity alone is large enough to meet the nodal peak
- JP-W's dependence on gas and oil
- KR's renewable capacity relatively small

	China-North (nodal peak load : 150)	China whole (800)	Japan-West (78)	Japan whole (157)	Korea (79)
Coal	180	1044	30	48	37
Gas	5	85	45	90	31
Oil	0	6	53	41	5
Nuclear	8	39	9.8		23
Biomass	0.12	1.3	0.1	0.637	0.5
Geothermal		0.03	0.2	0.55	
PV	18	176	25	53	8
Wind	30	176	3	4	6
Marine	0	0		0	1.9
Other renewables		10.7		1.3	
Hydro-dam	8	340	15	22	2
Hydro-pumped	5	10	15	2	1
ESS batteries					1

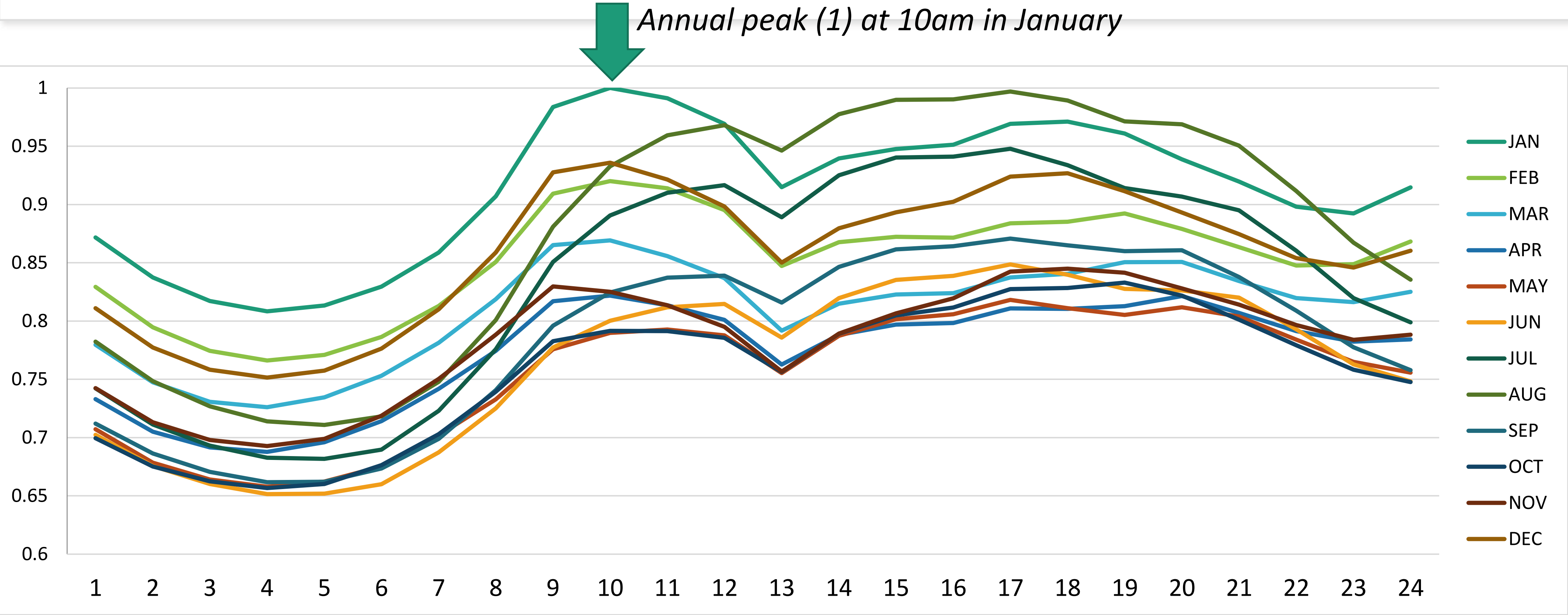
(Enerdata 2018)

Methodology. Data

2050 Demand

Demand (node, 12month, 24hour):

- Average hourly load curve for each month in peak ratio in 2019:
- Nodes differ in magnitude but have the same shape apart from differences in the time zone
- 2050 Nodal peak load (GW) CN-N : 2300*0.22=506, KR: 150, JP-W: 200*0.5=100


Annual peak (1) at 10am in January

(2019 KPX)

Methodology

: Assumptions

Capacity reserve margin (20%)

- No trade scenario : each node is required to equip 20% of capacity reserve margin
- Trade scenario: 20%, but reserve location endogenous

Trade limits

- *Net trade inflow and outflow* to be under 15% of nodal demand – energy security concerns

Methodology

: Variables

TC	Total discounted cost
$XP_{n,t,mt,hr}$	Amount of power output by node (n)– technology (t) – month (mt)– hour (hr) [GWh]
$KN_{n,t,}$	Newly added generation capacity at n by t [GW]
$KSN_{n,st}$	Newly added storage capacity at n by st [GW]
$KCN_{n,t,\mathit{ccs}}$	Newly added CCS capacity at n linked to thermal technology t [GW]
$KLN_{I,j}$	Newly added line capacity between node I and j [GW]
$STE_{n,st,mt,hr}$	Stored electricity of storage type st during mt at local time hr at n [GWh]
$XDC_{n,st,mt,hr}$	Discharged electricity of storage type st during mt at time hour at n [GWh]
$XCH_{n,st,mt,hr}$	Charged electricity of storage type st during mt at hr at node n [GWh]
$XL_{i,j,mt,hr}$	Exported power from node i to j during mt at hr [GWh]
$XCA_{n,t,ccs,mt,hr,e}$	Carbon Emission Avoided from t by pollutant (e) during mt at each hr[t]
$XC_{n,t,ccs,mt,hr}$	Electricity controlled using CCS at each hr [GWh]

Methodology

Objective function $\boldsymbol{MIN\,TC = CI + CO + CF + CE}$

Costs for Investment (CI), O&M (CO), fuel (CF), CO2 emissions (CE)

$$CI = \sum_{n,t} \mathrm{ckn}_{\mathrm{n,t}} * \mathrm{KN}_{\mathrm{n,t}} + \sum_{\mathrm{n},st} \mathrm{cksn}_{\mathrm{n,st}}\mathrm{KSN}_{\mathrm{n,st}} + \sum_{n,\mathrm{thermal}\ ccs} \mathrm{cks}_{\mathrm{n,thermal,ccs}} * \mathrm{KCN}_{\mathrm{n,thermal,ccs}} + \sum_{a(\mathrm{n},j)} \mathrm{ckln}_{\mathrm{n,j}} * \mathrm{KLN}_{\mathrm{n,j}}/2$$

where $\mathrm{ckn}_{\mathrm{n,t}}$: levelized capital cost for generation technology t at node n [million USD/GW]

$\mathrm{cksn}_{\mathrm{n,st}}$: levelized capital cost for storage technology st at node n [million USD/GW]

$\mathrm{cks}_{\mathrm{n,t,ccs}}$: levelized capital cost for CCS technology ccs attached to thermal technology t at node n [million USD/GW]

$\mathrm{ckln}_{\mathrm{n,j}}$: levelized capital cost for line construction between node n,j [million USD/GW]

Methodology

Objective function $\boldsymbol{MIN\,TC = CI + CO + CF + CE}$

Investment (CI), operation and maintenance (CO), fuel (CF), emission cost (CE)

$$CO = \sum_{n,t} \mathrm{cfk}_{\mathrm{n,t}} * (\mathrm{kx}_{\mathrm{n,t}} + \mathrm{KN}_{\mathrm{n,t}})$$

$$+ \sum_{n,st} cfs_{n,st} * \left(ksx_{n,st} + \boldsymbol{KSN_{n,st}}\right) + \sum_{n,thermal,ccs} cfc_{n,thermal,ccs} * KCN_{n,thermal,ccs} + \sum_{a(i,j)} \mathrm{cfl}_{\mathrm{n,j}} * \mathrm{KLN}_{\mathrm{n,j}} +$$

$$+\sum\nolimits_{n,t,mt,hr} \mathrm{cvk}_{\mathrm{n,t,hr}} * \mathrm{XP}_{\mathrm{n,t,mt,hr}} * \mathrm{days}_{\mathrm{mt}}$$

where $\mathrm{cfk}_{\mathrm{n,t}}$: levelized fixed O&M cost for generation technology t at node n [million USD/GW]
$\mathrm{cfs}_{\mathrm{n,st}}$: levelized fixed O&M cost for storage technology st at node n [million USD/GW]
$\mathrm{cfc}_{\mathrm{n,t,ccs}}$: levelized fixed O&M cost for CCS technology ccs attached to thermal technology t at node n [million USD/GW]
$\mathrm{cfl}_{\mathrm{n,j}}$: levelized fixed O&M cost for line construction between node n,j [million USD/GW]
$\mathrm{cvk}_{\mathrm{n,t}}$: levelized variable O&M cost for generation technology t at node n [million USD/GWh]
$\mathrm{days}_{\mathrm{mt}}$: number of days in month mt

Methodology

Objective function $\boldsymbol{MIN\ TC = CI + CO + CF + CE}$

Investment (CI), operation and maintenance (CO), fuel (CF), emission cost (CE)

$$CF$$

$$=\sum_{n,t,mt,hr} \mathrm{XP}_{\mathrm{n,t,mt,hr}} * \mathrm{fuelprice}_{\mathrm{n,t}} * \mathrm{days}_{\mathrm{mt}}$$

$$CE$$

$$=\sum_{n,t,e,mt,hr}\left(XP_{n,t,mt,hr} * emission_t - XCA_{n,thermal,ccs,mt,hr}\right) * carbonprice * days_{mt}$$

Where $\mathrm{fuelprice}_{\mathrm{n,t}}$: fuel price of generating technology t at node n [million USD/GWh]

$emission_{\mathrm{t}}$: Emission factor of technology t [tCO2/GWh]

Technical constraints:

Supply-demand balance

$$\underline{\sum_t \mathrm{XP}_{\mathrm{n,t,mt,hr}}} + \underline{\sum_{a(j,n)} \mathrm{XL}_{\mathrm{j,n,mt,hr}} * \mathrm{eff}_{\mathrm{j,n}} - \sum_{a(n,j)} \mathrm{XL}_{\mathrm{n,j,mt,hr}}} + \underline{\sum_{st} \left(\mathrm{XDC}_{\mathrm{n,st,mt,hr}} - \mathrm{XCH}_{\mathrm{n,st,mt,hr}}\right)} = \mathrm{d}_{\mathrm{n,mt,hr}} \qquad (2)$$

Where $\mathbf{eff}_{\mathrm{j,n}}$ transmission efficiency loss

Technical constraints:

Generation capacity

$$\mathrm{maxcapacity}_{n,t,} \geq \underline{\mathrm{kx}_{n,t} + \mathrm{KN}_{n,t}} \tag{4}$$

$$\sum_{n,t} \mathrm{capcredit}_{n,t} * \left(\underline{\mathrm{kx}_{n,t,} + \mathrm{KN}_{n,t}}\right) + \sum_{n,st} \mathrm{capcredit}_{n,st} * (\underline{\mathrm{ksx}_{n,st} + \mathrm{KSN}_{n,st})}$$
$$\geq \textstyle\sum_{n}(1 + \mathrm{rv}_{n}) * \mathrm{d}_{n,mt,hr} \tag{5}$$

where $\mathrm{maxcapacity}_{n,t,}$: maximum deployable capacity of renewable technology tp, at node n [GW]

$\mathrm{capcredit}_{n,t}$: capacity credit of technology t at node n [%]

rv_{n} reserve margin [%]

Technical constraints:

Generation – technology availability

$$\mathrm{resav}_{n,t,mt,hr} * \left(\mathrm{kx}_{n,t} + \mathrm{KN}_{n,t}\right) \geq \mathrm{XP}_{n,t,mt,hr} \qquad (6)$$

Where $\mathrm{resav}_{n,t,mt,hr}$: resource availability of generating technology t at each mt and hr at node n

Technical constraints:

Storage (hydro pumped storage, batteries)

$$\mathrm{ksx}_{\mathrm{n,st}} + \mathrm{KSN}_{\mathrm{n,st}} \geq \mathrm{STE}_{\mathrm{n,st,mt,hr}} \tag{7}$$

$$\mathrm{steff}_{\mathrm{st}} * \mathrm{STE}_{\mathrm{n,st,mt,hr-1}} + \mathrm{XCH}_{\mathrm{n,st,mt,hr}} * \mathrm{ceff}_{\mathrm{st}} - \mathrm{XDC}_{\mathrm{n,st,mt,hr}} \geq \mathrm{STE}_{\mathrm{n,st,mt,hr}} \tag{8}$$

$$\mathrm{maxcapacity}_{\ \mathrm{n,st}} \geq \mathrm{ksx}_{\mathrm{n,st}} + \mathrm{KSN}_{\mathrm{n,st}} \tag{9}$$

Where $\mathrm{steff}_{\mathrm{st}}$: self discharge rate of storage technology st

$\mathrm{ceff}_{\mathrm{st}}$: cycle efficiency

Technical constraints:

Line development and power transmission

$$\mathrm{KLN}_{\mathrm{n,j}} \geq \mathrm{XL}_{\mathrm{n,j,mt,hr}} \qquad (10)$$

: The amount of Power flow between one node to another (XL) bound to size of line capacity between the nodes

$$0.15 * d(n, mt, hr) \geq \textstyle\sum_j (\mathbf{XL}(\mathbf{j}, \mathbf{n}, mt, hr) * leff(j, n) - \mathbf{XL}(\mathbf{n}, \mathbf{j}, mt, hr)) \qquad (11)$$

$$0.15 * d(n, mt, hr) \geq \textstyle\sum_j (\mathbf{XL}(\mathbf{n}, \mathbf{j}, mt, hr) - \mathbf{XL}(\mathbf{j}, \mathbf{n}, mt, hr) * leff(j, n)) \qquad (12)$$

: Net inflow and outflow at each node should be smaller than a certain percentage of the nodal demand (d)

Technical constraints:

Ramp up/down for thermal technologies

$$(1 - ramp_t) * XP_{n,t,s,hr-1} \leq \; XP_{n,t,s,hr} \; \leq (1 + ramp_t) * XP_{n,t,s,hr-1}$$

Where $ramp_t$: ramping rate of thermal technology t

Key Insight from Results

1. Trade lowers TC regardless of carbon pricing
    - Direction of Trade flows reflects where produces cheaper electricity;
        - Mostly CN-N to KR, KR to JP-W
        - CN-N net exporters and KR, JP-W net importers at all level of carbon prices

2. For equitable trade impact, proper carbon pricing is essential
    - At zero carbon price: trade depends on CN-N's cheap fossil fuels in reducing total cost.
    - Higher level of carbon pricing required for both KR, JP-W to engage in exportation making two-way flows.

Key Insight from Results

3. Trade accelerate renewable transition only with carbon pricing
    - At NEA regional level, trade increases renewable penetration in generation mix
    - At the local level, the transition is bound to local renewable availability as well as carbon pricing.
    - To overcome limited renewable potentials, trade further increase renewable output in exporting node for transmission.

4. Cost-wise,

New investment for transmission , renewable expansion in export nodes **<** further savings in avoided fuel and emission cost in import node

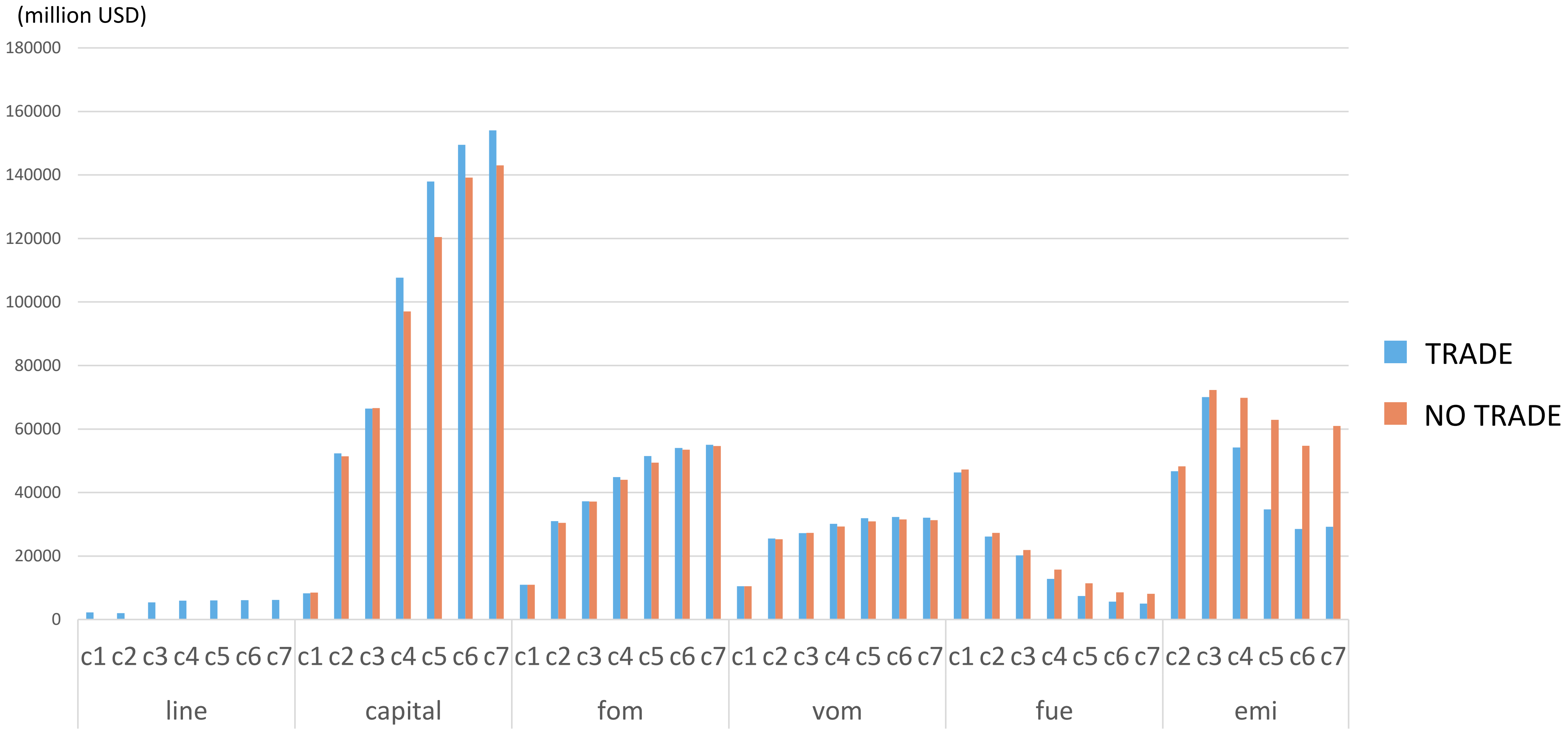
Results: 1. Trade lowers the TC

- At all levels of CO2 pricing ($0-180)
- Cost savings with trade increases as carbon prices go up

Emission price (USD/ton of CO2 emitted)	Total Cost : Trade (million USD)	Cost savings with Trade (%)	Line capacity (GW)	Trade volume (GWh)	Trade volume (% of total generation)
C1: 0	230773.0	-0.3	38.8	165069.1	3.06
C2: 30	548013.4	0.0	35.1	151337.6	2.80
C3: 60	671173.4	-0.7	93.1	346989.7	6.40
C4: 90	757994.0	-1.3	100.0	249478.2	4.56
C5: 120	803162.2	-2.6	103.9	294642.0	5.35
C6: 150	827236.5	-4.1	104.8	292885.0	5.30
C7: 180	846969.1	-5.3	106.0	305593.7	5.53

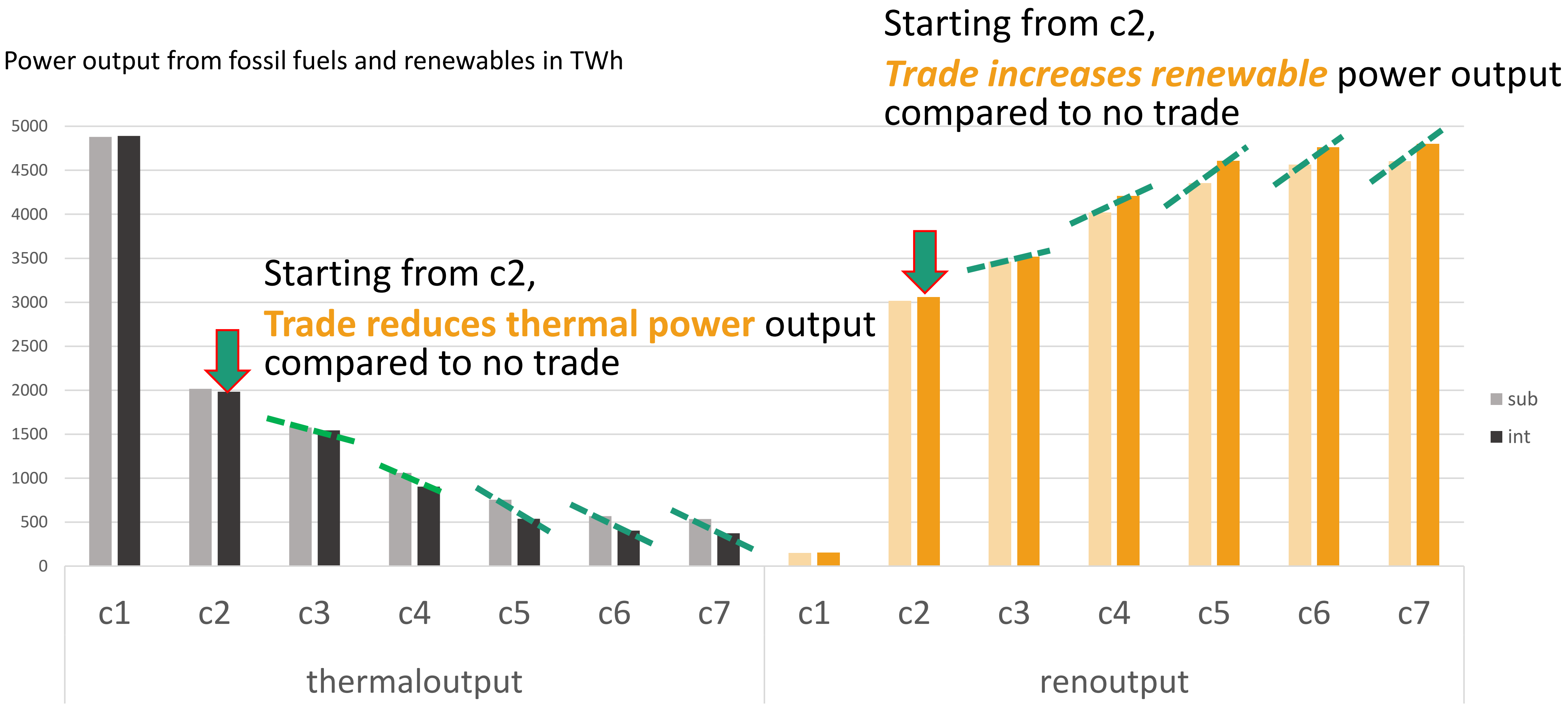
Results: 1. Trade lowers the TC

Cost savings come from reduced fuel & emission cost



Results 2. Trade accelerate regional renewable transition with adoption of carbon pricing

Power output from fossil fuels and renewables in TWh



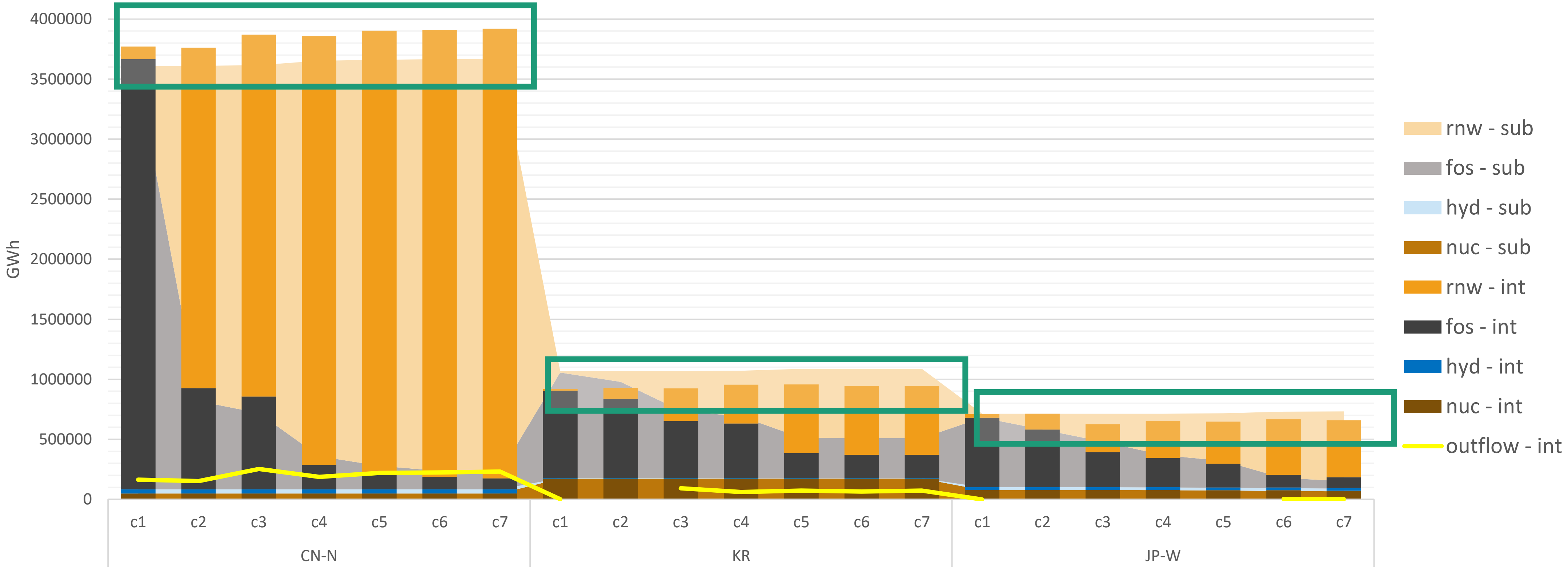
Starting from c2,
Trade reduces thermal power output compared to no trade

Starting from c2,
Trade increases renewable power output compared to no trade

Result 3. For equitable trade impact, proper carbon pricing is essential

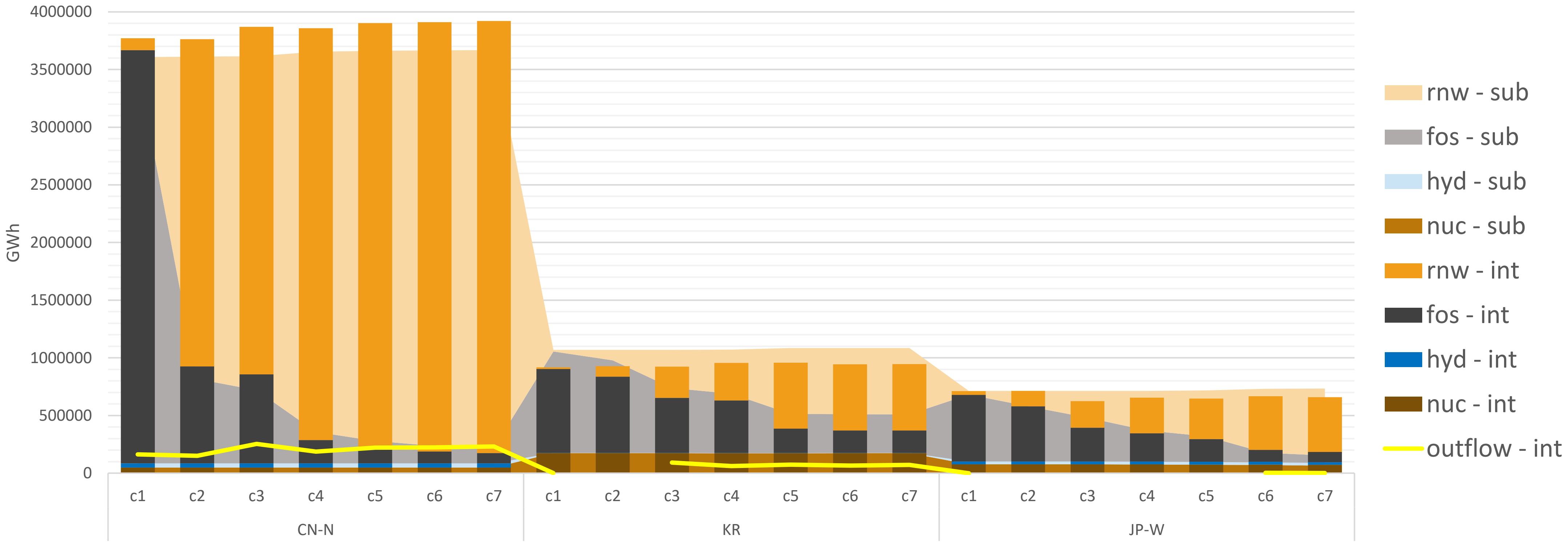
- CN-N: net exporter and KR and JP-W: net importers

Power Output with Trade (bar) and No Trade (area)



Result 3. For equitable trade impact, proper carbon pricing is essential

- Each node embark on the renewable transition at <u>different levels of carbon price.</u>
- Higher carbon pricing required for KR(C3), JP-W(C6) to embark on renewable transition and export.
- Transmissions are mostly one way at lower level of CO2 prices : CN-N to KR, KR to JP-W



Result 3. For equitable trade impact, proper carbon pricing is essential

node	Carbon price	Annual Power output (GWh)	% change compared to no trade				
		With trade	total	fossil fuels	ren	nuc	hyd
CN-N	c1	3771126	4.52	4.52	0.00	0.00	0.00
	c2	3762020	4.18	3.02	1.16	0.00	0.00
	c3	3870178	7.03	3.81	3.23	0.00	0.00
	c4	3858471	5.62	-1.94	7.55	0.00	0.00
	c5	3902751	6.60	-1.70	8.30	0.00	0.00
	c6	3910131	6.64	-1.28	7.92	0.00	0.00
	c7	3921001	6.87	-1.27	8.14	0.00	0.00
KR	c1	918262.8	-14.17	-14.18	0.01	0.00	0.00
	c2	927055.5	-13.31	-13.31	0.00	0.00	0.00
	c3	923704.7	-13.66	-7.86	-5.80	0.00	0.00
	c4	955790.6	-10.82	-5.60	-5.28	0.06	0.00
	c5	957587.6	-11.86	-11.81	-0.12	0.07	0.00
	c6	944514.3	-13.03	-13.01	-0.05	0.03	0.00
	c7	945453.6	-12.94	-12.87	-0.10	0.03	0.00
JP-W	c1	711683.9	-0.17	-0.17	0.00	0.00	0.00
	c2	713025.3	0.02	0.02	0.00	0.00	0.00
	c3	625418.2	-12.27	-12.27	0.00	0.00	0.00
	c4	655145.5	-8.22	-3.65	-4.88	0.32	0.00
	c5	646427.8	-9.87	-3.58	-6.62	0.33	0.00
	c6	667342	-8.69	3.08	-12.40	0.63	0.00
	c7	659646.6	-10.01	3.16	-14.10	0.93	0.00

- At low level of carbon pricing, CN-N increases power output for transmission **using fossil fuels**

- CN-N benefits renewable transition with trade above **C4 ($90)**

Result 3. For equitable trade impact, proper carbon pricing is essential

node	Carbon price	Annual Power output (GWh)	% change compared to no trade				
		With trade	total	fossil fuels	ren	nuc	hyd
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	c4	3858471	5.62	-1.94	7.55	0.00	0.00
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	c6	3910131	6.64	-1.28	7.92	0.00	0.00
	c7	3921001	6.87	-1.27	8.14	0.00	0.00
KR	c1	918262.8	-14.17	-14.18	0.01	0.00	0.00
	c2	927055.5	-13.31	-13.31	0.00	0.00	0.00
	c3	923704.7	-13.66	-7.86	-5.80	0.00	0.00
	c4	955790.6	-10.82	-5.60	-5.28	0.06	0.00
	c5	957587.6	-11.86	-11.81	-0.12	0.07	0.00
	c6	944514.3	-13.03	-13.01	-0.05	0.03	0.00
	c7	945453.6	-12.94	-12.87	-0.10	0.03	0.00
JP-W	c1	711683.9	-0.17	-0.17	0.00	0.00	0.00
	c2	713025.3	0.02	0.02	0.00	0.00	0.00
	c3	625418.2	-12.27	-12.27	0.00	0.00	0.00
	c4	655145.5	-8.22	-3.65	-4.88	0.32	0.00
	c5	646427.8	-9.87	-3.58	-6.62	0.33	0.00
	c6	667342	-8.69	3.08	-12.40	0.63	0.00
	c7	659646.6	-10.01	3.16	-14.10	0.93	0.00

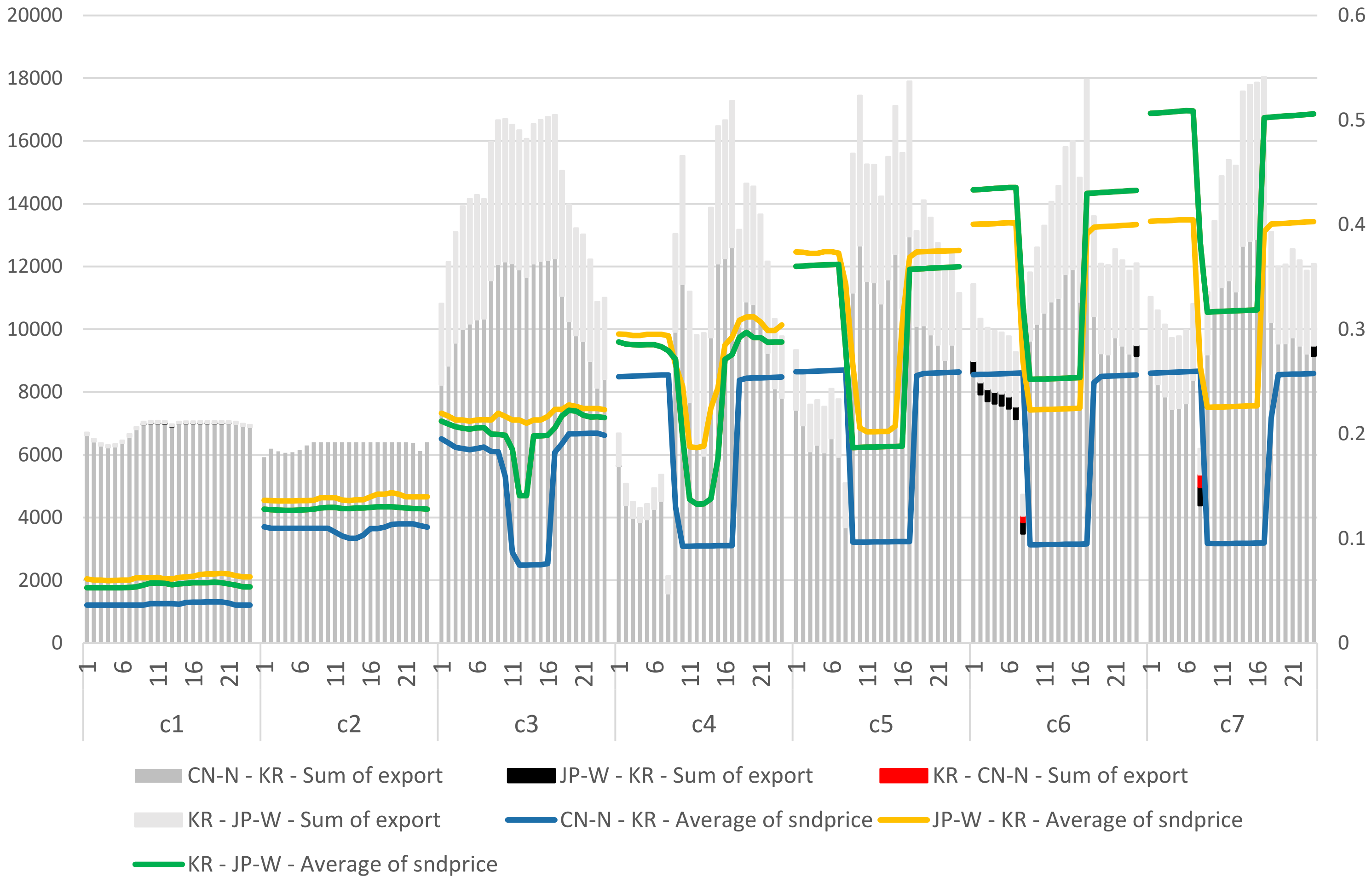
- At low level of carbon pricing, CN-N increases power output for transmission **using fossil fuels**

- CN-N benefits renewable transition with trade above **C4 ($90)**

- KR, with trade, avoids thermal power generation by 5-15 % compared to autarkic generation

- Above c6 JP turn to nuclear to export to KR

Trade responds to changes in nodal generation cost



- Hourly nodal generation cost consistent throughout a day at 0-30 carbon price.

- **Higher renewable penetration increases price variations across hours and countries and trade volume increases at hours with cheaper cost**

- CN-N price stabilizes at c5 meaning coal consumption minimized

- KR's nodal price surpassing JP's, JP-W starts exporting to KR

Overcoming Limited Renewable Availability with Trade

Node	C	PV		wind	
		Optimal capacity (GW)	Max installable capacity (GW)	Optimal capacity (GW)	Max installable capacity (GW)
CN-N	c1	23.00	12979.00	46.00	970.00
	c2	450.27	12979.00	970.00	970.00
	c3	668.88	12979.00	970.00	970.00
	c4	1229.17	12979.00	970.00	970.00
	c5	1359.17	12979.00	970.00	970.00
	c6	1423.11	12979.00	970.00	970.00
	c7	1491.68	12979.00	970.00	970.00
JP-W	c1	25.00	807.00	3.00	60.00
	c2	25.00	807.00	3.00	60.00
	c3	25.00	807.00	60.00	60.00
	c4	99.05	807.00	60.00	60.00
	c5	137.94	807.00	60.00	60.00
	c6	246.13	807.00	60.00	60.00
	c7	256.96	807.00	60.00	60.00
KR	c1	8.00	444.00	7.00	33.00
	c2	8.00	444.00	7.00	33.00
	c3	179.13	444.00	7.00	33.00
	c4	232.55	444.00	7.00	33.00
	c5	444.00	444.00	33.00	33.00
	c6	444.00	444.00	33.00	33.00
	c7	444.00	444.00	33.00	33.00

Maximum installable renewable capacity from Bognadov & Beyer 2016

- KR reaches its maximum installable capacity for solar and wind at c5.

- Carbon pricing above c5 will only increase generation cost without promoting further renewable transition
- -> makes JP-W start to export in morning hours to KR to reduce thermal output

Conclusion and Implications

- Trade accelerates renewable transition with proper carbon pricing
  - (At zero carbon price) International dependence on China’s thermal consumption should be seriously re-valued in assessing economic/environmental impact.
  - Higher renewable penetration is the key in making more flexible two-way flows.

Conclusion and Implications

- Trade increases renewable power output in export nodes during daytime for transmission to avoid fuel/emission cost in import nodes
  - Cost reduction from avoided emission/fuel consumption is bigger than investment for line construction and renewable expansion.
- At local level, nodes embark on renewable transition at different levels of carbon price.
  - KR: Carbon pricing has limited impact with resource constraints
  - With nuc development suppressed, Solar/Wind alone cannot supply 2050 power demand. Needs diversification in clean technology portfolio.

Accelerating Renewable Transitions of Power Sectors: Options and Challenges

Chapters

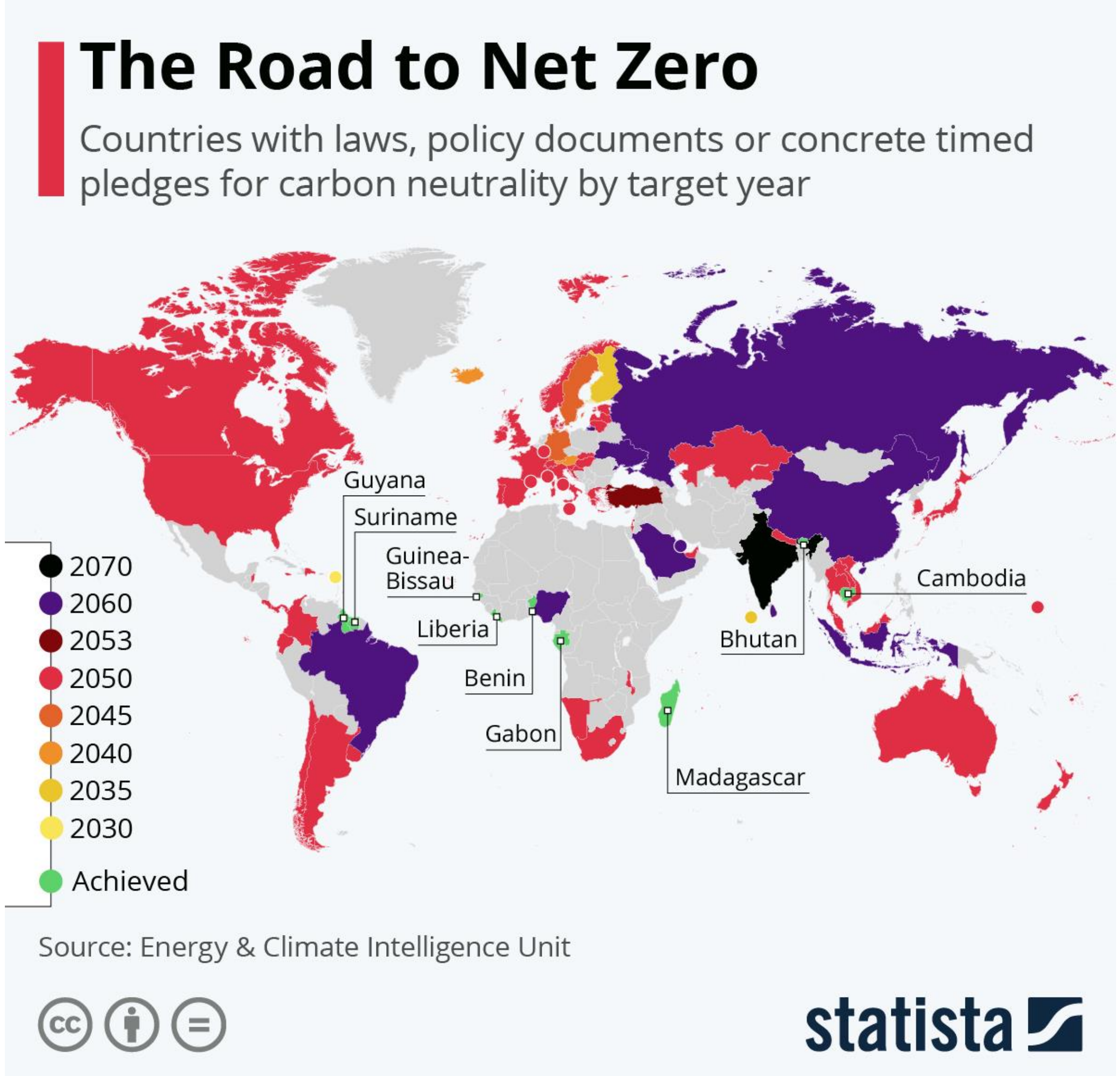
1. The Role of Bioenergy in Coal Shutdowns
2. Asia Super Grid and Carbon Pricing
3. Asia Super grid for Carbon Neutrality

Trade impacts for emission targets
Carbon pricing to ensure optimal tech pathways

Chapter 3:
Grid Interconnections & Decarbonization Pathways for Carbon Neutrality of Northeast Asia

Background and Questions

- Net zero pledges as a global trend
  - *137 countries* have committed to carbon neutrality as of June 2021 = 73% of global emissions (NPUC 2021).
  - China for 2060 , South Korea and Japan for 2050
- Power sector takes a leading position in carbon neutrality.



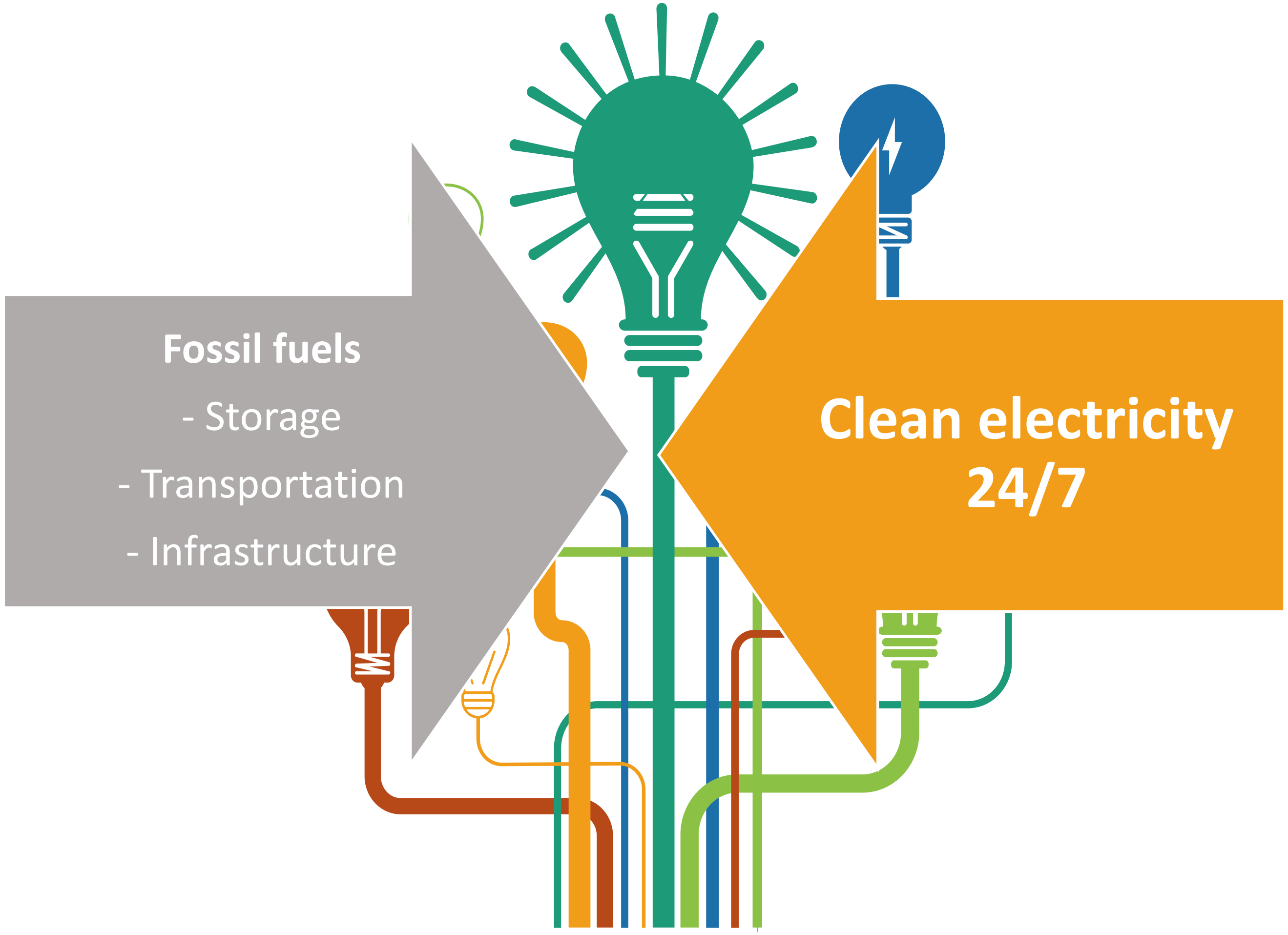
The Road to Net Zero

Countries with laws, policy documents or concrete timed pledges for carbon neutrality by target year

Source: Energy & Climate Intelligence Unit

Source: Statistica 2021

Carbon Neutrality:
Replacing 70% of Fossil Fuels in Generation Mix



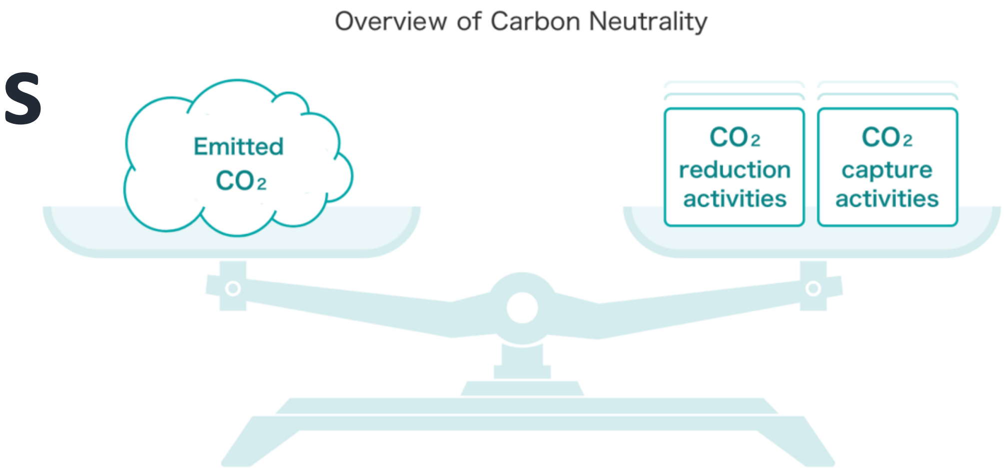
Fossil fuels

- Storage
- Transportation
- Infrastructure

Clean electricity 24/7

- Carbon neutral technologies (hydrogen, BECCS) substituting existing carbon-based assets
- Growing needs to assess integration of negative emission technologies in energy system and technology substitutions towards complete decarbonizations.

Mixed signals and Questions



Long term policy goals towards 2050 - 2060

Rapid technology advancement and cost reductions in renewables, hydrogen and CCS

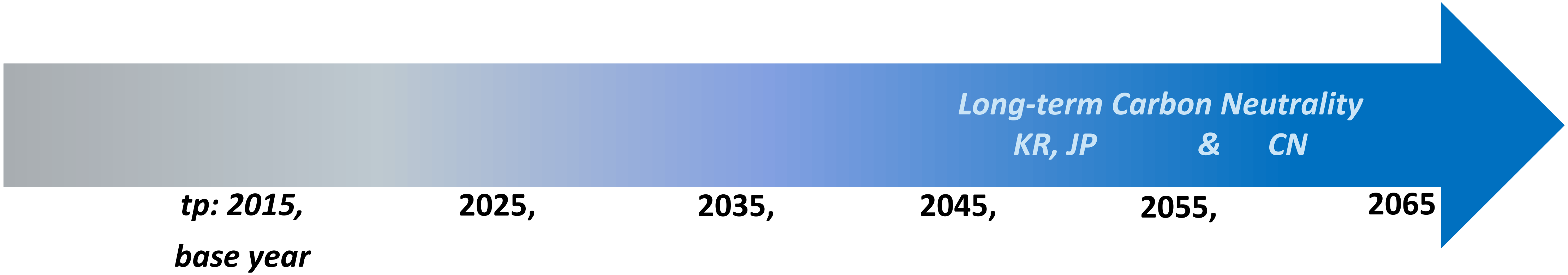
New coal additions scheduled

Nuclear phaseout?

- **Under changing energy environment (new tech options, price drops), trade impacts on coal/technology investment (technology substitutions) towards carbon neutrality?**
- **Optimal technology pathways towards 2065**

Methodology

Bottom-up Dynamic Investment Model (2015-2065)



- **Dynamic**: evolution of energy system over a time horizon

vs. Static: energy system configuration in a target year

Bottom-up Dynamic Investment Model (2015-2065)

Long-term Carbon Neutrality
KR, JP & CN

tp: 2015,
base year
2025,
2035,
2045,
2055,
2065

- **Dynamic**: evolution of energy system until the target year

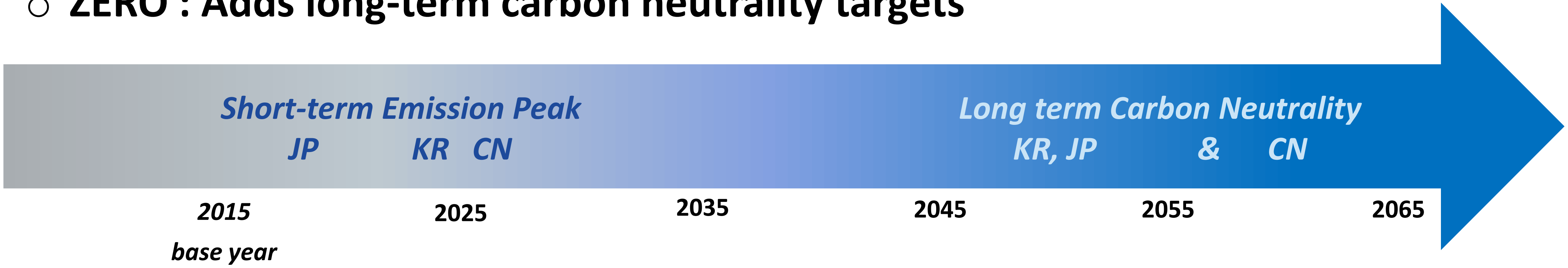
  vs **Static**: energy system configuration in a target year

- **Decomposing a multistage problem into a sequence of interrelated one-stage problems** (Prina et al. 2020)
  - **Split the time horizon into expansion phases** : 10-year time intervals
    - Time periods (tp): 2015, 2025, 2035, 2045, 2055, 2065
  - Capacity investment decisions of time periods tp, and tp+1 linked to each other
  - The optimization within tp (energy system dispatch) follows a static manner

Methodology

Two Emission Tracks (short-term / long-term)

- **BAU : Short-term emission peak**
- **ZERO : Adds long-term carbon neutrality targets**



Short-term Emission Peak
JP KR CN

Long term Carbon Neutrality
KR, JP & CN

2015
base year
2025
2035
2045
2055
2065

- Trade impacts at different carbon prices
  - Apply a flat carbon price over the time horizon to affect cost competitiveness of generation technologies
  - P0, 100, 200, 300 (USD/tCO2)

Methodology

Scenarios

*ALL scenarios assume **limited nuclear deployment** for KR, JP-W

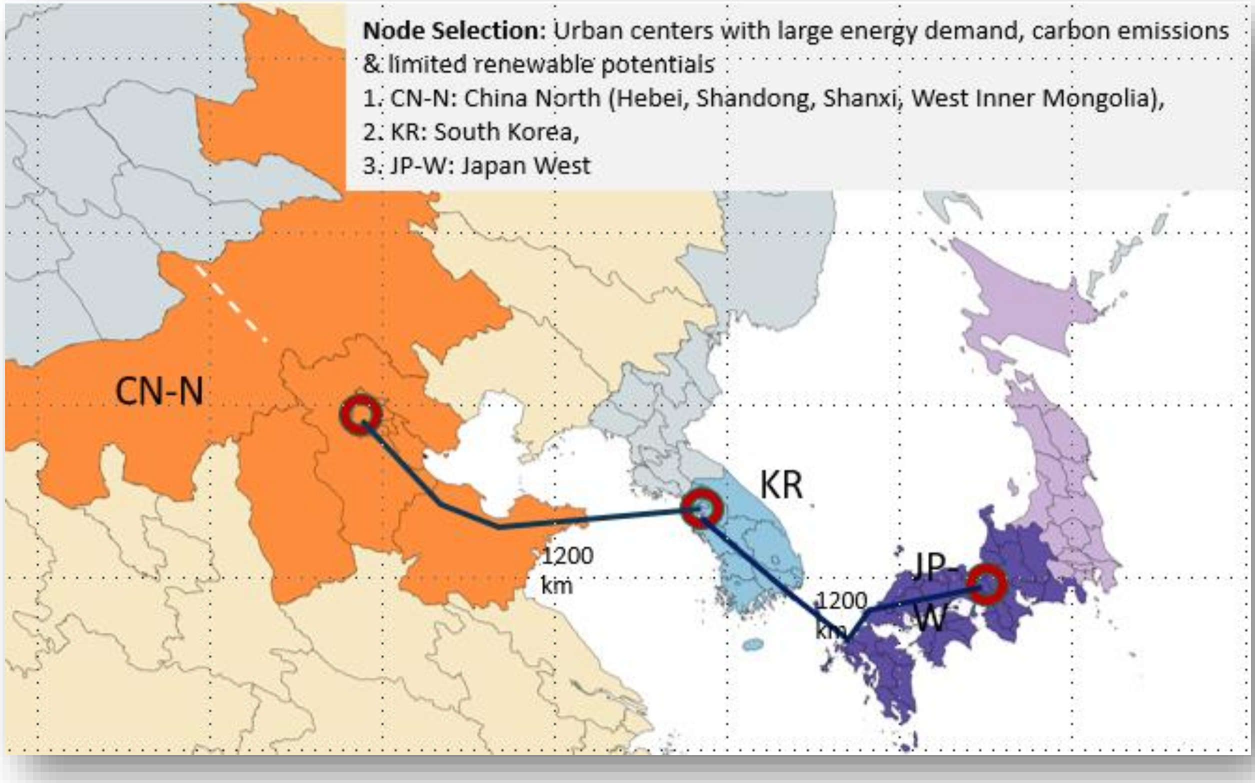
Trade option	Emission targets	Carbon price (USD/tCO2)	Scenarios
Trade	BAU	0	TBAUP0
		100	TBAUP100
		200	TBAUP200
		300	TBAUP300
	ZERO	0	TZEROP0
		100	TZEROP100
		200	TZEROP200
		300	TZEROP300
No Trade	BAU	0	NTBAUP0
		100	NTBAUP100
		200	NTBAUP200
		300	NTBAUP300
	ZERO	0	NTZEROP0
		100	NTZEROP100
		200	NTZEROP200
		300	NTZEROP300

Methodology

Sets (subsets)

Spatial resolution: 3 nodes
Time resolution: each time period has 96 time slices: 24 hours/day*1 representative day/season *4 seasons/year

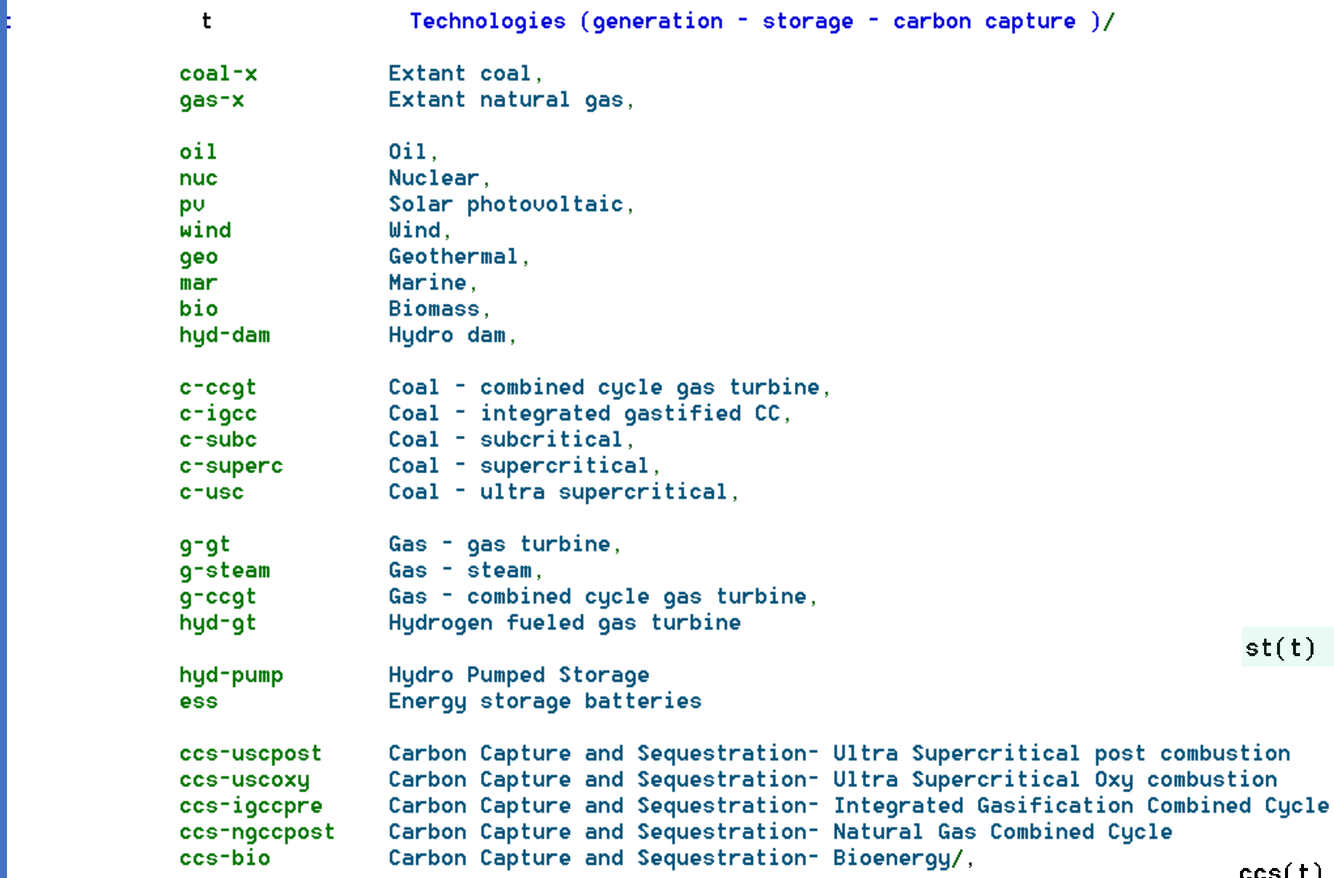
```
          yr        Years      /2015*2065/;

set      tp(yr)  Time periods in the model /2015,2025,2035,2045,2055,2065

          s  Seasons in the model /SPR,SUM,AUT,WIN/,

         hr      Hours (current time in Korea) /1*24/;

          n       Nodes /

                         CN-N    China - North grid
                         JP-W    Japan - West grid [60Hz]
                         KR      Korea/,

          a(n,n)  Network arcs (undirected) /
                         CN-N. KR
                         KR.JP-W/,
```



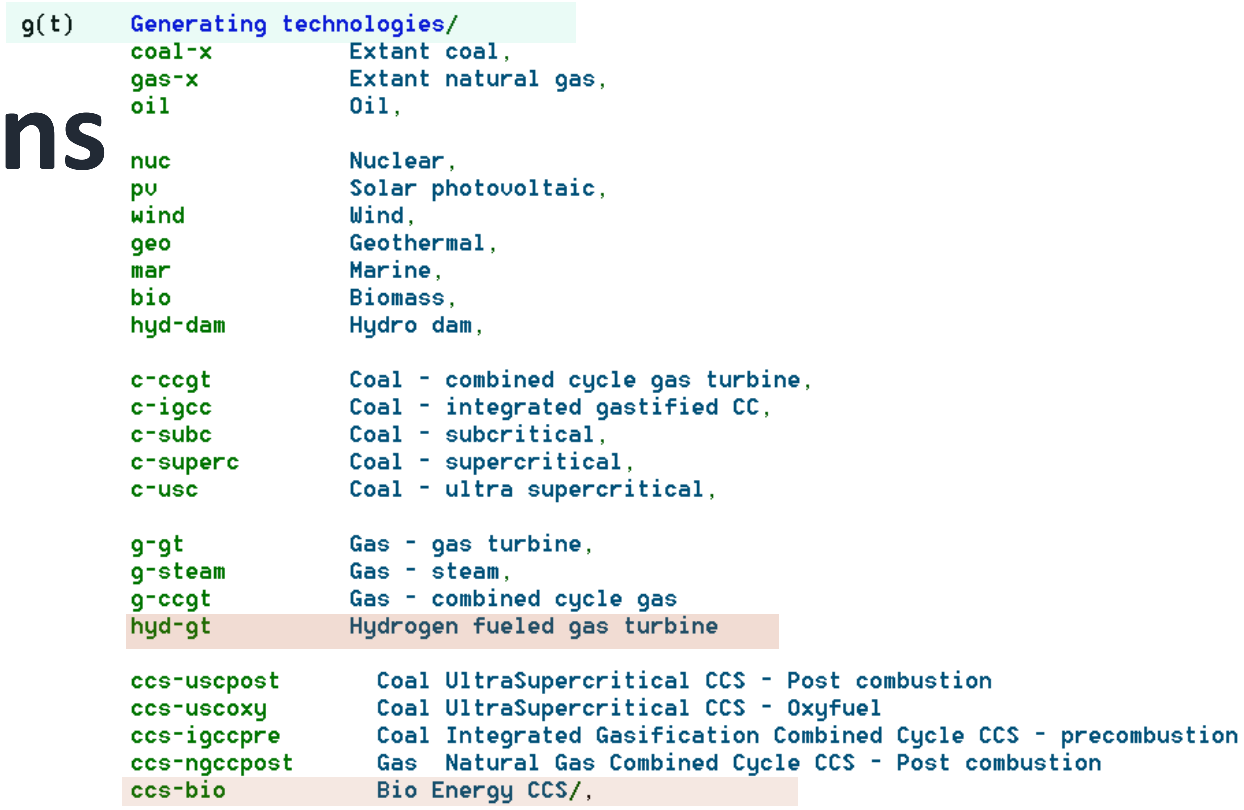
Node Selection: Urban centers with large energy demand, carbon emissions & limited renewable potentials
1. CN-N: China North (Hebei, Shandong, Shanxi, West Inner Mongolia),
2. KR: South Korea,
3. JP-W: Japan West

Methodology

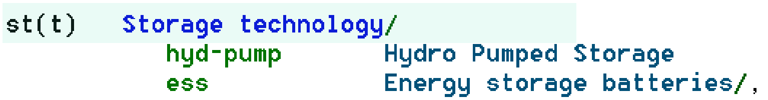
Sets_technology options



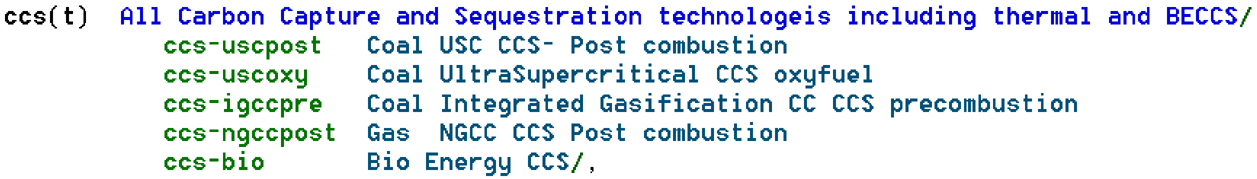
```
t                Technologies (generation - storage - carbon capture )/

coal-x          Extant coal,
gas-x           Extant natural gas,

oil             Oil,
nuc             Nuclear,
pv              Solar photovoltaic,
wind            Wind,
geo             Geothermal,
mar             Marine,
bio             Biomass,
hyd-dam         Hydro dam,

c-ccgt          Coal - combined cycle gas turbine,
c-igcc          Coal - integrated gastified CC,
c-subc          Coal - subcritical,
c-superc        Coal - supercritical,
c-usc           Coal - ultra supercritical,

g-gt            Gas - gas turbine,
g-steam         Gas - steam,
g-ccgt          Gas - combined cycle gas turbine,
hyd-gt          Hydrogen fueled gas turbine

hyd-pump        Hydro Pumped Storage
ess             Energy storage batteries

ccs-uscpost     Carbon Capture and Sequestration- Ultra Supercritical post combustion
ccs-uscoxy      Carbon Capture and Sequestration- Ultra Supercritical Oxy combustion
ccs-igccpre     Carbon Capture and Sequestration- Integrated Gasification Combined Cycle
ccs-ngccpost    Carbon Capture and Sequestration- Natural Gas Combined Cycle
ccs-bio         Carbon Capture and Sequestration- Bioenergy/,
```



```
g(t)    Generating technologies/
        coal-x          Extant coal,
        gas-x           Extant natural gas,
        oil             Oil,

        nuc             Nuclear,
        pv              Solar photovoltaic,
        wind            Wind,
        geo             Geothermal,
        mar             Marine,
        bio             Biomass,
        hyd-dam         Hydro dam,

        c-ccgt          Coal - combined cycle gas turbine,
        c-igcc          Coal - integrated gastified CC,
        c-subc          Coal - subcritical,
        c-superc        Coal - supercritical,
        c-usc           Coal - ultra supercritical,

        g-gt            Gas - gas turbine,
        g-steam         Gas - steam,
        g-ccgt          Gas - combined cycle gas
        hyd-gt          Hydrogen fueled gas turbine

        ccs-uscpost       Coal UltraSupercritical CCS - Post combustion
        ccs-uscoxy        Coal UltraSupercritical CCS - Oxyfuel
        ccs-igccpre       Coal Integrated Gasification Combined Cycle CCS - precombustion
        ccs-ngccpost      Gas  Natural Gas Combined Cycle CCS - Post combustion
        ccs-bio           Bio Energy CCS/,
```



```
st(t)   Storage technology/
            hyd-pump        Hydro Pumped Storage
            ess             Energy storage batteries/,
```



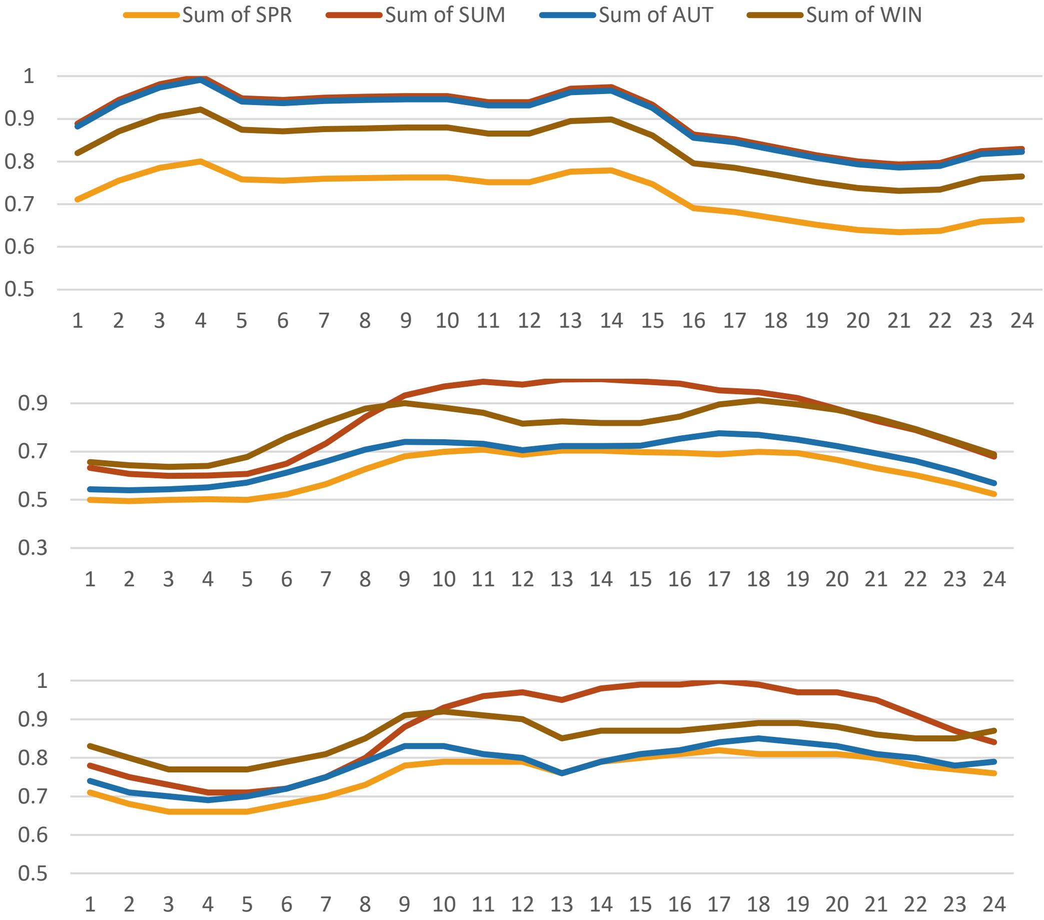
```
ccs(t)  All Carbon Capture and Sequestration technologeis including thermal and BECCS/
            ccs-uscpost    Coal USC CCS- Post combustion
            ccs-uscoxy     Coal UltraSupercritical CCS oxyfuel
            ccs-igccpre    Coal Integrated Gasification CC CCS precombustion
            ccs-ngccpost   Gas  NGCC CCS Post combustion
            ccs-bio        Bio Energy CCS/,
```

Additional technology options for deep emission cuts

Methodology

Demand

- Demand (node, *timeperiod*, season, hour) => 6x4x24 time slices for 3 nodes
- Multiply average hourly peak ratio of each season (s,hr) by peakload (yr,n)



CN-N
Harvard
dataverse
2015

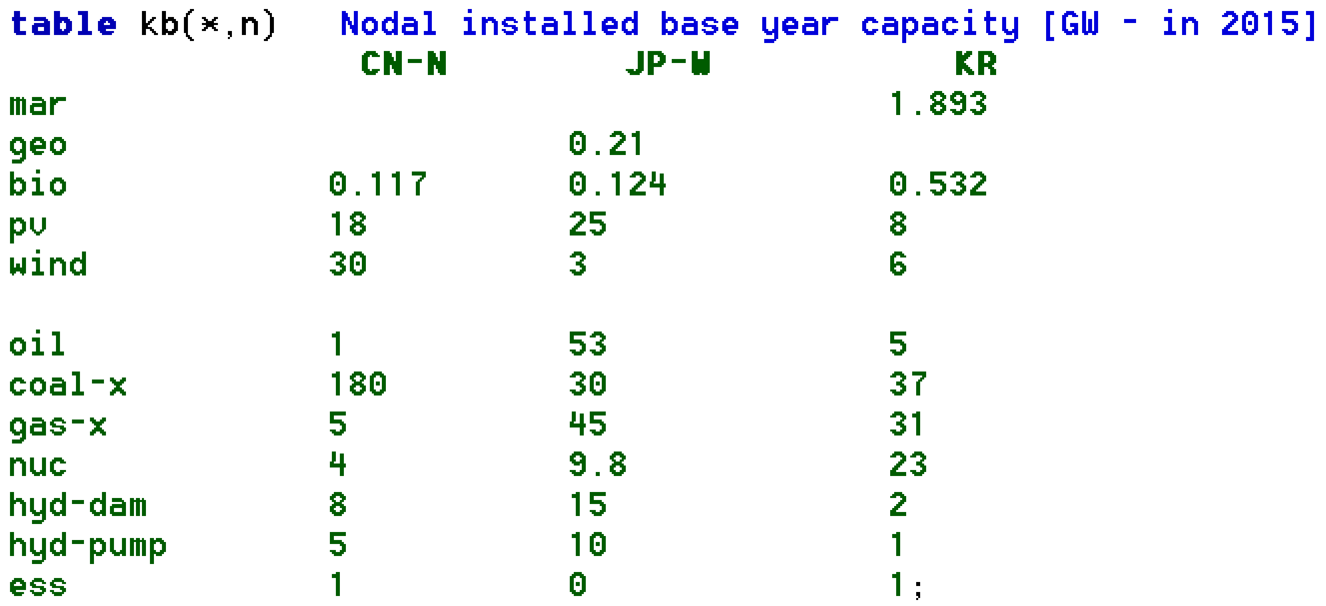
KR
KAPEX
2019

JP-W
Tepco
2019

```
table     peakload(yr,n)  Nodal peak load (GW)

              CN-N        JP-W          KR
2015         147.3        66.2        71.2
2016         156.1        66.2        71.2
2017         167.9        64.6        72.9
2018         182.6        65.2        75.0
2019         190.5        65.7        75.6
2020         197.0        66.1        77.0
2021         203.3        66.8        78.4
2022         208.9        67.2        80.0
2023         214.4        67.5        81.7
2024         219.9        67.9        83.1
2025         225.4        68.2        84.5
2026         230.6        68.6        85.7
2027         236.3        68.9        87.0
2028         241.8        69.3        88.1
2029         247.4        69.6        89.4
2030         253.0        70.0        90.5
2031         258.5        70.3        91.7
2032         263.8        70.5        92.7
2033         269.1        70.7        93.8
2034         274.2        70.9        94.8
2035         279.7        71.2        95.9
2036         284.5        71.3        97.0
2037         289.1        71.4        98.2
2038         293.2        71.4        99.3
2039         297.6        71.4       100.5
2040         301.5        71.4       101.7
2041         306.9        71.4       102.9
2042         312.3        71.5       104.1
2043         318.1        71.5       105.4
2044         324.0        71.6       106.6
```

Methodology

Supply capacity (base year)



```
table kb(*,n)   Nodal installed base year capacity [GW - in 2015]
                 CN-N         JP-W            KR
mar                                         1.893
geo                         0.21
bio             0.117       0.124           0.532
pv              18          25              8
wind            30          3               6

oil             1           53              5
coal-x          180         30              37
gas-x           5           45              31
nuc             4           9.8             23
hyd-dam         8           15              2
hyd-pump        5           10              1
ess             1           0               1;
```

Methodology

Maximum deployable capacity (GW)

Technology	CN-N	JP-W	KR
Marine	10	10	10
Geothermal	0.03	1.3	0.05
Bio	2	2	2
Bio-CCS	18	18	18
PV	12979	807	477.9
Wind	970	60	41.5
Hyd-dam	24	8	1.2
Other renewables	14	5	1
hyd-pump	6.4	32	8.8
nuc	+inf	15	23

Source: Beyer 2016, MOTIE 2021

***Nuclear constraints**:*
JP-W nuclear : only additional 5.3 GW ready for restart allowed to be added at no cost
KR: no capacity additions

Methodology

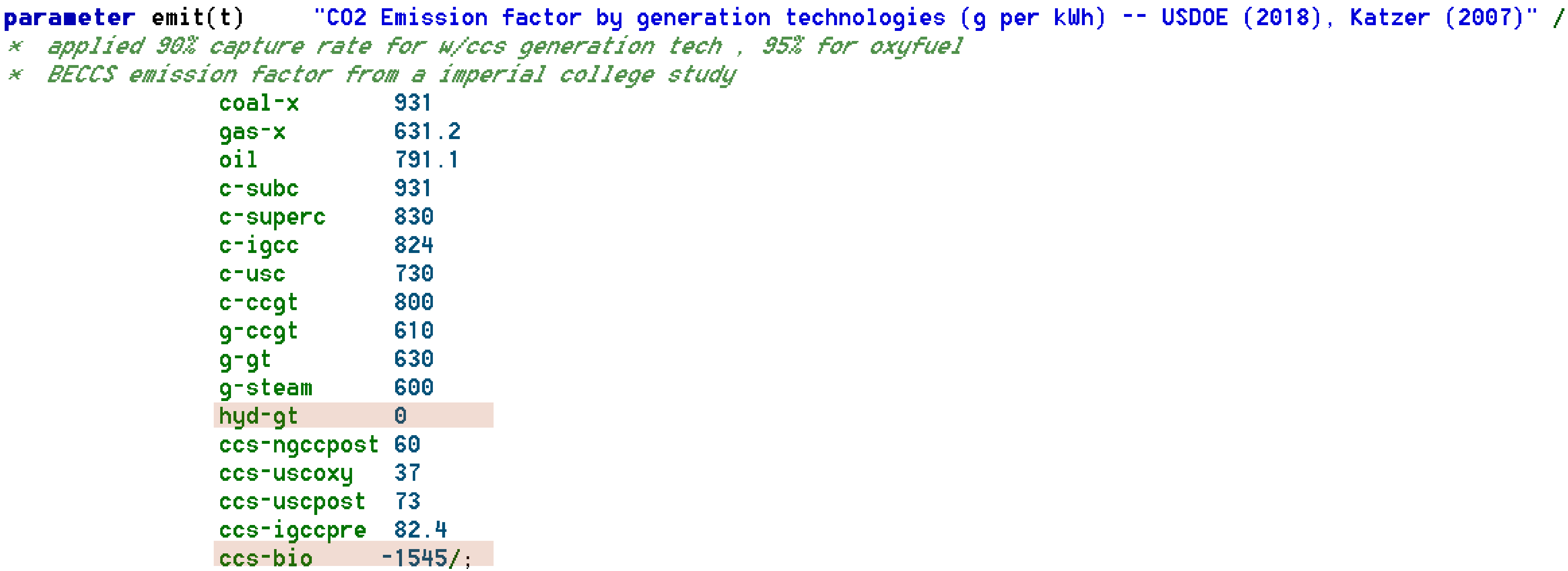
Technology cost

- Rapid cost reductions in green technologies needs to be addressed (He et al. 2020)
- Takes the annual reduction rate from ASSET cost projection data (2019) and incorporate technology advancement and price drops for clean technologies since 2020:
  - Solar: 3.2%, Wind: 1.2%
  - ESS 3%
  - CCS 0.4%
  - Hydrogen fuel 1%

Generation/ storage	Technology category	Generation/storage Technologies	CN-N	JP-W	KR
Generation technologies	Thermal excluding nuclear **(Thermal)**	gas	900	900	900
		oil	800	1900	1900
		coal-ccgt	900	1400	1100
		coal-igcc	1800	1800	1800
		coal-subc	900	1400	1100
		coal-superc	863	2649	1289
		coal-usc	606	1461	648
		g-gt	900	900	900
		g-steam	1300	1300	1300
		g-ccgt	646	1242	868
	Nuclear **(NUC)**	nuc	2007	4313	217
	Renewables **(RNW)**	pv	951	2301	1821
		wind	1245	2500	2518
		geo	1900	1900	1900
		mar	13000	13000	13000
		bio	2000	2600	2600
		othren	2000	2600	2600
		hyd-dam	664	9651	6000
	Hydrogen**(HDRG)**	Hdrg-gt	864	864	864
	Thermal CCS **(THCCS)**	USC w/ CCS post combustion	3400	3900	3600
		USC w/ CCS Oxy-combustion	3600	4100	3800
		IGCC w/ CCS	4400	4500	4500
		NGCC w/ CCS	2096	2692	2318
	Bioenergy CCS **(BECCS)**	Bioenergy w/ CCS	4758	4758	4758
Storage	Storage	hyd-pump	2500	6000	2500
		ESS	829	829	829

Methodology

Emission factor



```
parameter emit(t)     "CO2 Emission factor by generation technologies (g per kWh) -- USDOE (2018), Katzer (2007)" /
*  applied 90% capture rate for w/ccs generation tech , 95% for oxyfuel
*  BECCS emission factor from a imperial college study
                coal-x       931
                gas-x        631.2
                oil          791.1
                c-subc       931
                c-superc     830
                c-igcc       824
                c-usc        730
                c-ccgt       800
                g-ccgt       610
                g-gt         630
                g-steam      600
                hyd-gt       0
                ccs-ngccpost 60
                ccs-uscoxy   37
                ccs-uscpost  73
                ccs-igccpre  82.4
                ccs-bio     -1545/;
```

Methodology

Variables

TC	Total discounted cost
$K_{n,t,tp}$	Generating - storage- CCS capacity at node n and time period tp [GW]
$IK_{n,t,tp}$	Generation investment of technology t, at node n and time period tp [GW]
$L_{i,j}$	Line capacity between node i and j [GW]
$XP_{n,g,tp,s,hr}$	Power output of generating technology g by node - technology - season - hour [GWh]
$STE_{n,st,tp,s,hr}$	Stored electricity of storage type st at local time hr at node n [GWh]
$XDC_{n,st,tp,s,hr}$	Discharged electricity of storage type st at time hour at node n [GWh]
$XCH_{n,st,tp,s,hr}$	Charged electricity of storage type at hour at node n [GWh]
$XL_{i,j,tp,s,hr}$	Exported power from node i to j at time period tp, during seasons s at hour hr [GWh]
$NETEMISSION_{n,tp,s,hr}$	Emissions by tp and node at season s, and hour hr [million tCO2]

Methodology

Objective Function: Minimizing the present value of total energy system cost

$$\mathrm{MIN\ TC} = \sum_{tp} \mathrm{pv}_{\mathrm{tp}} * \{\sum_{n,t} \underline{\mathrm{cinv}_{\mathrm{t,n,tp}} * \mathrm{IK}_{\mathrm{n,t,tp}}} + \sum_{n,t} \underline{\mathrm{cfk}_{\mathrm{n,t,tp}} * \mathrm{K}_{\mathrm{n,t,tp}}} + \sum_{n,\mathrm{t,s,hr}} (\mathrm{cvk}_{\mathrm{n,t,tp}} + \mathrm{fuelcost}_{\mathrm{n,t,tp}} + \mathrm{pemit} * \mathrm{emit}_{\mathrm{t}}) * \underline{\mathrm{XP}_{\mathrm{n,t,tp,s,hr}} * \mathrm{days}_{\mathrm{s}}} + \sum_{\mathrm{i,j}} \underline{(\mathrm{cil}_{\mathrm{I,j}} + \mathrm{cfl}_{\mathrm{i,j}}) * \mathrm{L}_{\mathrm{i,j}}\}}$$

- Capital investment (cinv) for newly adopted capacity IK ,
- Fixed O&M (cfk) for all installed capacity K
- Variable O&M(cvk), fuel cost and emission cost (pemit) that are dependent on size of annual power output XP
  Days(s): no. of days in season s
- transmission line (L) investment (cil) and O&M (cfl) cost

Constraints:

Supply and demand balance

$$\underline{\sum_t \mathrm{XP}_{\mathrm{n,t,tp,s,hr}}} + \underline{\sum_{a(j,n)} \mathrm{XL}_{\mathrm{j,n,s,hr}} * \mathrm{eff}_{\mathrm{j,n}} - \sum_{a(n,j)} \mathrm{XL}_{\mathrm{n,j,s,hr}}} + \underline{\sum_{st}\left(\mathrm{XDC}_{\mathrm{n,st,s,hr}} - \mathrm{XCH}_{\mathrm{n,st,s,hr}}\right)} = \mathrm{d}_{\mathrm{n,tp,s,hr}}$$

At each node, time period, season and hour,

- Sum of power output of all generating technologies,
- + Net inflow of electricity to n with transmission losses
  (size of incoming electricity transmission XL(j,n,s,hr) from j to n with transmission efficiency loss considered, minus outflow transmission XL(n,j,s,hr) from n to j)
- + Release of electricity
  (discharged energy XDC of storage technology st, at season s, hour hr, minus charged energy XCH)

= Demand at node n, season s, hour hr

Constraints: capacity development

Intertemporal capital accumulation

$$\mathrm{K}_{\mathrm{n,t,tp+1}} \leq \mathrm{K}_{\mathrm{n,t,tp}} * (1 - \mathrm{deprate}) + \mathrm{betaI} * \mathrm{IK}_{\mathrm{n,t,tp}} + \mathrm{alphaI} * \mathrm{IK}_{\mathrm{n,t,tp+1}}$$

- K: Capacity of technology t
- IK: New Capacity Investment matures in both tp, tp+1
- Deprate: per period depreciation rate (annual: 2.5%)
- alphaI, betaI : Investment maturation factors for the own/subsequent period (Rutherford 2001)
  - Zero profit in investment
  - Zero profit in capital supply
  - Steady-state capital stock
  - alphaI = $\frac{1}{(r-g)}\left(\frac{r+d}{a\_r+a\_d} - \frac{g+d}{a\_g+a\_d}\right)$, betaI = $\frac{1}{(r-g)}\left[\frac{g+d}{a\_g+a\_d}(1+r) - \frac{r+d}{a\_r+a\_d}(1+g)\right]$

    * g: per period capital growth rate. assume capital k needs to increases at rate of growth in peak load *a_g: annual growth 1.4%

    * d: per period depreciation rate, * a_d: annual depreciation 2.5%

    - r: per period interest rate *a_r: annual interest rate :4%
- Capital stock in the first post terminal period (tp=2075) targets the steady state capital stock.

Constraints:

Power generation and storage

$\mathrm{XP}_{\mathrm{n},\boldsymbol{g},\mathrm{s},\mathrm{hr}} \leq \mathrm{resav}_{\mathrm{n,g,s,hr}} * \mathrm{K}_{\mathrm{n,g,tp}} \ \ \forall\ n,g,s,hr$	Hourly power output of generating technology g, XP, not larger than the size of installed capacity K(g) and the technology’s hourly availability
$\mathrm{STE}_{\mathrm{n,st,s,hr}} \leq \mathrm{K}_{\mathrm{n,st,tp}} * \mathrm{resav}_{\mathrm{n,st,s,hr}} \quad \forall n,st,s,hr$	Hourly electricity storage STE not larger than the size of installed storage capacity K(st) and hourly resource availability

Constraints:

Resource availability

$K_{n,t,tp} \leq maxcapacity_{n,t}$ *maximum deployable capacity for renewable power*

$\sum_{s,hr,bio} XP_{n,bio,tp,s,hr} * days_s \leq biopotential_n$ *Annual biomass availability*

Constraints:

Reserve margin

Under no trade

$$(1 + rv_n) * d_{n,tp,s,hr} \leq K_{\mathrm{n,t,tp+1}} * capcredit_{n,t}$$

<u>At each node</u>, readily available generation/storage capacity should be larger than demand and reserve margin (20%)

Under trade

$$\sum_n \{(1 + rv_n) * d_{n,tp,s,hr}\} \leq \sum_n \{K_{n,t,tp} * capcredit_{n,t}\}$$

With trade, regional power supply equip with reserve margin of 20% of the total demand across nodes (<u>location endogenously</u> decided)

Constraints:

Ramp up and down constraint

$$XP_{n,g,tp,s,hr-1} * \left(1 - ramprate_g\right) \leq XP_{n,g,tp,s,hr} \leq XP_{n,g,tp,s,hr-1} * (1 + ramprate_g)$$

For thermal technologies including all coal/gas/oil and nuclear,
Power output changeable within their ramping capabilities (ramping rate)

Constraints

Line capacity and power flow

$$XL_{a(i,j),tp,s,hr} \leq L_{a(i,j)}$$

Power flow between node I and j not larger than size of line capacity L between the nodes

Constraints: define

Emissions

$$NETEMISSION_{n,tp,s,hr} = \sum_{g}(XP_{n,g,tp,s,hr} * emit_{g})$$

Net emissions (NETEMISSION), at node n, timperiod tp, season s, and hour hr is sum of power output of each generating technology multiplied by its emission factor

Constraints:

Emission tracks

BaU scenario:

- $NETEMISSION_{CN-N,tp,s,hr} \leq NETEMISSION_{"CN-N","2025",s,hr}$
- $NETEMISSION_{"KR",tp,s,hr} \leq NETEMISSION_{"KR","2015",s,hr}$
- $NETEMISSION_{"JP-W",tp,s,hr} \leq NETEMISSION_{"JP-W","2015",s,hr}$

Zero scenario:

- $NETEMISSION_{"KR",tp\geq 2050,s,hr} \leq 0$
- $NETEMISSION_{"\mathrm{JP-W}",tp\geq 2050,s,hr} \leq 0$
- $NETEMISSION_{"\mathrm{CN-N}",tp\geq 2060,s,hr} \leq 0$

Constraints:

CO2 Storage capacity

$$\sum_{ccs,tp,s,hr} XP_{n,ccs,tp,s,hr} * capture_{ccs} * days_{s} * nyp \leq \mathrm{co2cap}_{2}$$

The amount of captured CO2 smaller than CO2 storage capacity at each node.

Key Insight from results:

For carbon neutrality,

- Diversification in clean technology portfolio needed
- Gaps in resource availability (+cost) is a driver for transitions
- Trade further increases clean power output where available-> reducing investment needs in costly hydrogen and accelerating thermal phaseout.

(reduce both TC, emissions)

- Carbon pricing to ensure equitable trade impact

Result outline:

1. Dynamic trade flows reduce the TC including emission/fuel
2. Rise of new technologies in capacity mixes
3. Technology pathways
    - Trade accelerate thermal reductions
    - Trade increases renewables and reduces investment hydrogen
4. Sensitivity to nuclear/ trade constraints

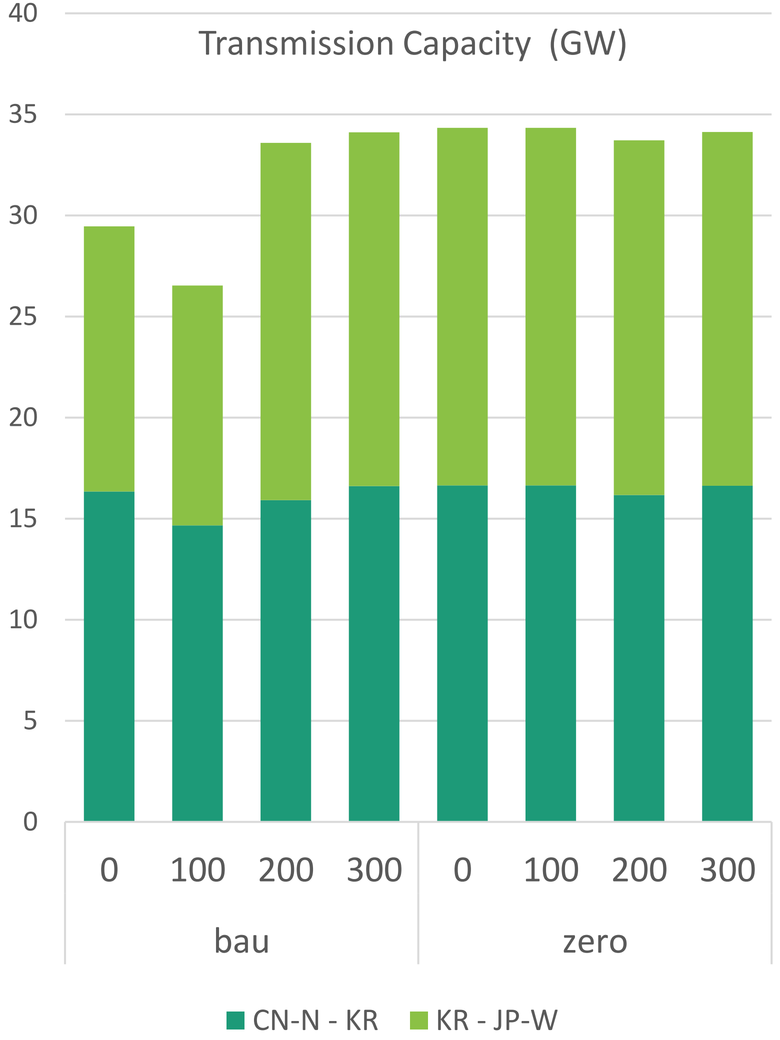
Result 1. **Cost savings and trade dynamics over time**

Two-way flows and cost savings for carbon neutrality.

Cost results by scneario

c	COMP	Regional	%	TC
TZEROP0	Cap	92026	-0.9	325374.0 (-3.2%)
	Fom	48655	-0.5	
	Vom	54326	0.2	
	Fuel	128901	-2.5	
	Lcap	1444	0.4	
	Lfom	22	0.0	
TZEROP100	Cap	159998	0.3	728838 (-1%)
	Fom	78110	0.0	
	Vom	69868	0.1	
	Fuel	107437	-1.0	
	Emit	311958	-0.5	
	Lcap	1444	0.2	
	Lfom	22	0.0	
TZEROP200	Cap	220725	0.5	991888 (-1.3%)
	Fom	102011	0.2	
	Vom	73833	0.0	
	Fuel	131686	-0.5	
	Emit	462210	-1.6	
	Lcap	1402	0.1	
	Lfom	22	0.0	
TZEROP300	Cap	243160	-0.1	1210868 (-1.4%)
	Fom	112187	0.1	
	Vom	74637	0.0	
	Fuel	153481	-1.4	
	Emit	625937	-0.2	
	Lcap	1443	0.1	
	Lfom	22	0.0	

Unit: million USD, percent cost change <u>compared to no trade</u>



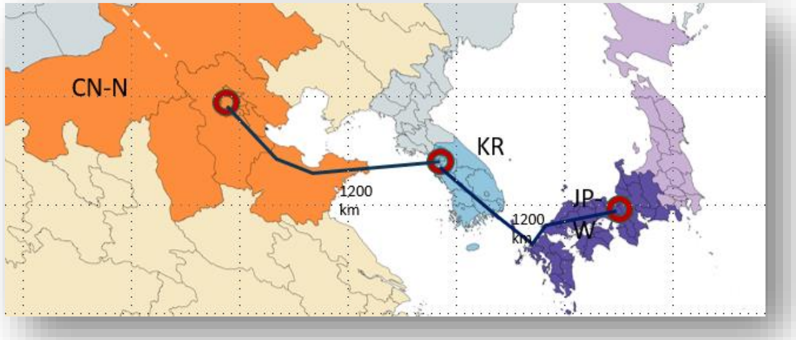
Focusing on ZERO,

- Trade reduces the TCs by 1-3.2% at P0-300
- Cost reductions in TC include savings in emission&fuel cost
- Line costs brings relatively marginal cost increase (by 0.1-0.4%)
- Optimal transmission line capacity almost even for two arcs CN-N- KR & KR-JP-W to an upper limit

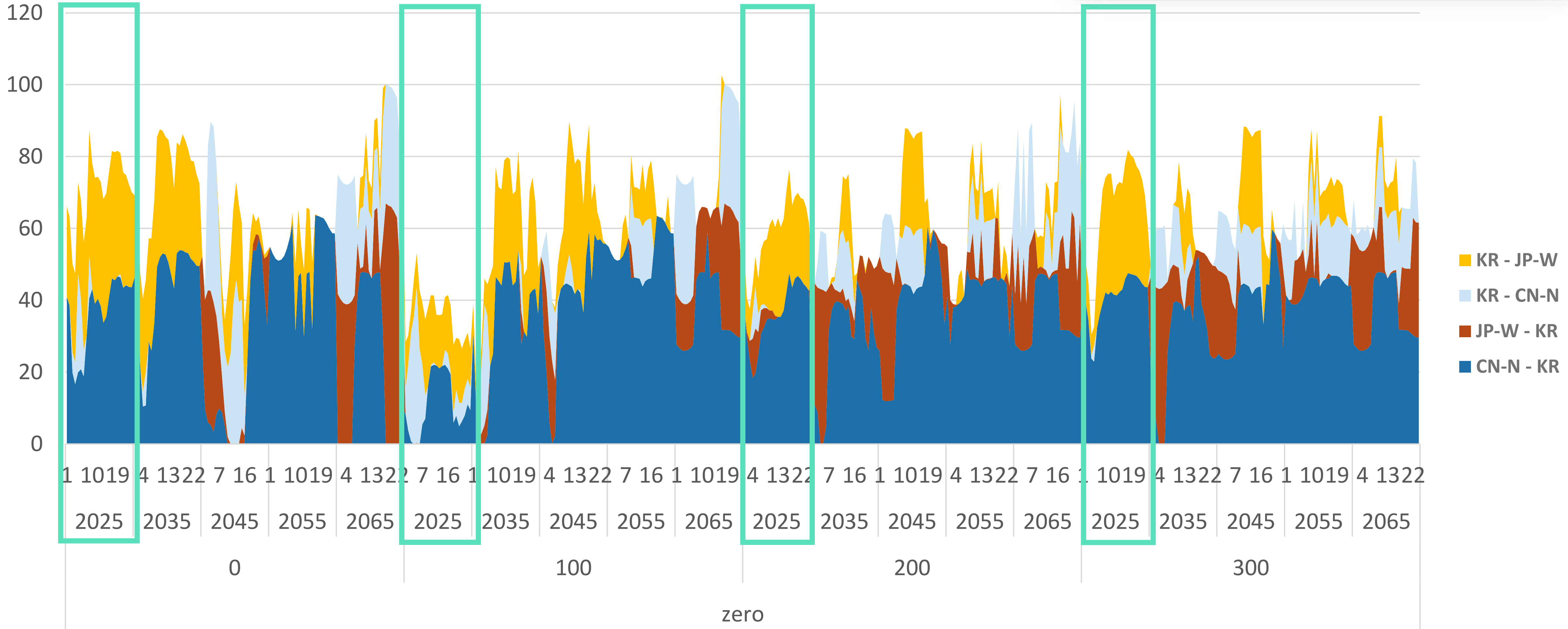
C: carbon price (USD/tCO2), COMP: cost component, CAP: capital cost, FOM: Fixed Operation and Maintenance cost, VOM: Variable Operation and Maintenance, LCAP: Transmission line capital investment, LFOM: Transmission Line Fixed Operation and Maintenance = (trade comp- no trade comp)/sum of no trade total

Result 1. **Cost savings and trade dynamics over time**

1 way (CN->KR->JP) in the earlier years,

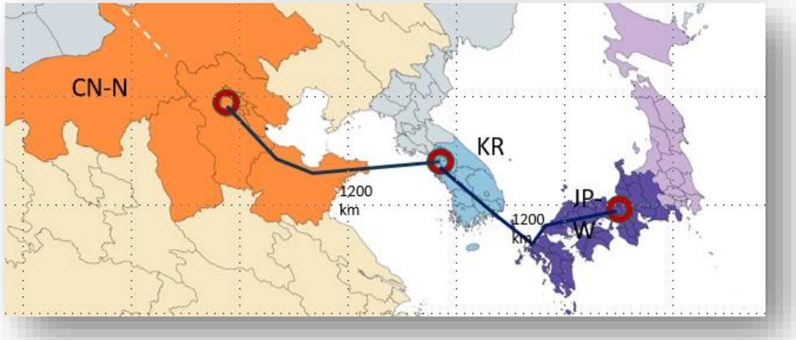


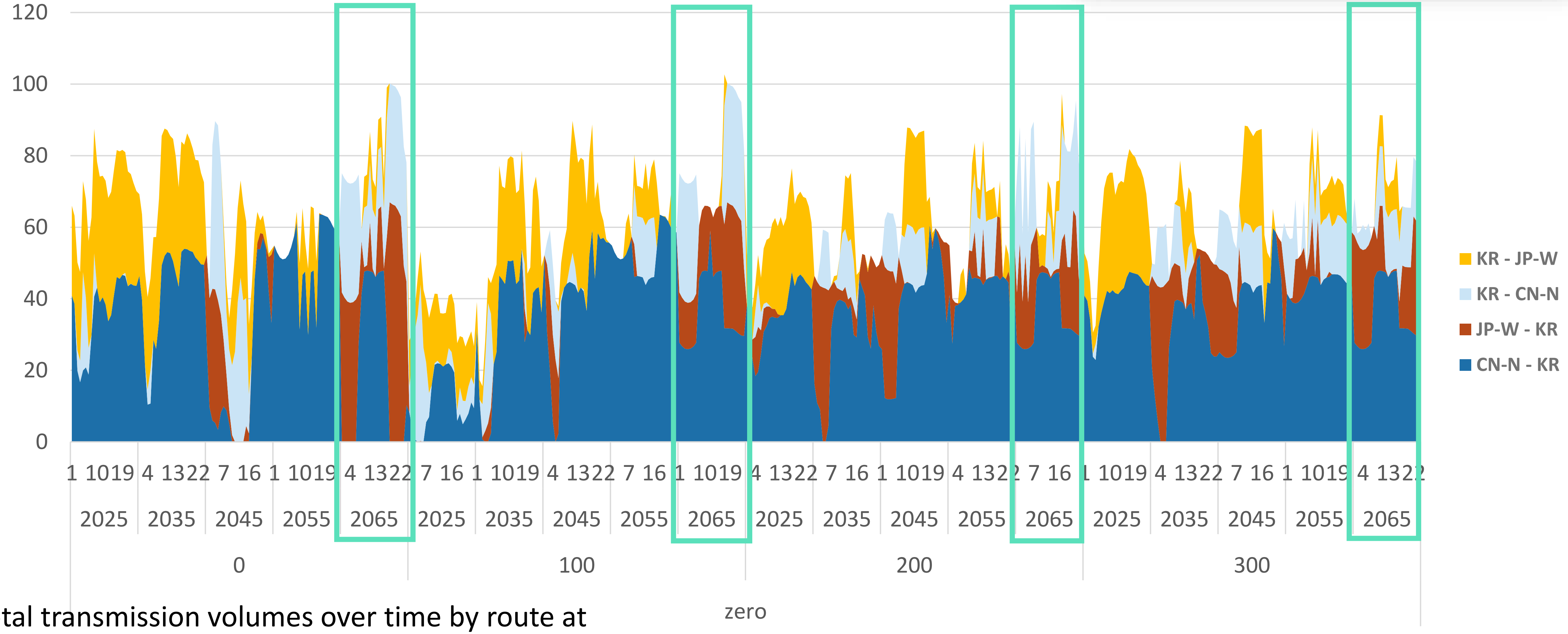
4- day aggregated transmission volumes over time periods (GWh)



Result 1. **Cost savings and trade dynamics over time**

1 way (CN->KR->JP) in the earlier years, to 2-way transmissions (CN<->KR<->JP) for achieving Carbon Neutrality



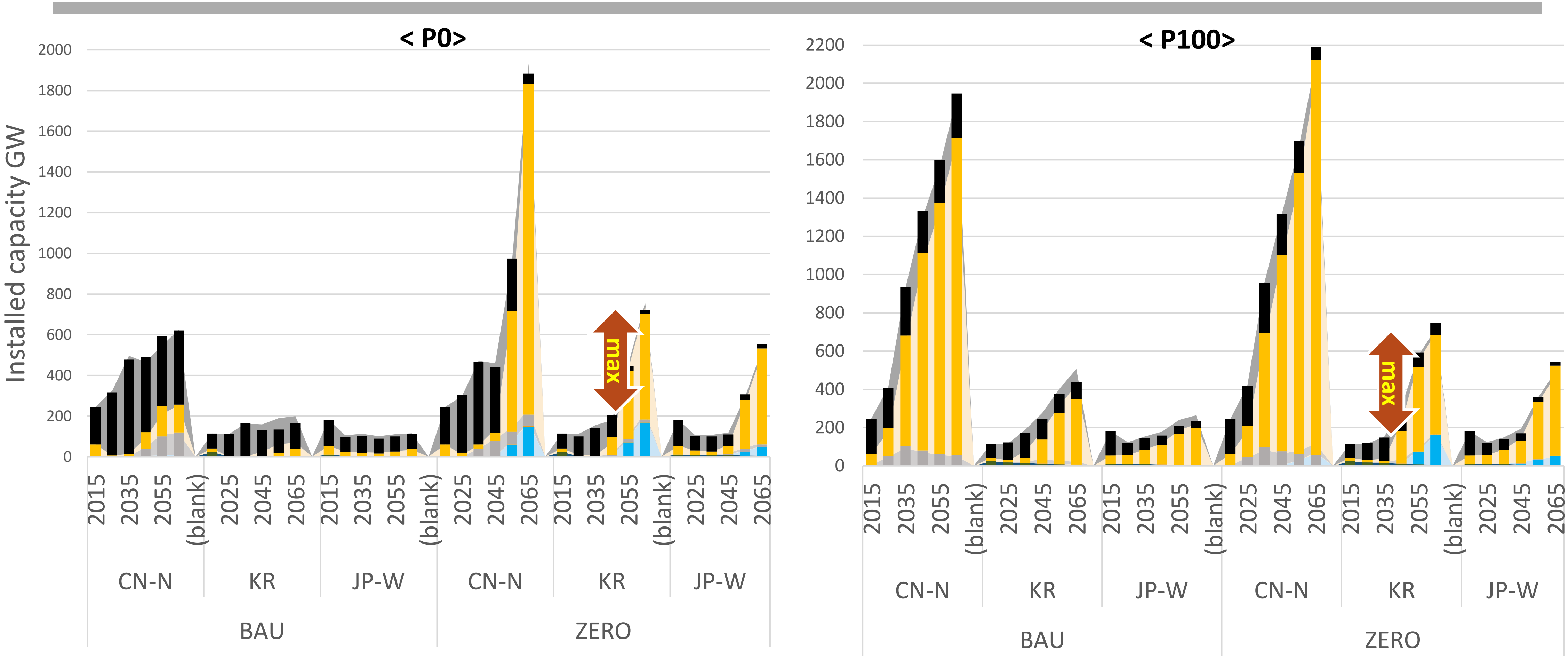


Total transmission volumes over time by route at different carbon prices (GWh)

Result 2. Optimal capacity mixes for emission targets

ZERO requires substantial growth in variable renewables + hydrogen

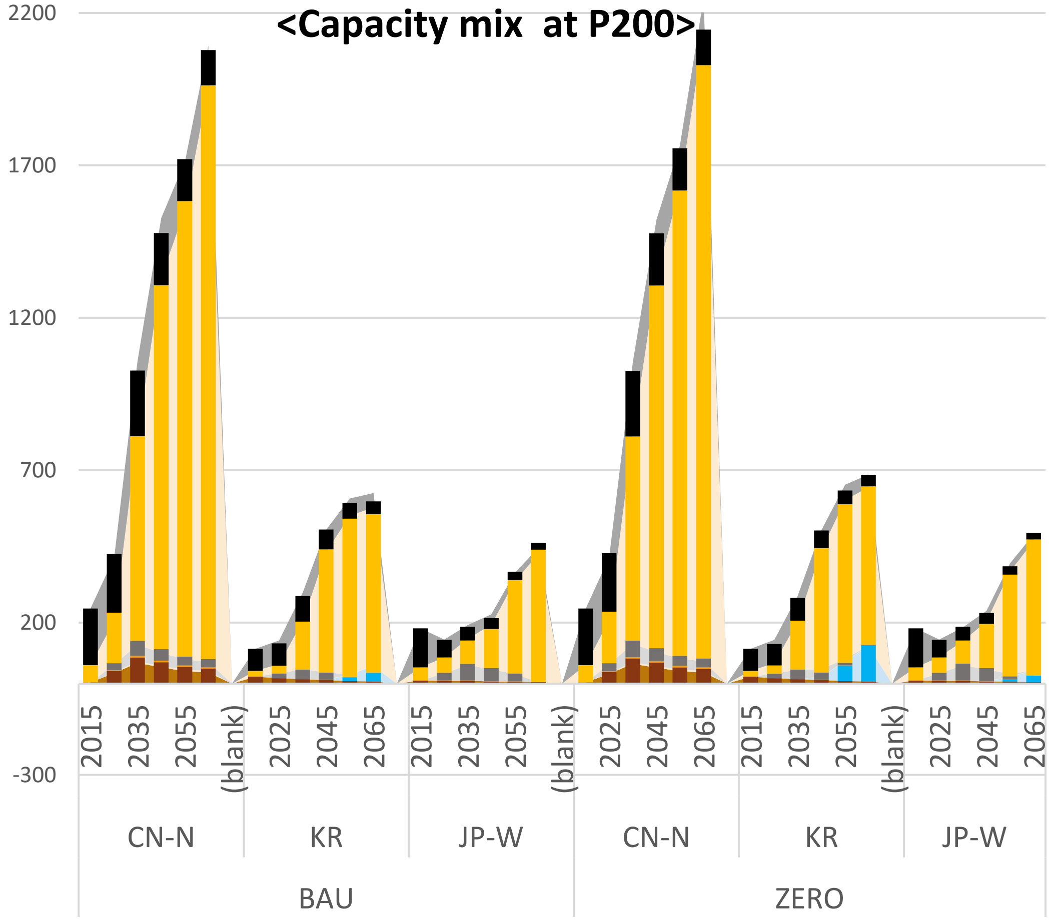
(P0)BAU maintains thermal consumptions at the peak level, ZERO requires significant increase in renewables & hydrogen close to netzero year (KR maxes out solar/wind capacity)

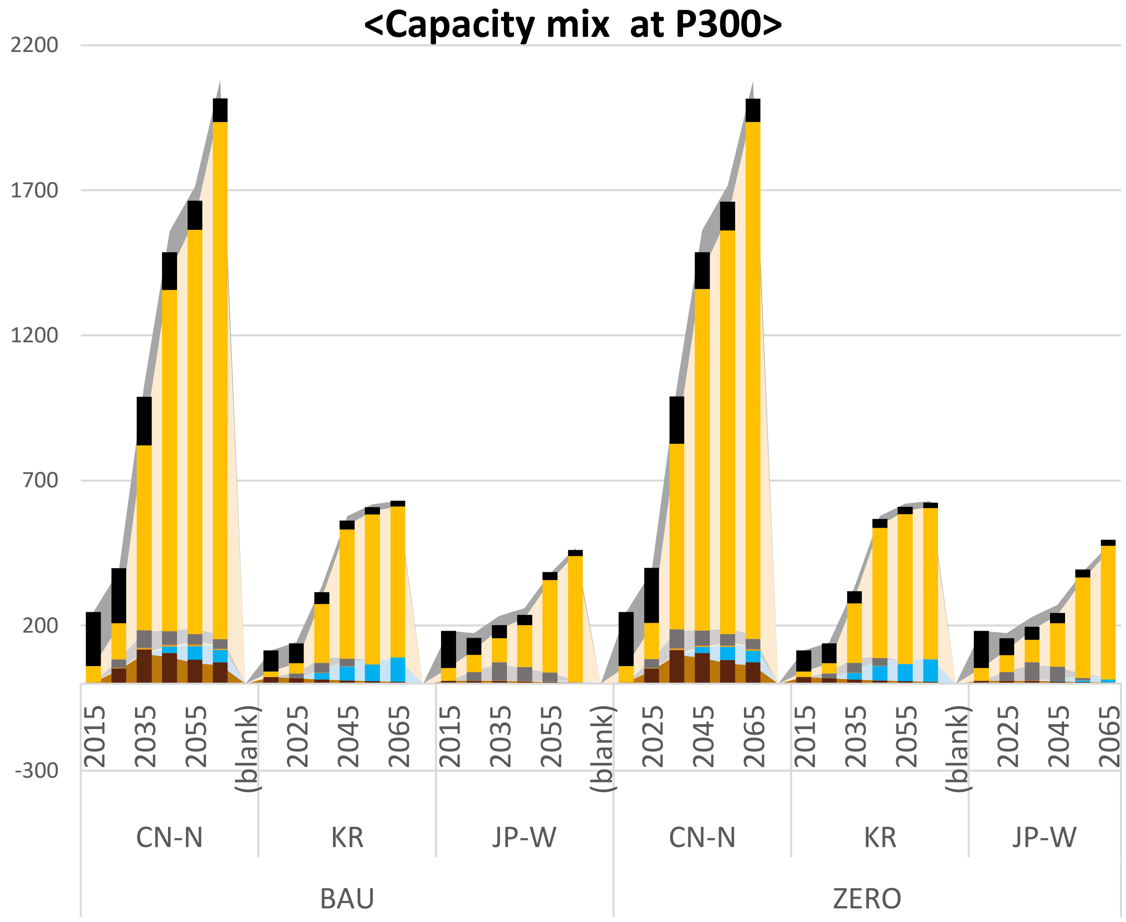


Result 2. Optimal capacity mixes for emission targets

Carbon pricing for earlier carbon reductions over time, reducing the gap btwn BAU &ZERO

At P200, CN-N chooses nuclear over hydrogen for earlier development in both BaU and ZERO

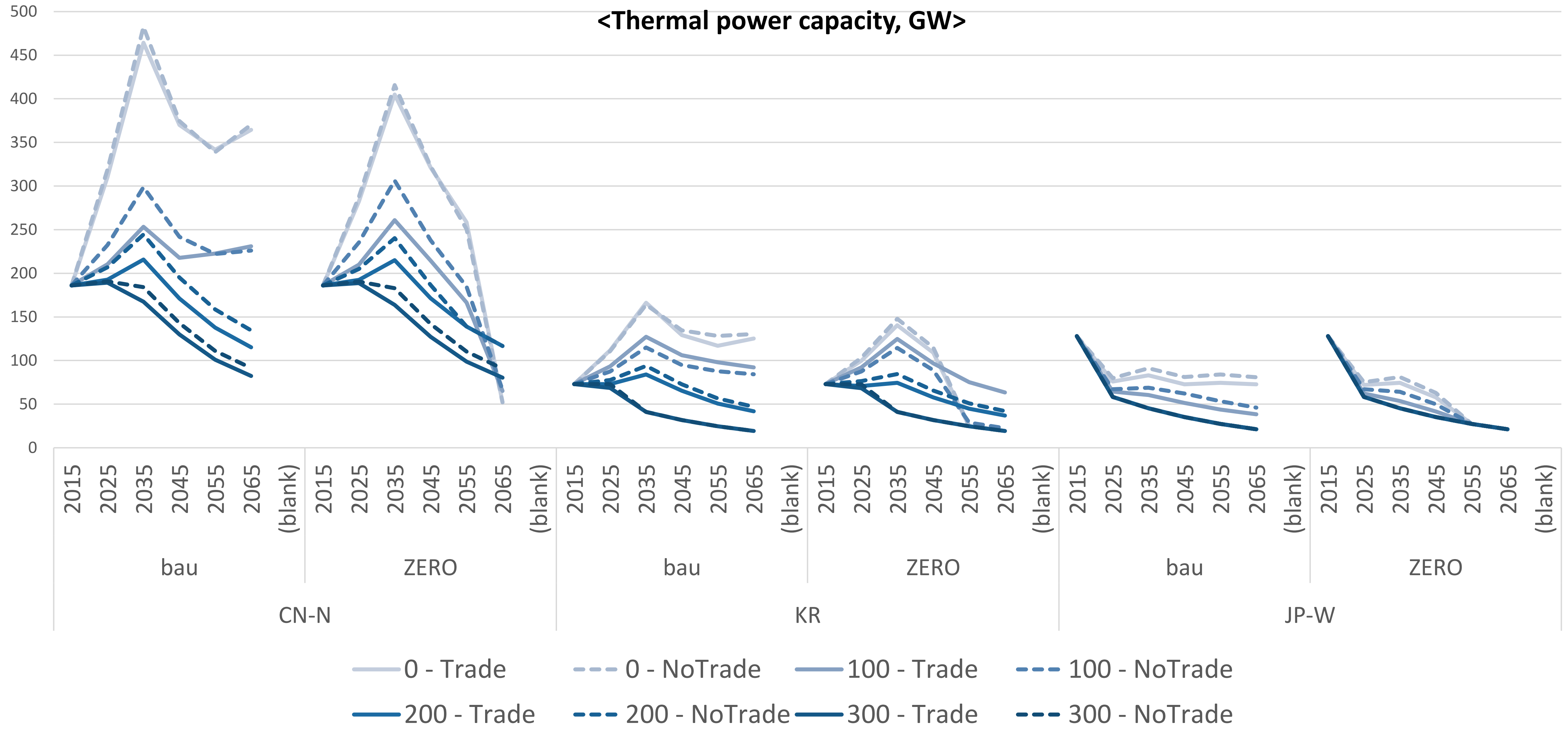




Result 3. Decarbonization pathways with trade

Higher carbon pricing enables earlier carbon reductions ($K_{thermal}$),

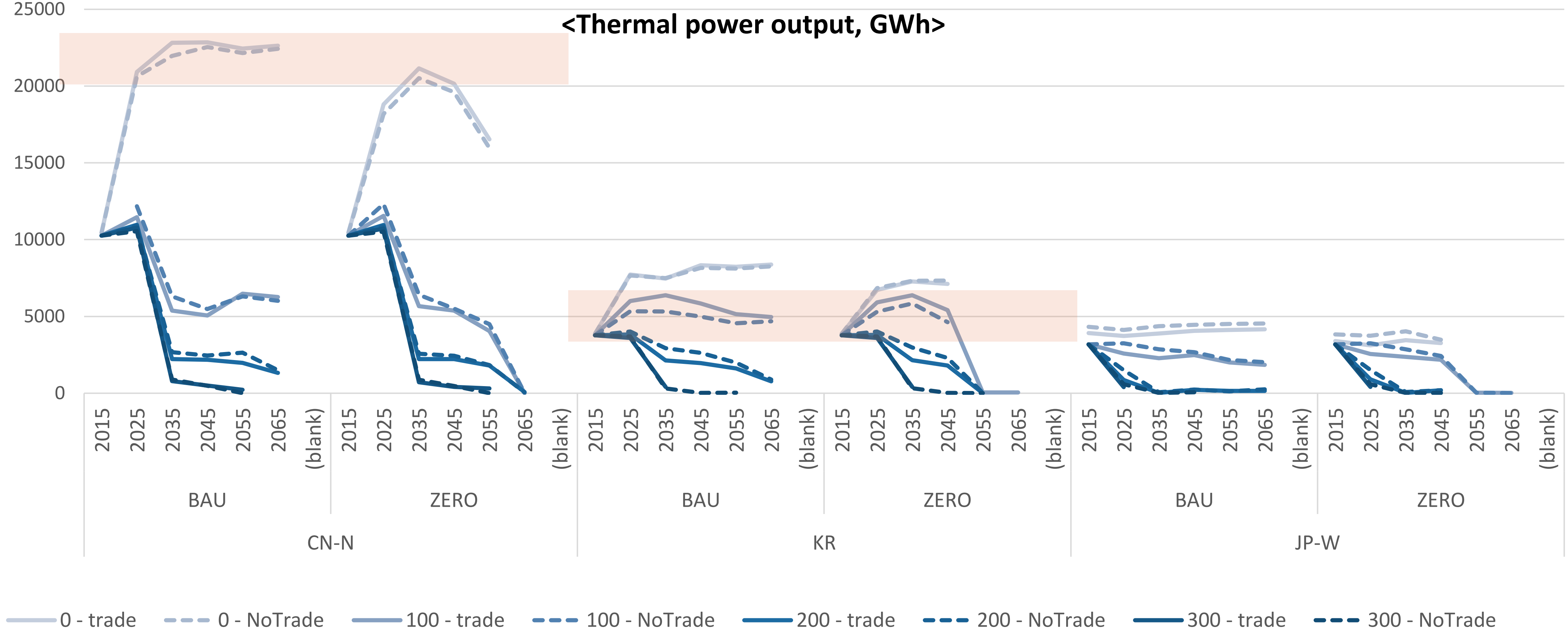
Trade in general further accelerates thermal reductions (gaps in dotted- solid lines at each P level)



Result 3. Decarbonization pathways with trade

Nodal impacts depends on carbon pricing $(XP_{thermal})$,

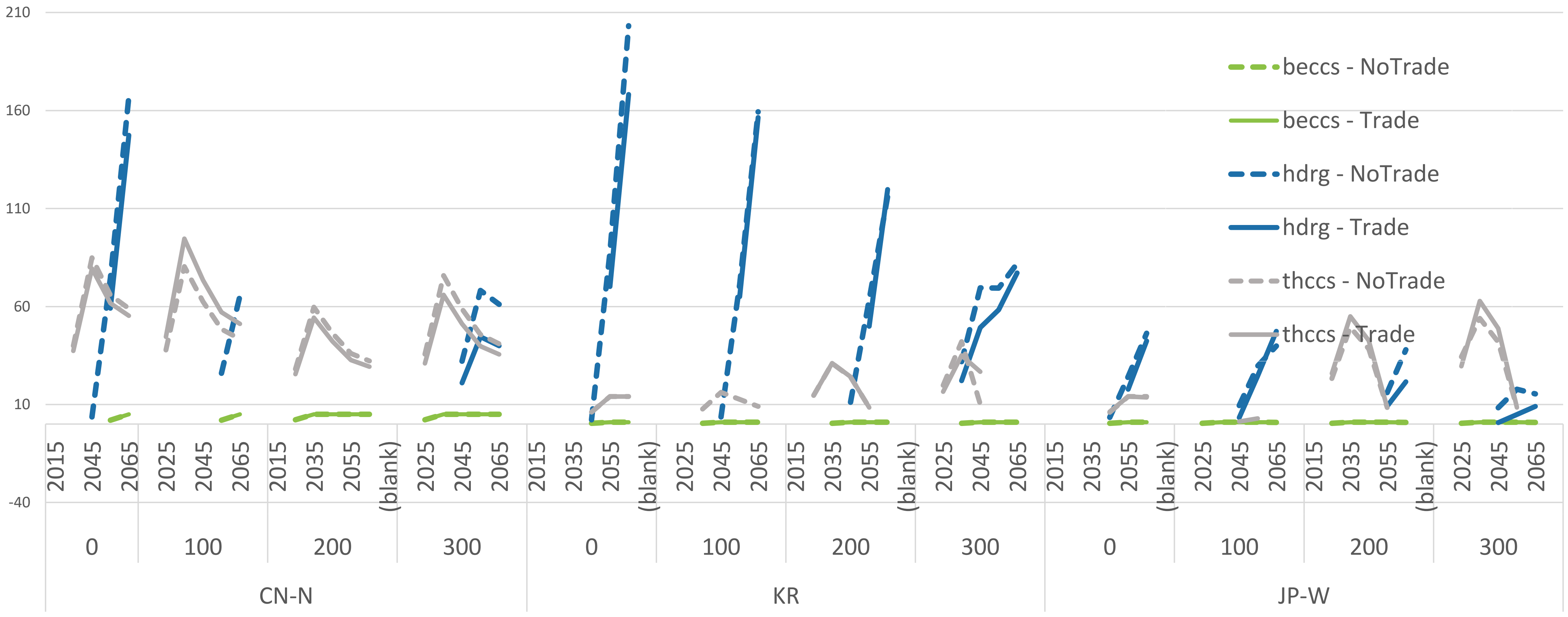
- P0, P100 trade increases CN-N, and KR thermal power output compared to notrade



Result 3. Decarbonization pathways with trade

Beyond solar/wind : Hydrogen, BECCS, thCCS

CN-N increasing renewable, nuclear utilizations W/TRADE-> significantly reduces hydro investment burden

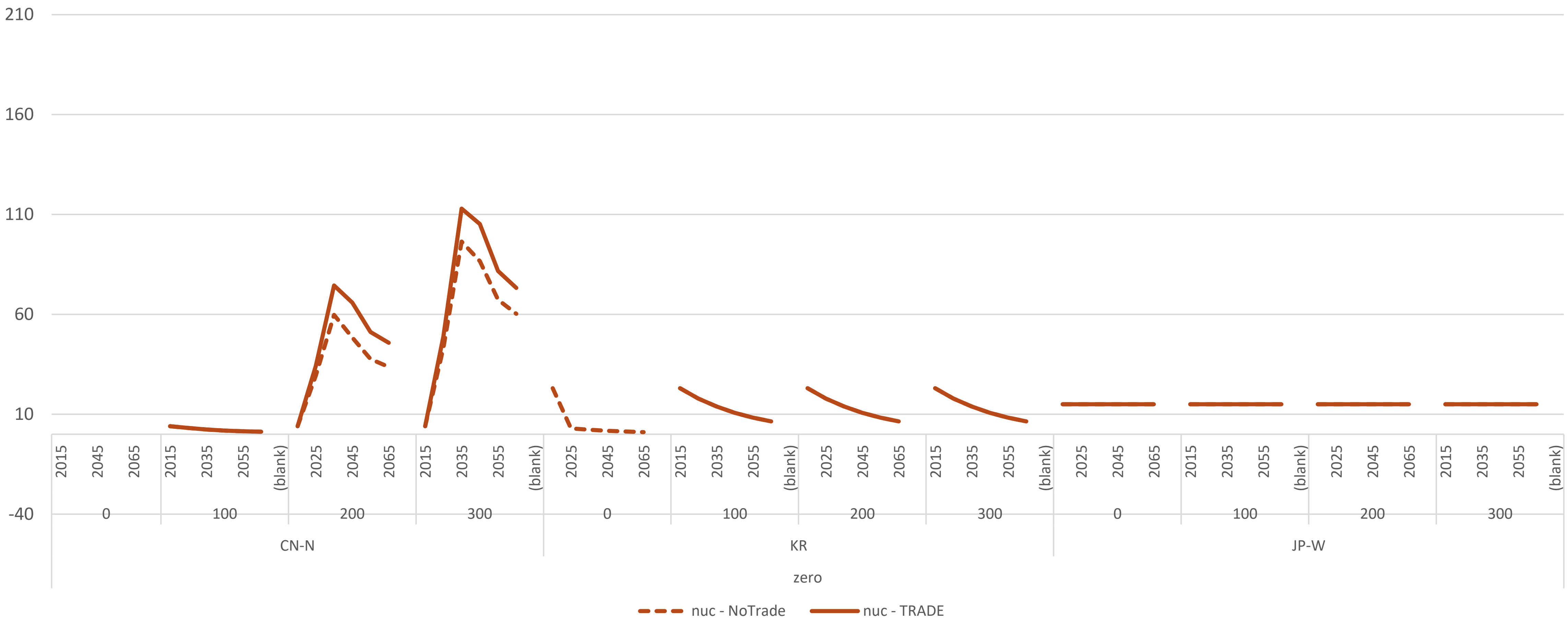


<Capacity development over time (GW)>

Result 3. Decarbonization pathways with trade

ZERO requires beyond solar&wind: 1) nuclear

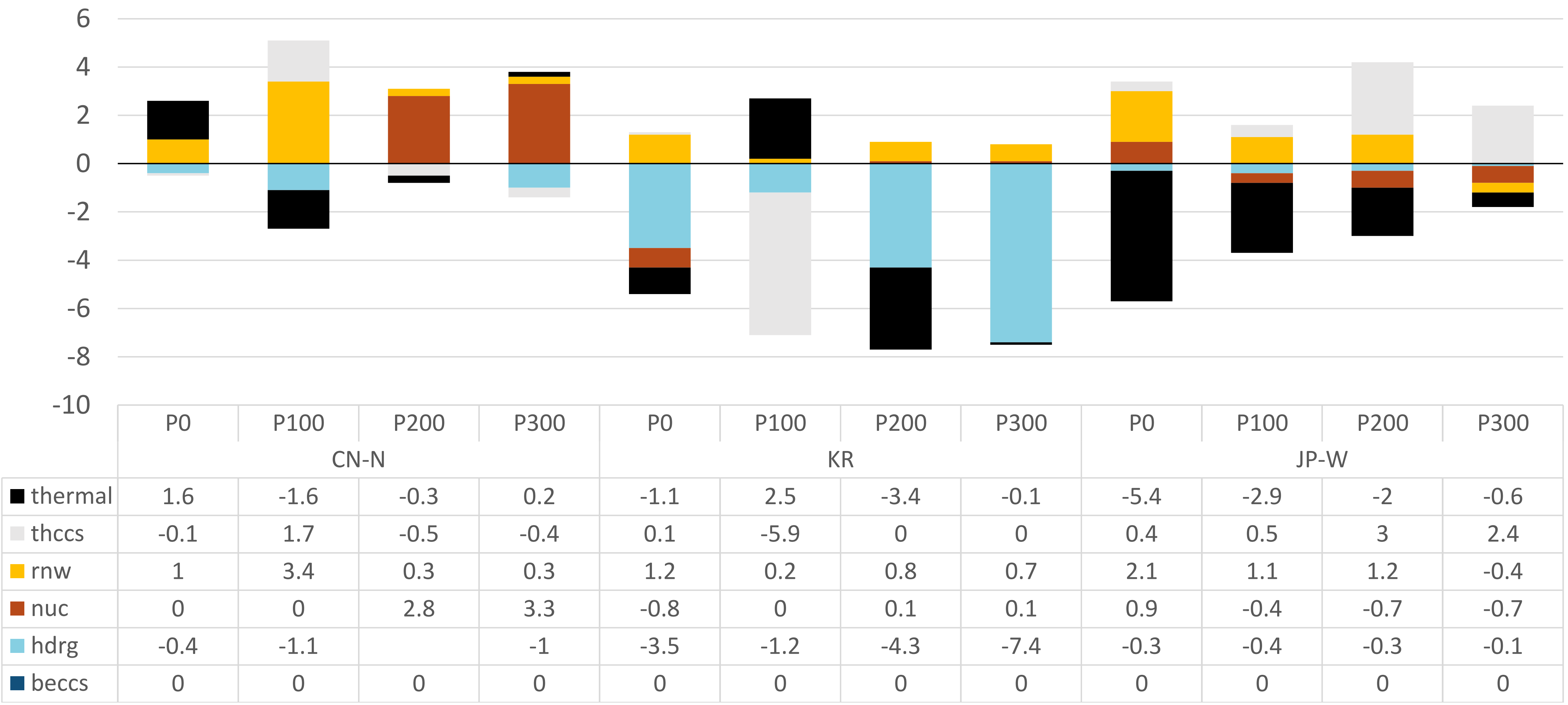
- While nuclear utilization constrained in KR, JP-W, Trade increases CN-N's nuclear development from P200



<Capacity development over time (GW)>

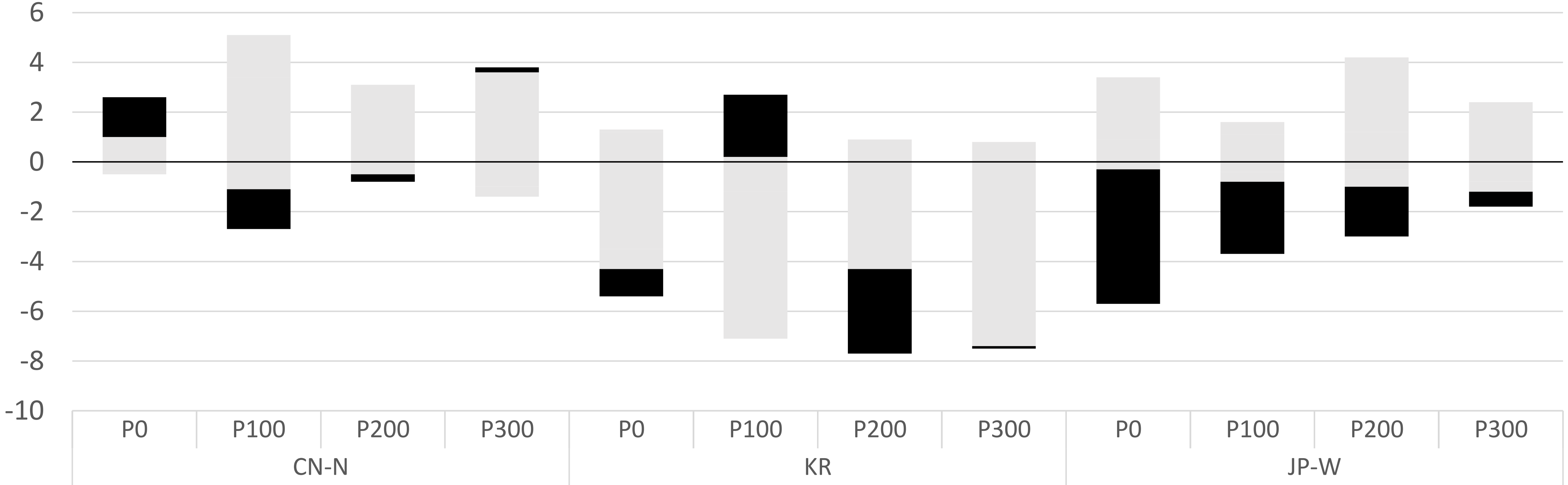
Trade impact on Technology Substitution for Carbon Neutrality

Technology Composite of Nodal output changes (% change compared to no trade total)



	CN-N				KR				JP-W			
	P0	P100	P200	P300	P0	P100	P200	P300	P0	P100	P200	P300
■ thermal	1.6	-1.6	-0.3	0.2	-1.1	2.5	-3.4	-0.1	-5.4	-2.9	-2	-0.6
■ thccs	-0.1	1.7	-0.5	-0.4	0.1	-5.9	0	0	0.4	0.5	3	2.4
■ rnw	1	3.4	0.3	0.3	1.2	0.2	0.8	0.7	2.1	1.1	1.2	-0.4
■ nuc	0	0	2.8	3.3	-0.8	0	0.1	0.1	0.9	-0.4	-0.7	-0.7
■ hdrg	-0.4	-1.1		-1	-3.5	-1.2	-4.3	-7.4	-0.3	-0.4	-0.3	-0.1
■ beccs	0	0	0	0	0	0	0	0	0	0	0	0

Trade impact on Technology Substitution for Carbon Neutrality
Carbon pricing to ensure all nodes reduce extra fossil fuel consumptions with trade
P100: KR's thermal based power generation still cheaper to JP's

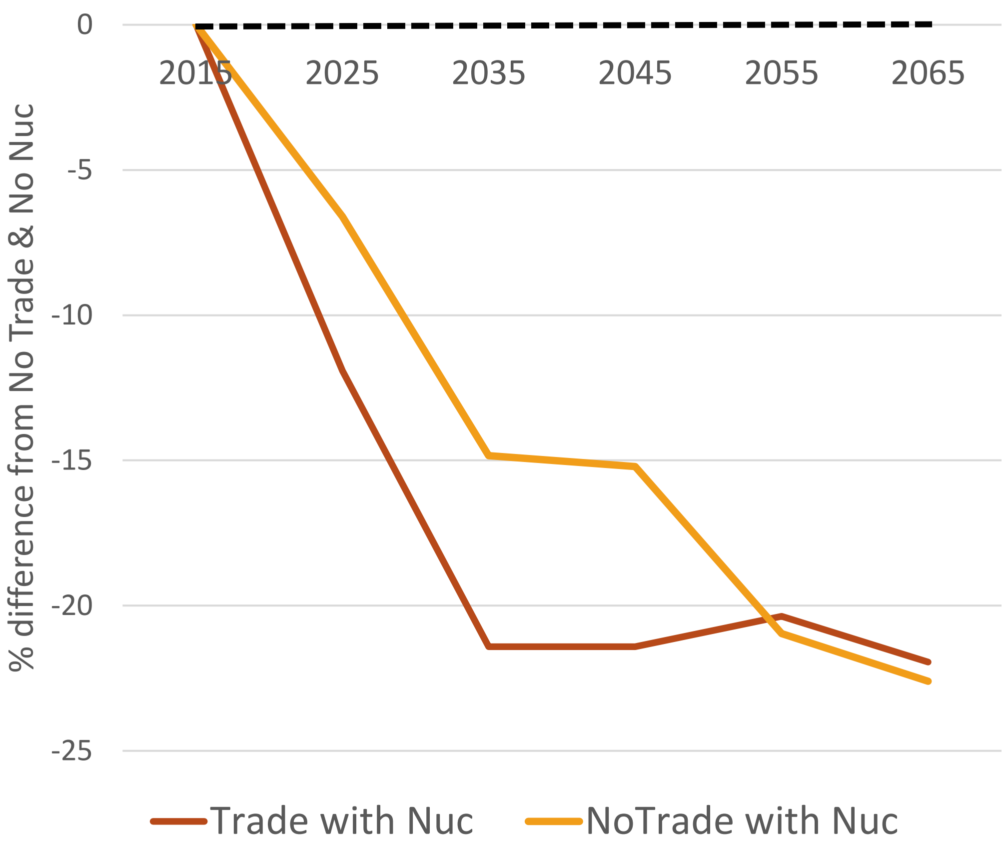


	CN-N P0	CN-N P100	CN-N P200	CN-N P300	KR P0	KR P100	KR P200	KR P300	JP-W P0	JP-W P100	JP-W P200	JP-W P300
■ thermal	1.6	-1.6	-0.3	0.2	-1.1	2.5	-3.4	-0.1	-5.4	-2.9	-2	-0.6
□ thccs	-0.1	1.7	-0.5	-0.4	0.1	-5.9	0	0	0.4	0.5	3	2.4
□ rnw	1	3.4	0.3	0.3	1.2	0.2	0.8	0.7	2.1	1.1	1.2	-0.4
□ nuc	0	0	2.8	3.3	-0.8	0	0.1	0.1	0.9	-0.4	-0.7	-0.7
□ hdrg	-0.4	-1.1		-1	-3.5	-1.2	-4.3	-7.4	-0.3	-0.4	-0.3	-0.1
■ beccs	0	0	0	0	0	0	0	0	0	0	0	0

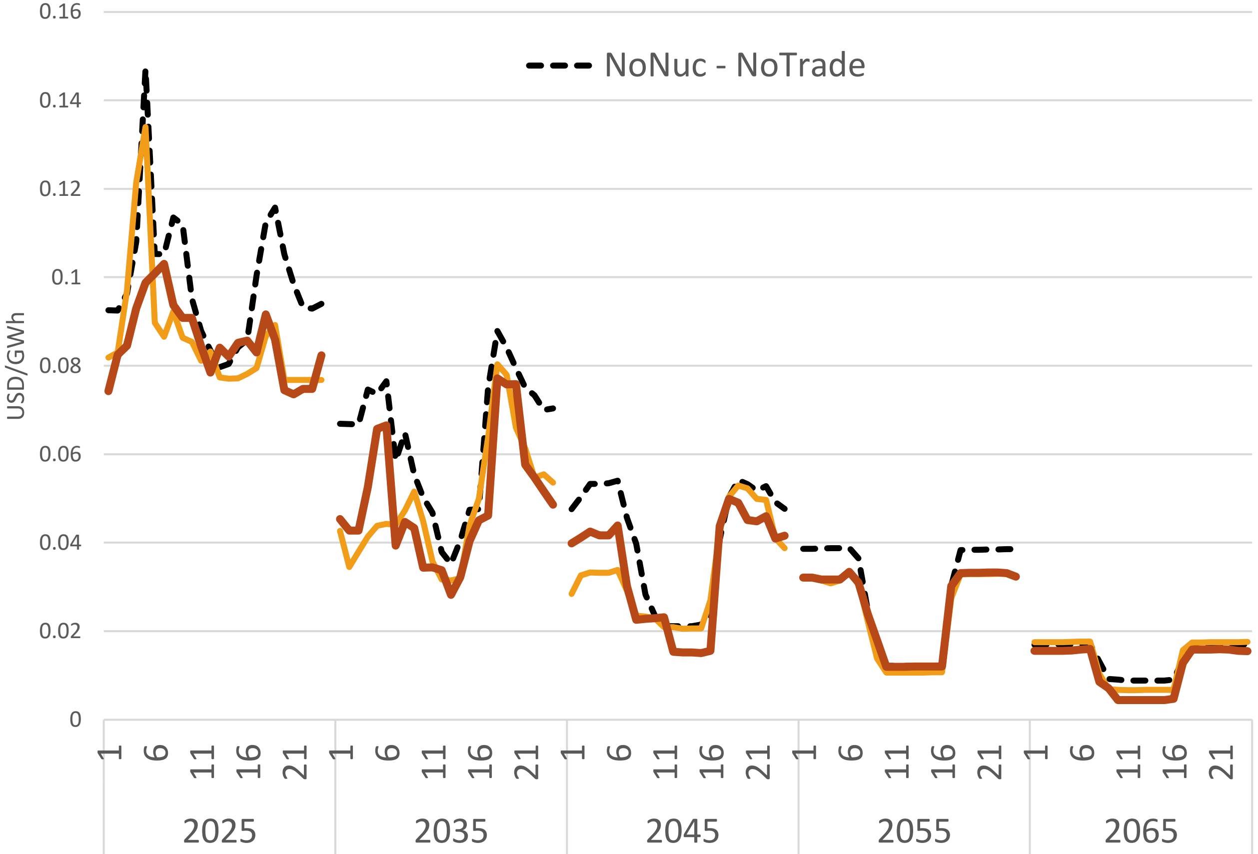
Sensitivity to nuclear deployment(ZEROP200)- Removing nuc constraint in KR and JP-W

- facilitates further carbon phaseout over time (trade>notrade)
- reduces hourly power generation cost at non-peak hours

<Regional thermal deployment over time $K_{thermal}$>



<Average hourly electricity price at P200>



Conclusion and Implications

- **Gaps in resource availability and cost makes trade accelerates renewable transitions for carbon neutrality.**
- Increased clean energy output with trade -> reduced emission cost, less investment in negative emission technologies, leading to lower TC
  - BAU and ZERO trajectory similar above P200
  - Trade accelerates cease of traditional fossil fuel consumption
    - At P300 stops thermal power generation KR: 2055-> 2035, JP: 2045-> 2025

Implications and limitations

Ambitious carbon pricing reducing the gap in technology pathways with short/long term goals

- Carbon pricing can face different susceptibility, but timely actions for correction of coal prices
  - i.e.) removal of fossil fuel subsidies, reformation of emission trading system
- Nuclear phaseout?
- Depoliticization of power sector planning
- Trade should be reinterpreted as an incentive for increasing clean electricity generation to reduce shared climate change impact

- Energy system modeling depends on lots of assumptions
  - Ever-changing energy environment (covid)
  - Research question to affect system complexity

Future research work

- Linking bottom up and top-down approaches to look into sectoral interactions and macroeconomic impact of carbon neutrality
- Gas power plants and hydrogen utilizations
- Interdisciplinary approach
    - Air pollution in NEA and Asia Supergrid

Accelerating Renewable Transitions of Power Sectors: Options and Challenges

Q&A