Modeling Grid Interconnections in NEA

International Workshop on Power Supply Modeling in NEA

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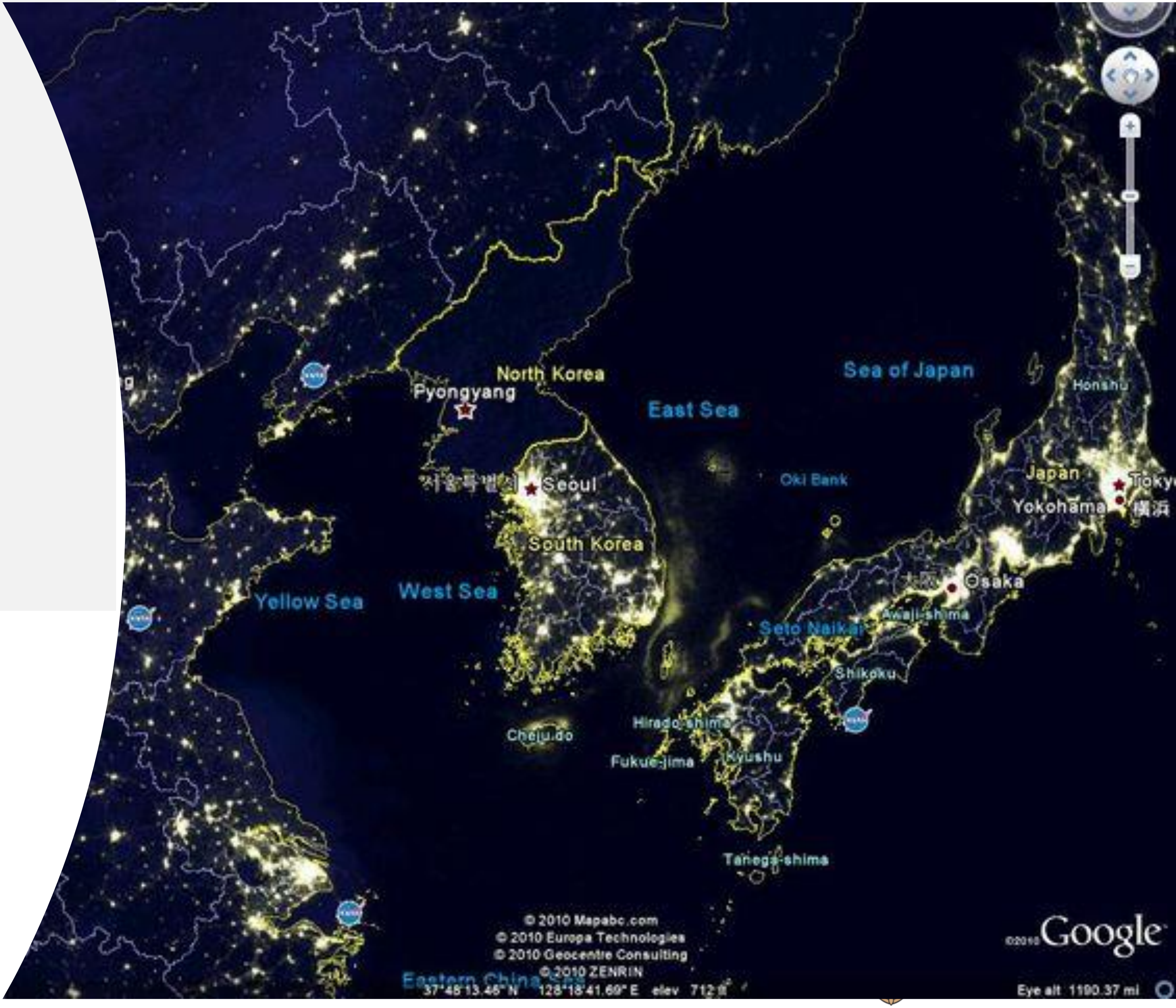
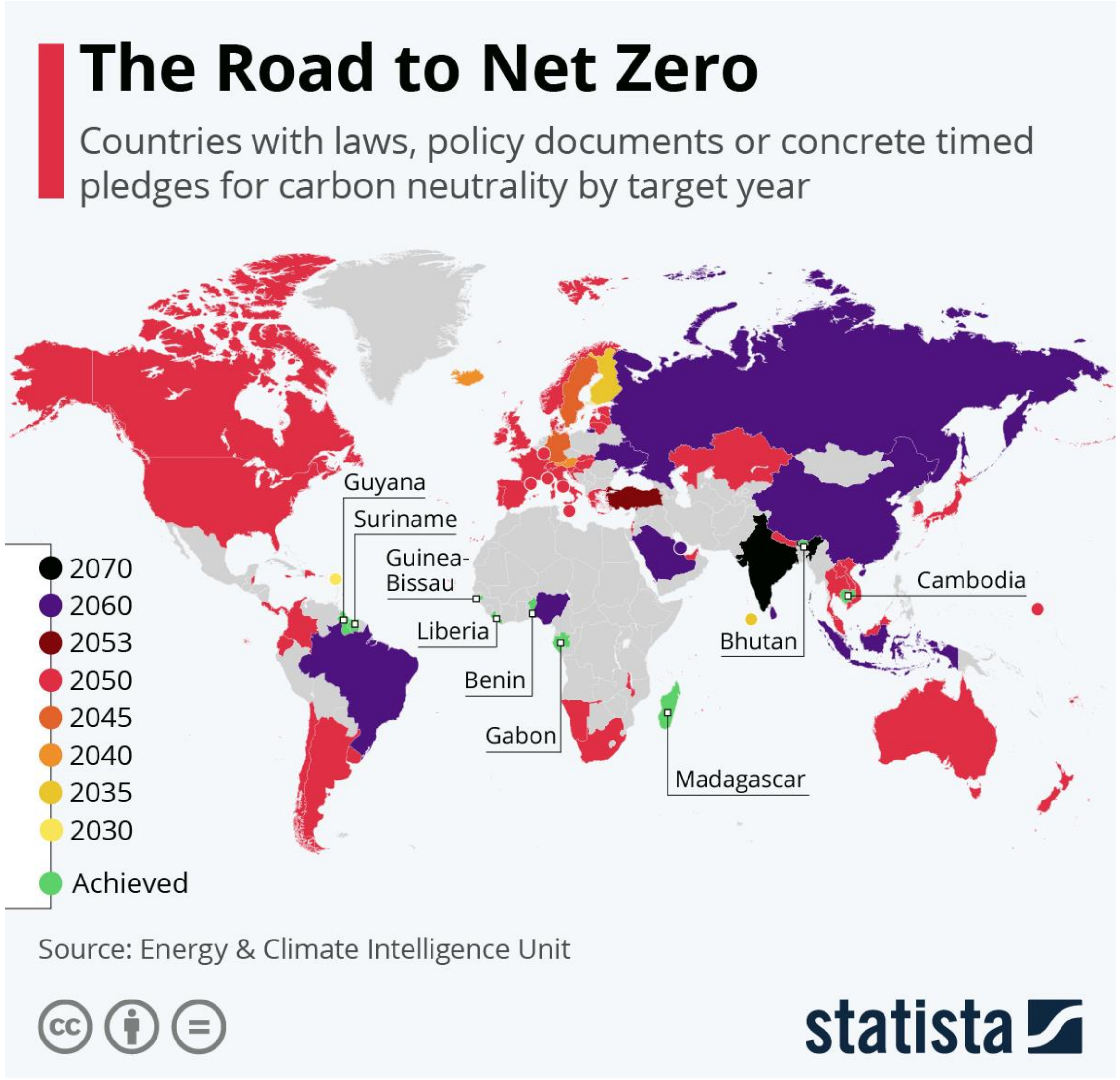


Acknowledgment

Dr. Thomas Rutherford, in Applied and Agricultural Economics, University of Wisconsin-Madison

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 2022).
  - China for 2060 , South Korea and Japan for 2050
- Power sector takes a leading position in carbon neutrality.

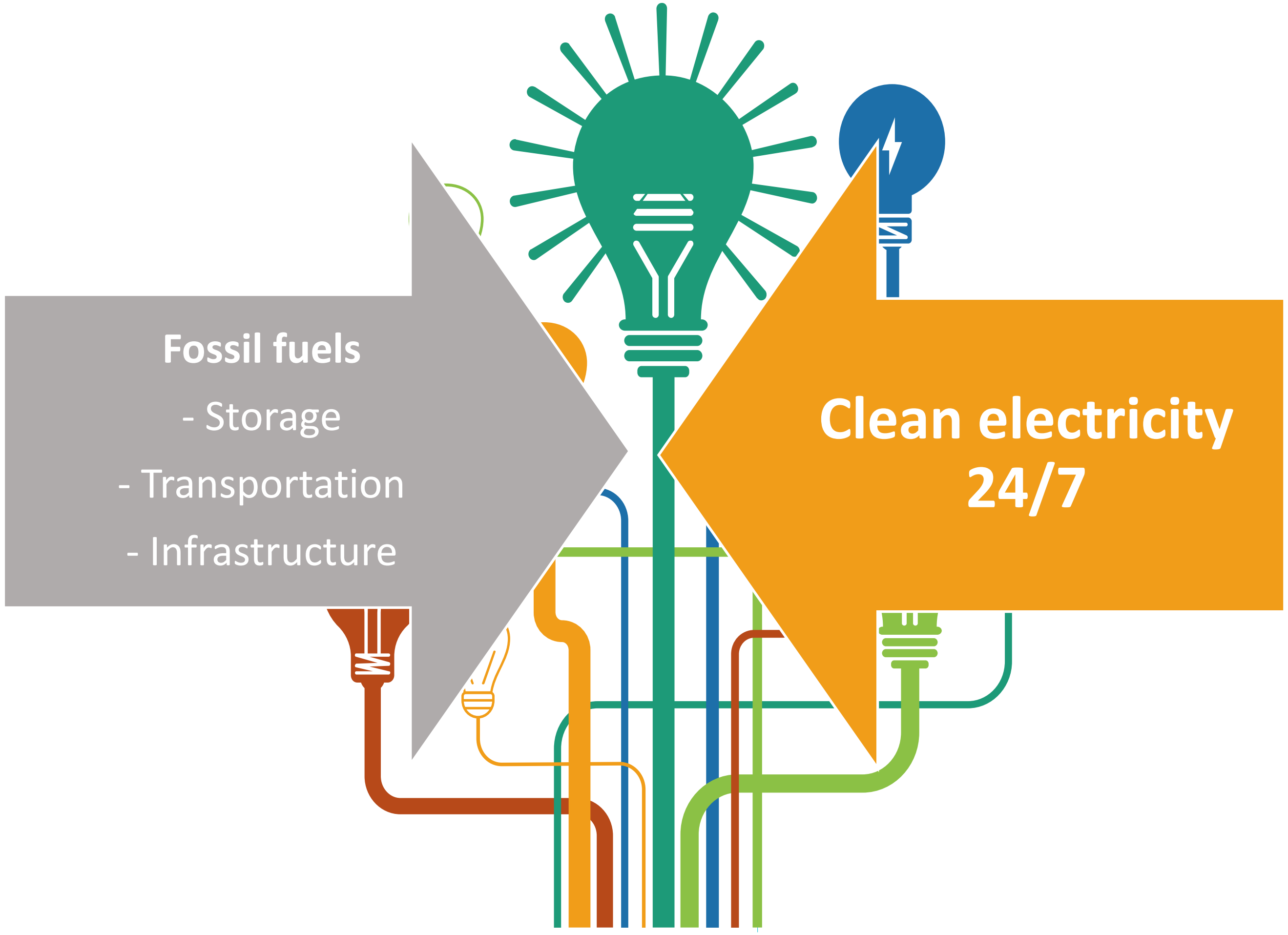


The Road to Net Zero

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

Source: Energy & Climate Intelligence Unit

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



Fossil fuels

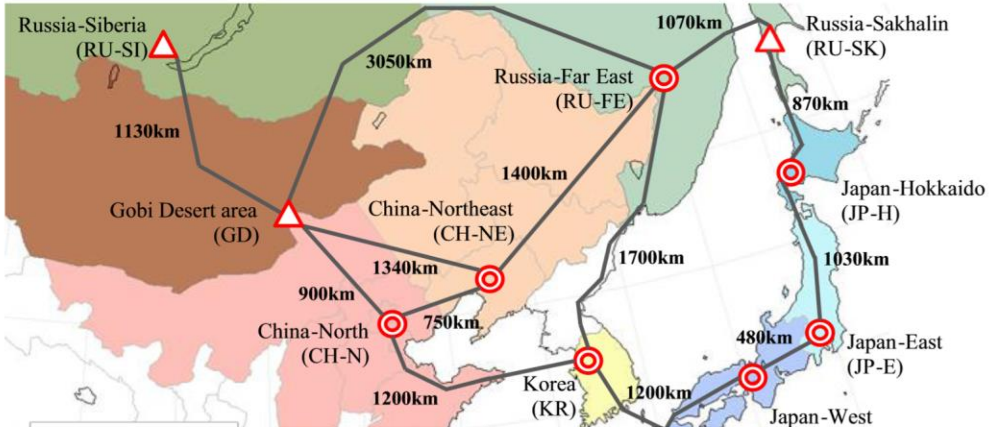
- Storage
- Transportation
- Infrastructure

Clean electricity 24/7

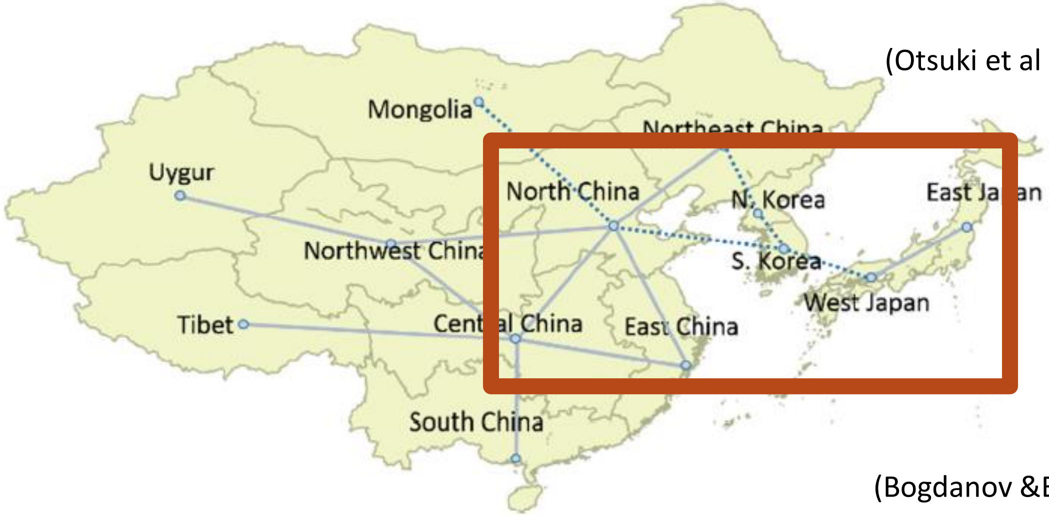
- Carbon neutral technologies (hydrogen, BECCS) substituting existing carbon-based assets
- Growing needs to assess integration of negative emission technologies in energy system and technology substitutions towards complete decarbonizations.

Grid Interconnections: Beyond Geographic Mismatch in Resource Availability and Power Demand

- 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)

Least cost technology pathways for Northeast Asia with power trade option?

Long term policy goals towards 2050 - 2060

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

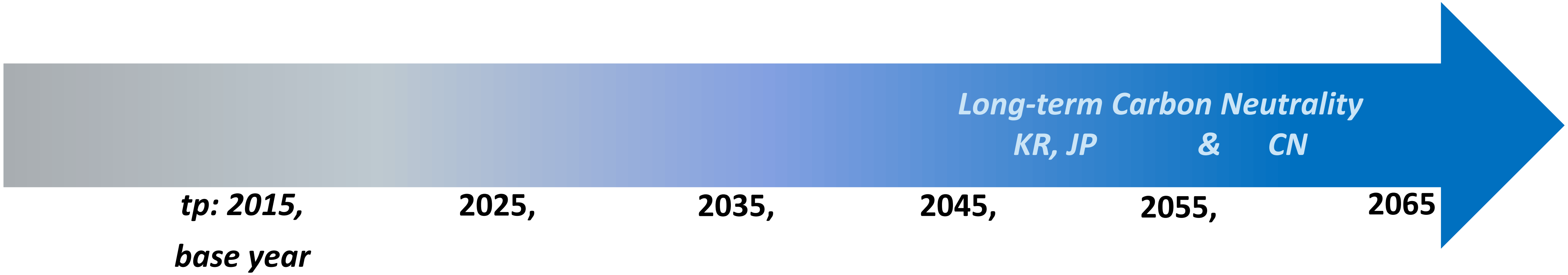
Power trade between CN-KR-JP

New coal additions scheduled

Nuclear phaseout?

- **Under changing energy environment (new tech options, price drops), *trade impacts* on technology substitutions towards carbon neutrality?**

Bottom-up Dynamic Investment Model (2015-2065)



- **Bottom-up optimization:** detailed technology options considered for power system analysis
- **Dynamic**: evolution of the power system until the target year
- **Decomposing a multistage problem into a sequence of interrelated one-stage problems** (Prina et al. 2020)

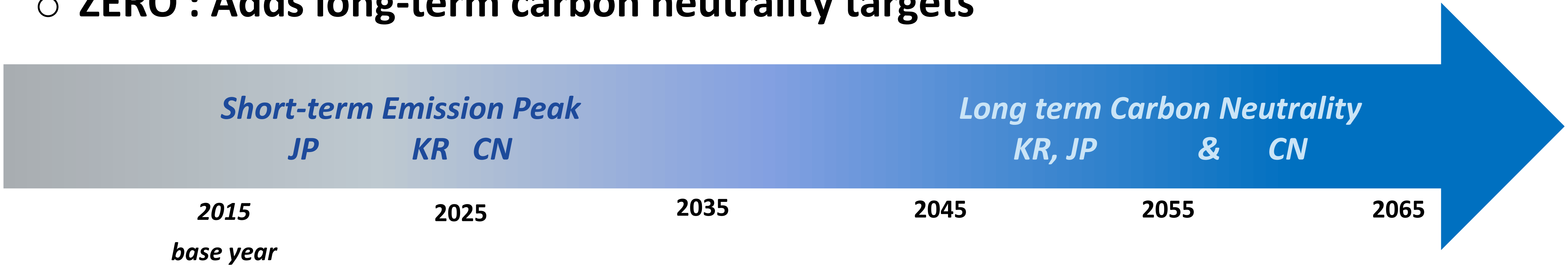
  Based on the 2015 existing capacity, the model makes sequential decisions on technology adoption and abandonment through 2065

  - **Split the time horizon into the 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)

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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

Data

- Supply side: 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 (base year)
- Demand side: Hourly load profile, peak demand
- Emissions
  - CO2 Emission factors by generating technology (ton of co2/ kWh) (US DOE)
  - CO2 prices at P0, 100, 200, 300 (USD /metric ton of CO2 emitted)

Methodology

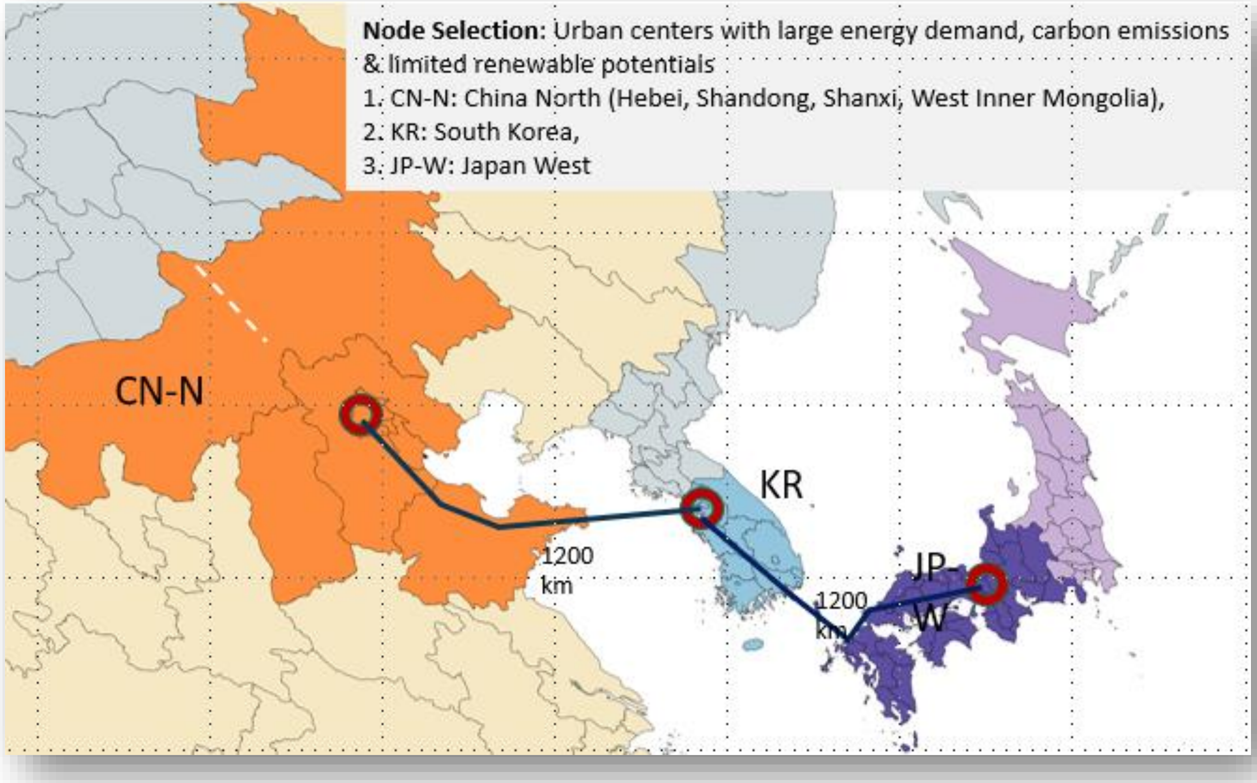
Resolutions

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

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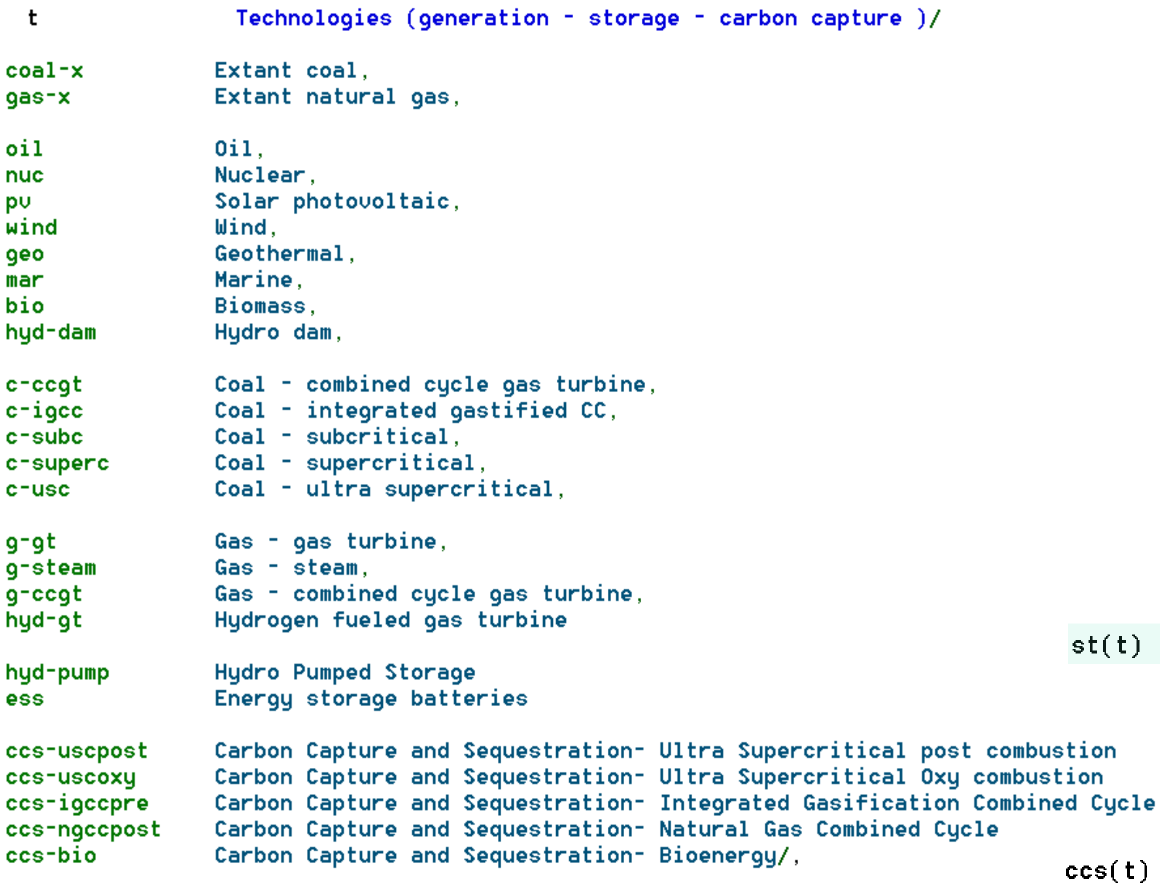
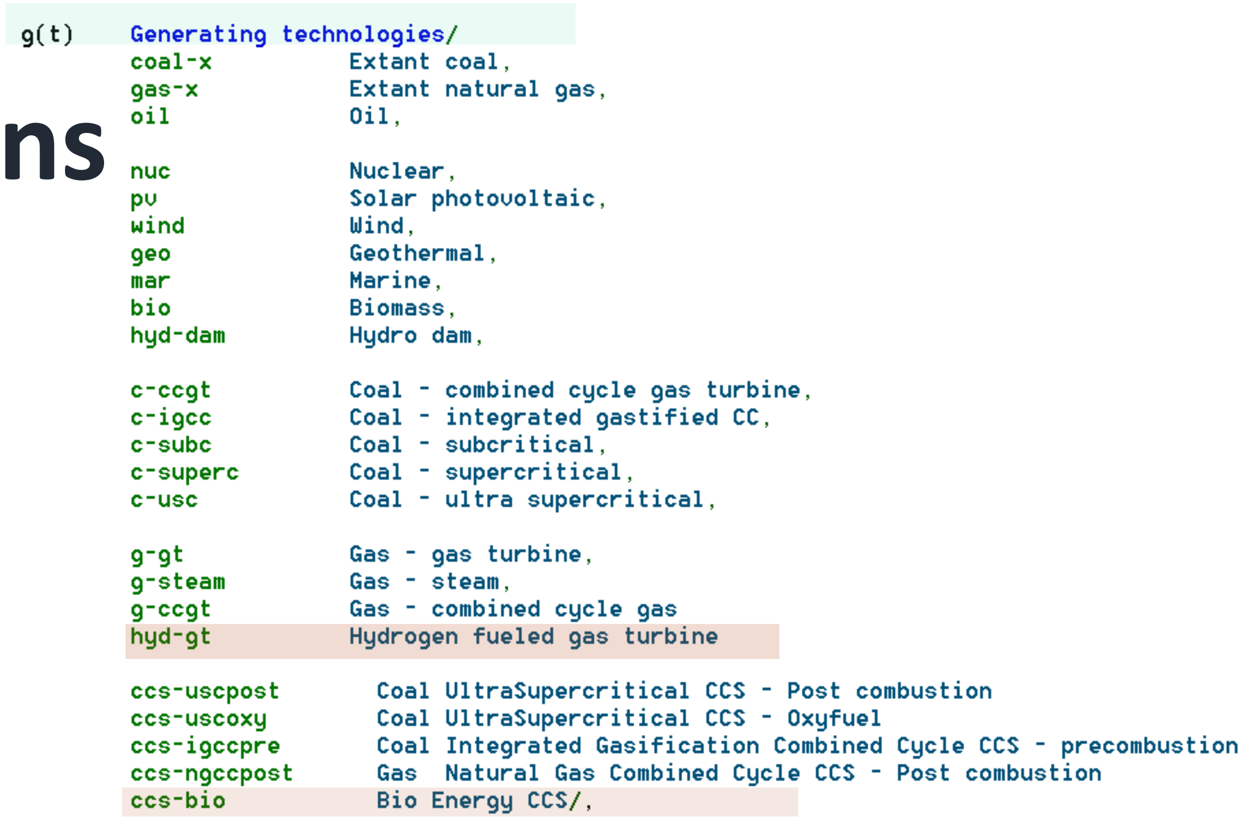
Methodology

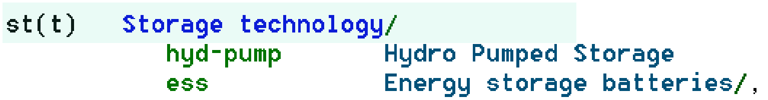
Sets_technology options



```
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/,
```



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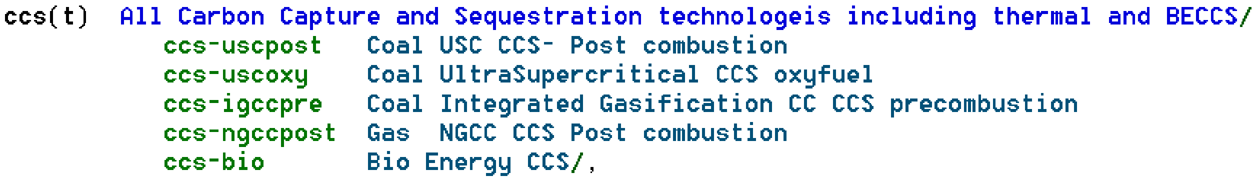
st(t)   Storage technology/
           hyd-pump        Hydro Pumped Storage
           ess             Energy storage batteries/,
```



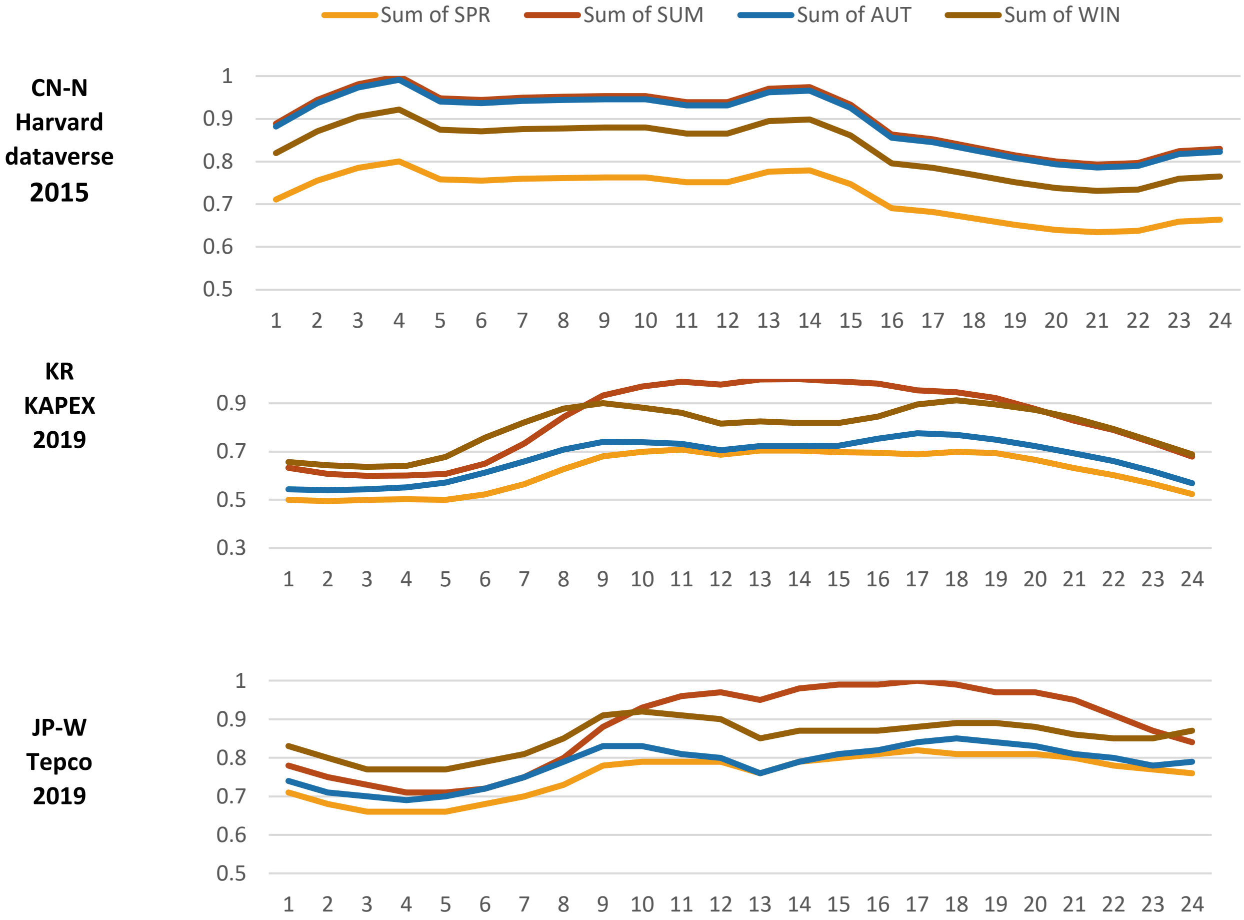
```
ccs(t)  All Carbon Capture and Sequestration technologeis including thermal and BECCS/
           ccs-uscpost    Coal USC CCS- Post combustion
           ccs-uscoxy     Coal UltraSupercritical CCS oxyfuel
           ccs-igccpre    Coal Integrated Gasification CC CCS precombustion
           ccs-ngccpost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

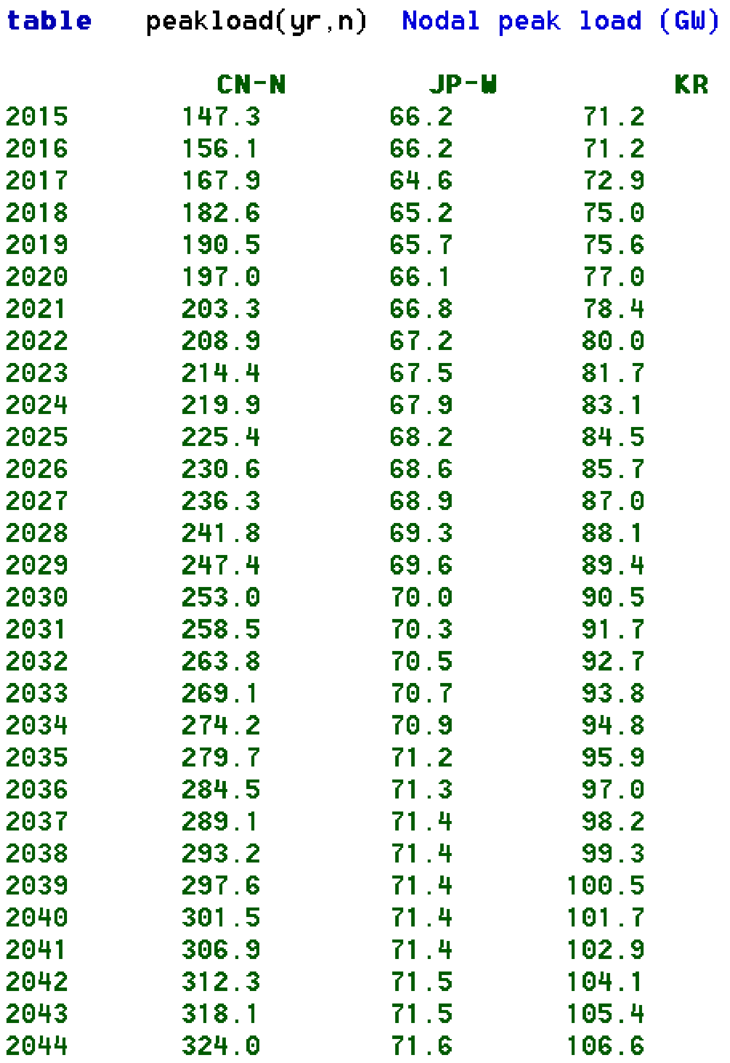
Additional technology options for deep emission cuts

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)



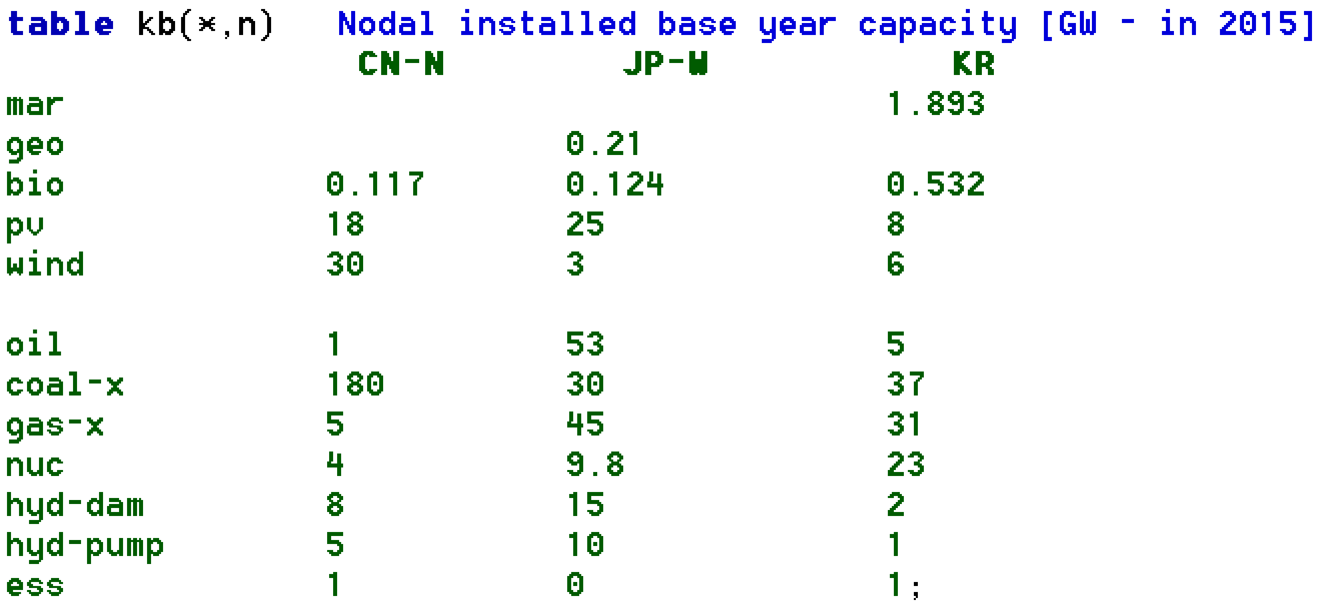


```
table    peakload(yr,n)  Nodal peak load (GW)

               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

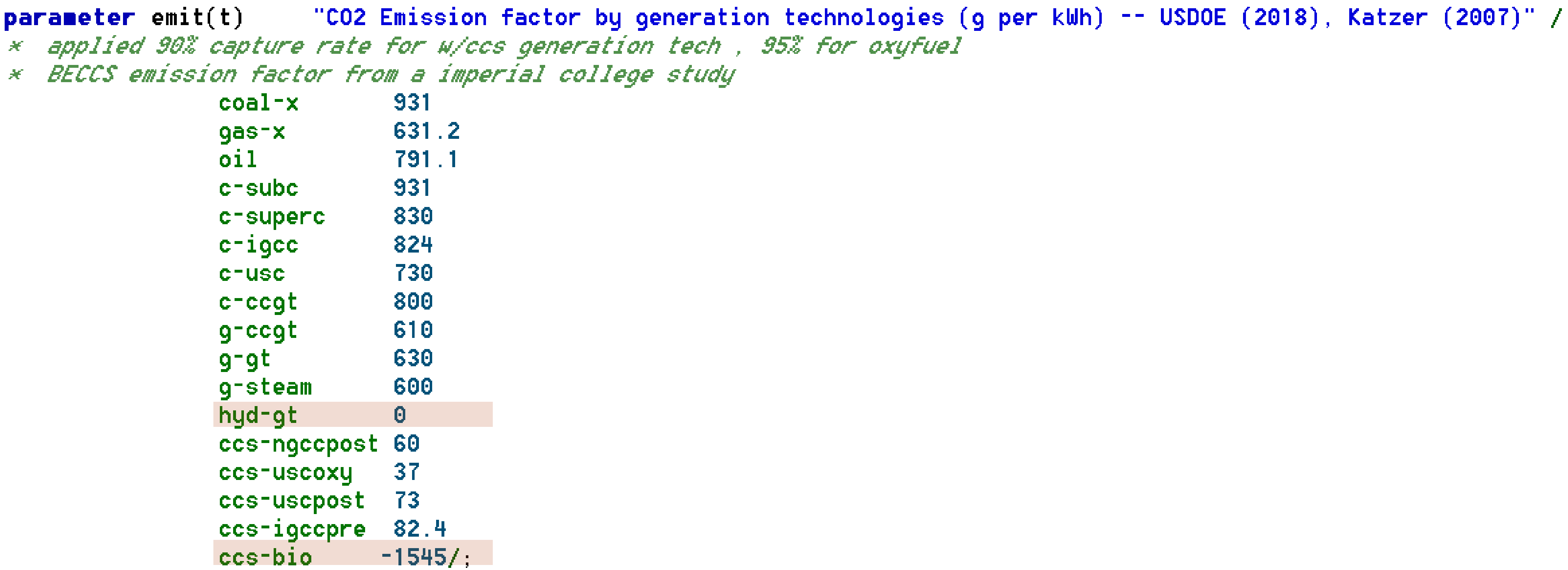
Technology cost

- 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



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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]

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

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

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 (hourly availability)

$$\mathrm{XP}_{\mathrm{n},\boldsymbol{g},\mathrm{s},\mathrm{hr}} \leq \mathrm{resav}_{\mathrm{n},\mathrm{g},\mathrm{s},\mathrm{hr}} * \mathrm{K}_{\mathrm{n},\mathrm{g},\mathrm{tp}}$$

Hourly power output of generating technology g, XP, not larger than the size of installed capacity K(g) and the technology's hourly availability

$$\mathrm{STE}_{\mathrm{n},\mathrm{st},\mathrm{s},\mathrm{hr}} \leq \mathrm{K}_{\mathrm{n},\mathrm{st},\mathrm{tp}} * \mathrm{resav}_{\mathrm{n},\mathrm{st},\mathrm{s},\mathrm{hr}}$$

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 of excess capacity 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

*maximum net inflow at each node : 15% of nodal demand

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

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Constraints:

Emission tracks

BaU scenario:

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

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
- In addition to cost, gaps in resource availability are a driver for interstate transmissions and faster transitions
- Trade further increases clean power output when/where available-> reducing investment needs in costly hydrogen and accelerating thermal phaseout.

Carbon pricing

- to ensure equitable trade impact
- To reduce the gap between short-term and long-term emission goals

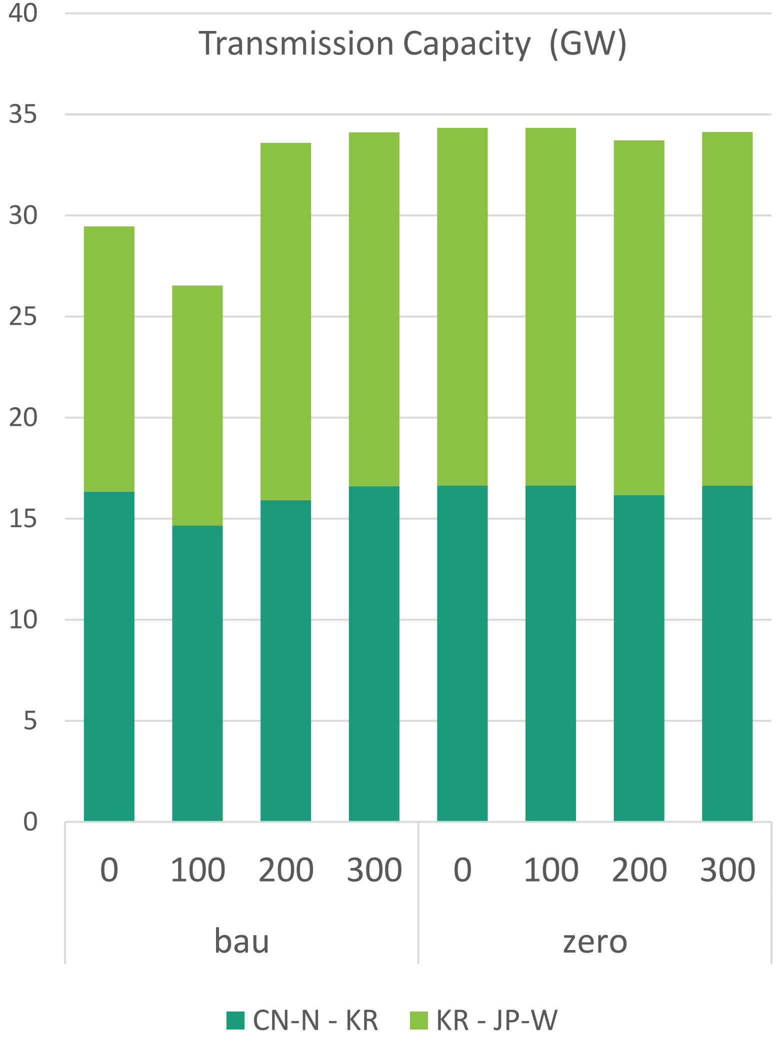
Result 1. **Cost savings and trade dynamics over time**

W/ Trade: cost savings in fuel consumption and emission penalties

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 compared to no trade



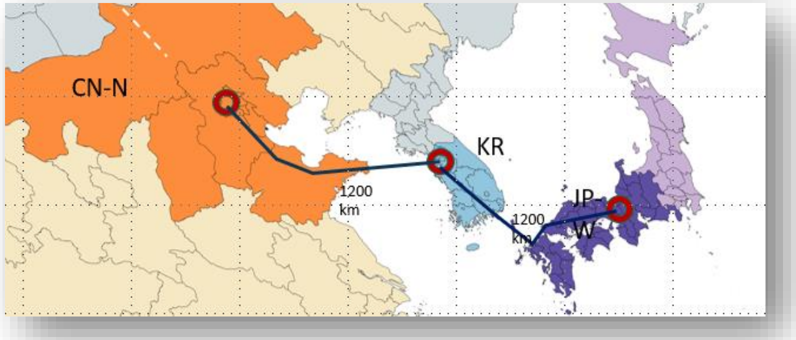
Focusing on ZERO,

- 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

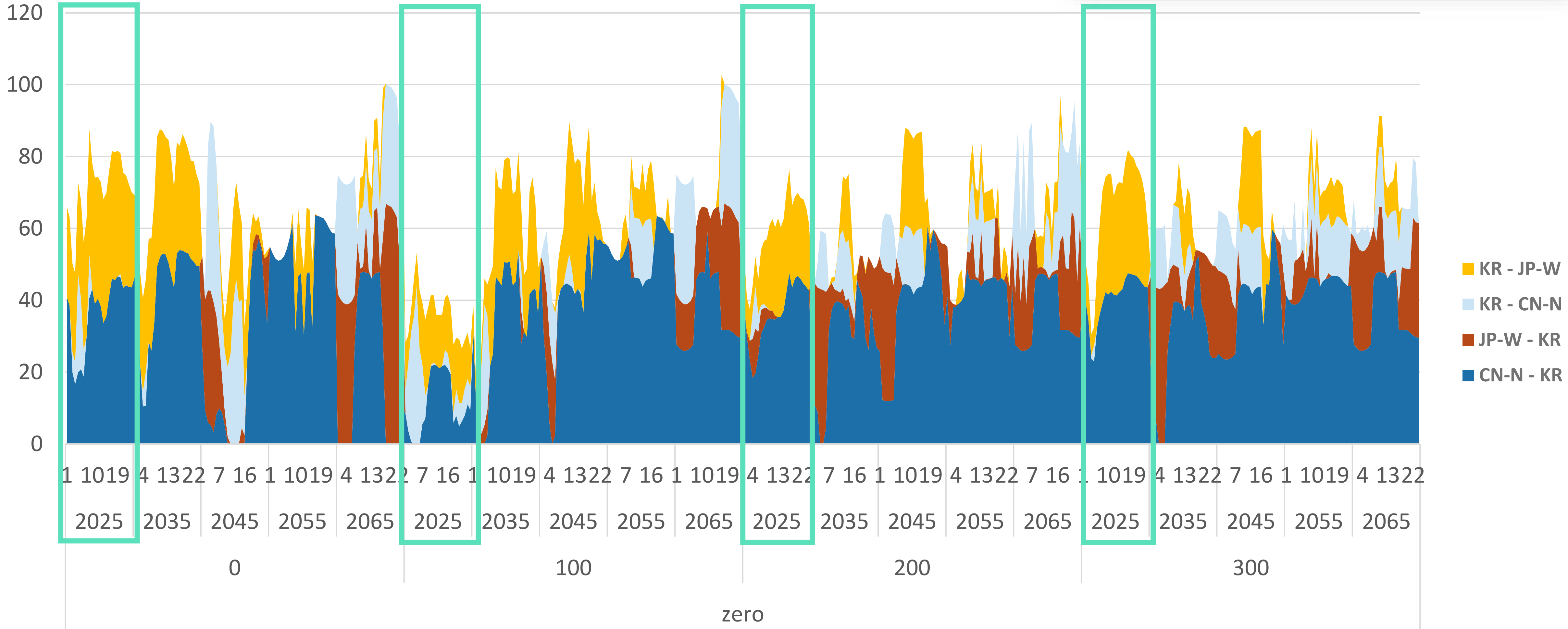
C: carbon price (USD/tCO2), COMP: cost component, CAP: capital cost, FOM: Fixed Operation and Maintenance cost, VOM: Variable Operation and Maintenance, LCAP: Transmission line capital investment, LFOM: Transmission Line Fixed Operation and Maintenance = (trade comp- no trade comp)/sum of no trade total

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

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



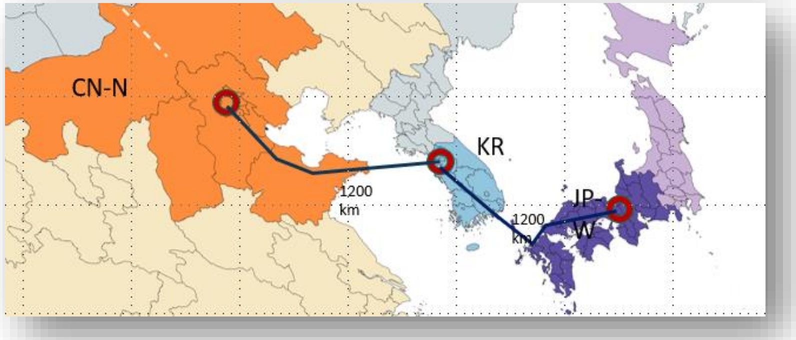
4- day aggregated transmission volumes over time periods (GWh)

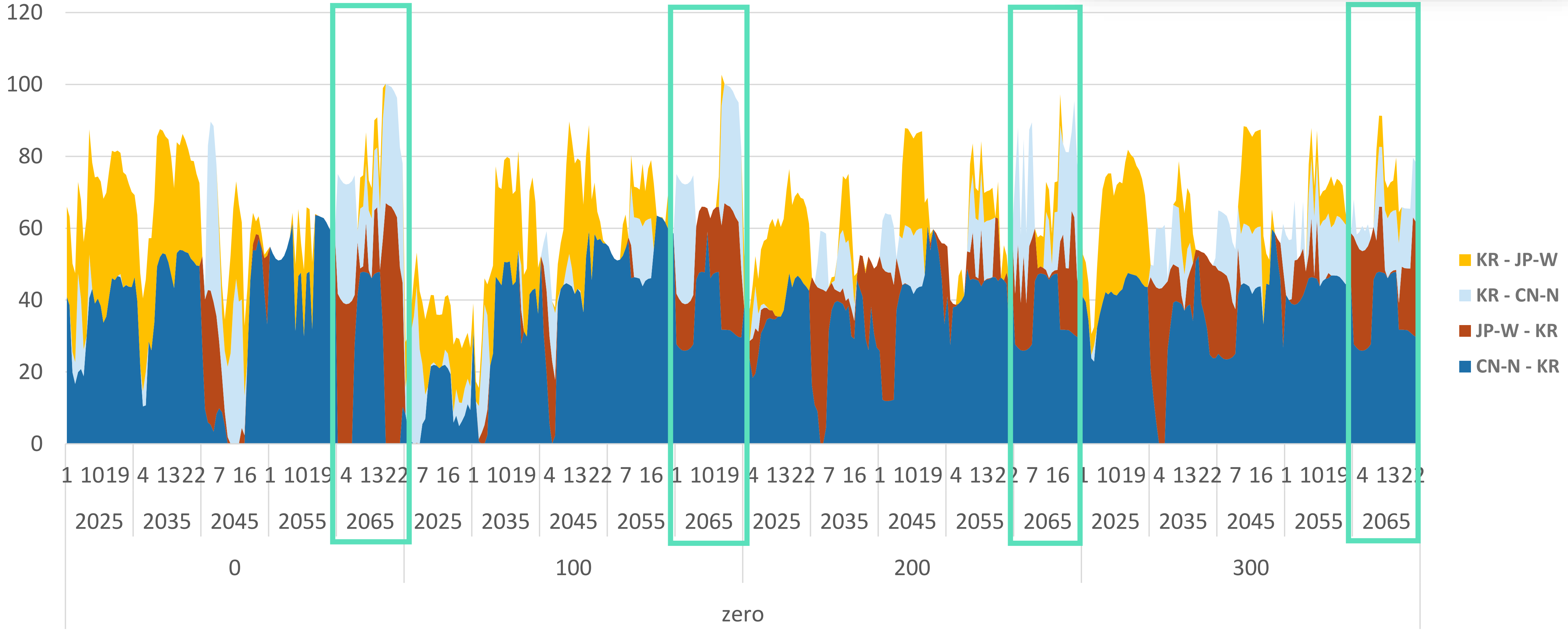


Result 1. **Cost savings and trade dynamics over time**

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

to 2-way transmissions (CN<->KR<->JP) for achieving Carbon Neutrality



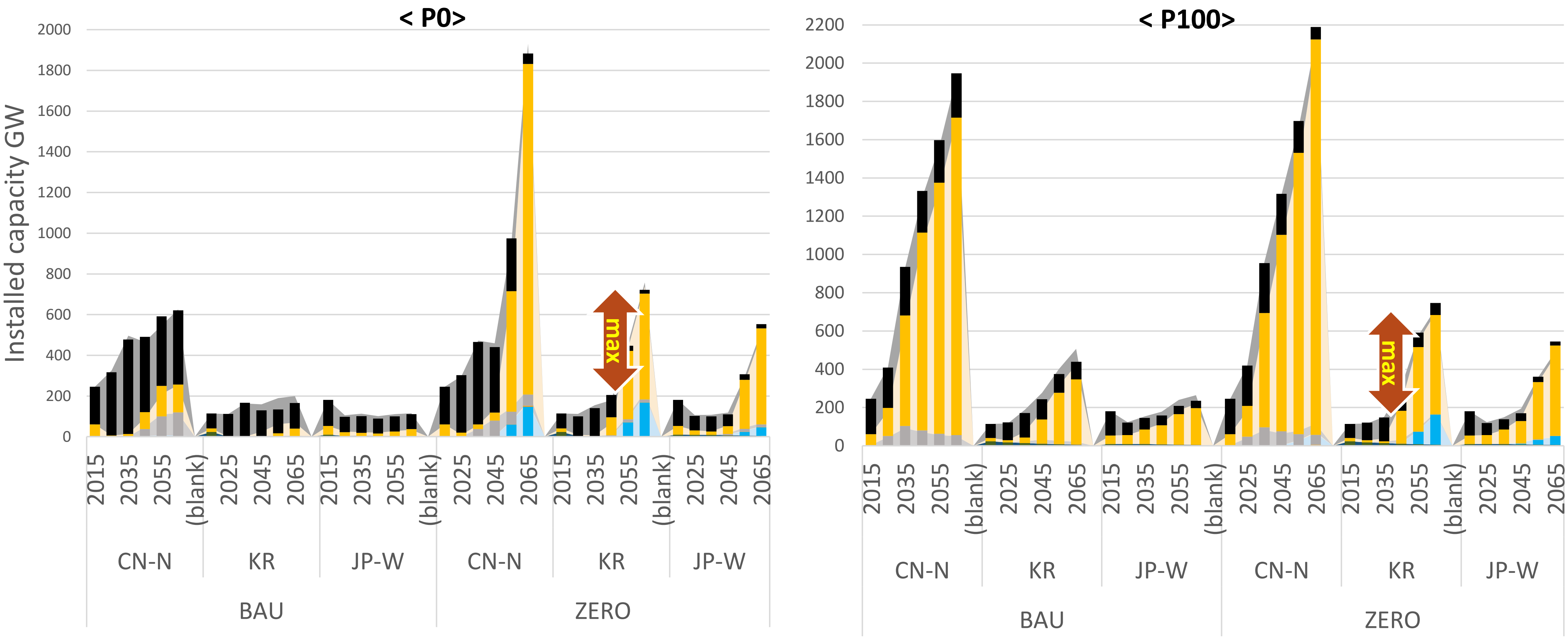


Result 2. Optimal capacity mixes for emission targets

ZERO requires substantial growth in variable renewables + hydrogen

(P0) ZERO requires significant increase in renewables & hydrogen close to netzero year (KR maxes out solar/wind capacity)

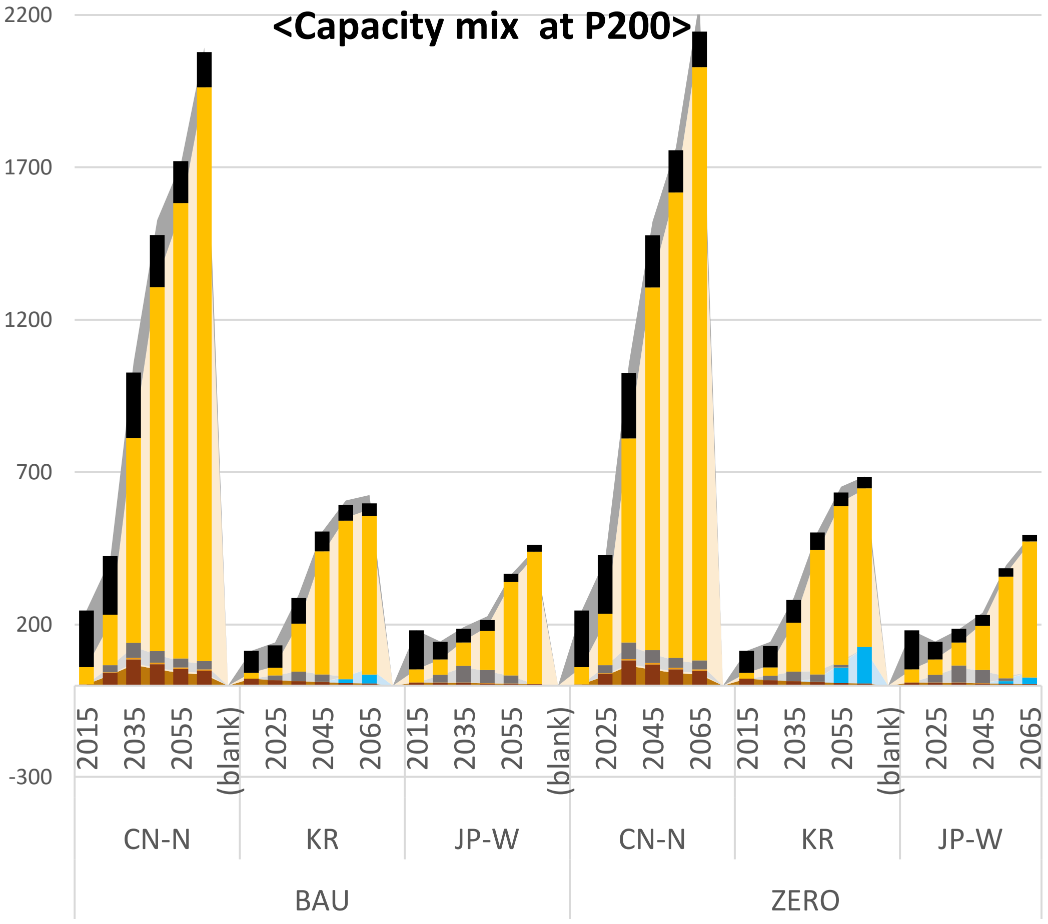
Higher carbon prices: renewables grow from earlier time periods

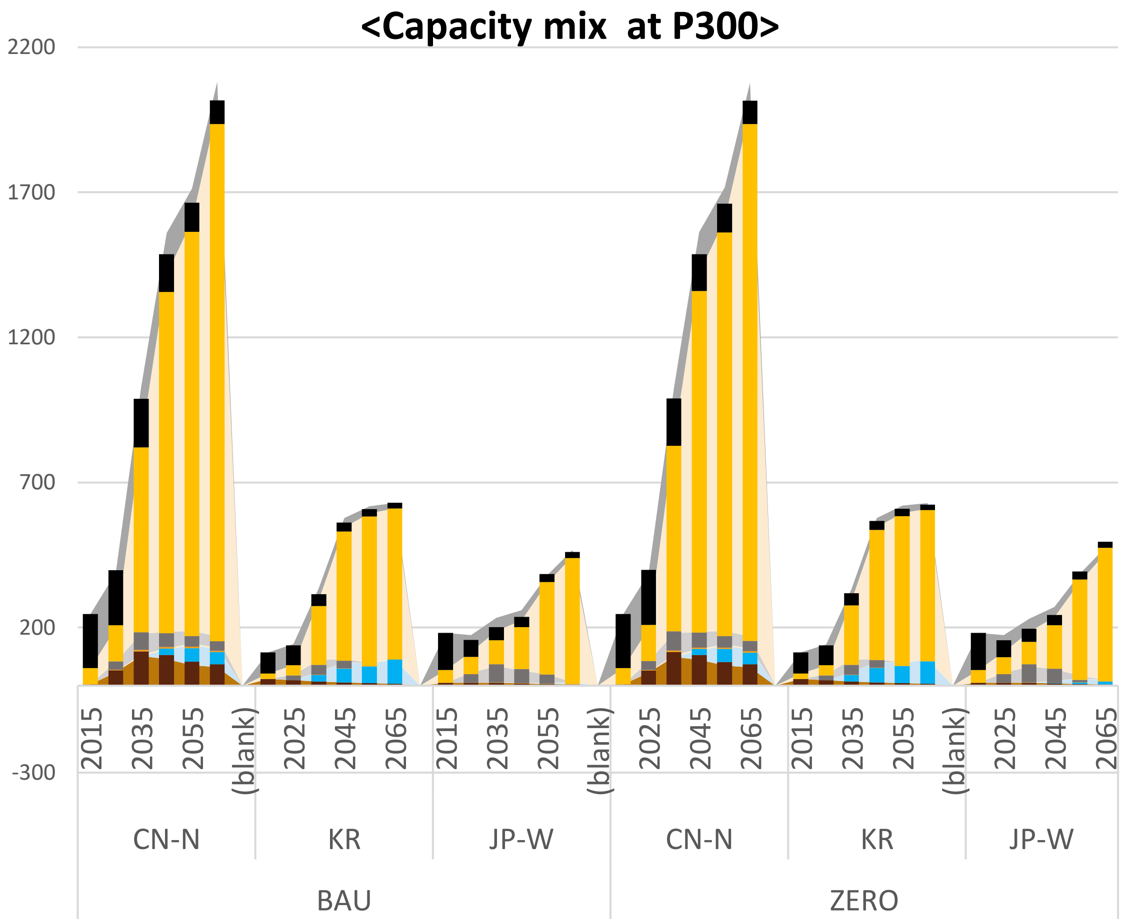


Result 2. Optimal capacity mixes for emission targets

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

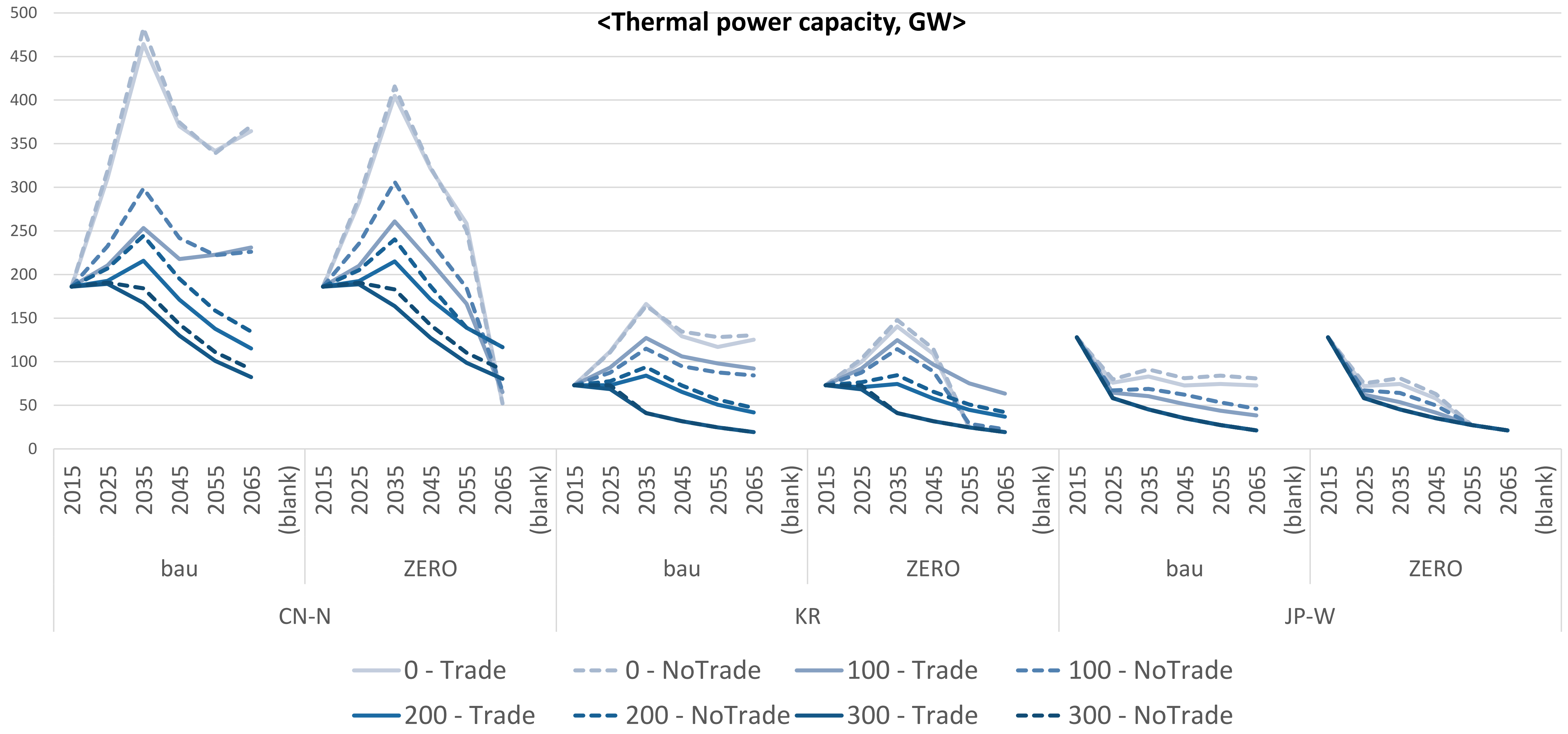

<Capacity mix at P200>


<Capacity mix at P300>

Result 2. Decarbonization pathways with trade

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

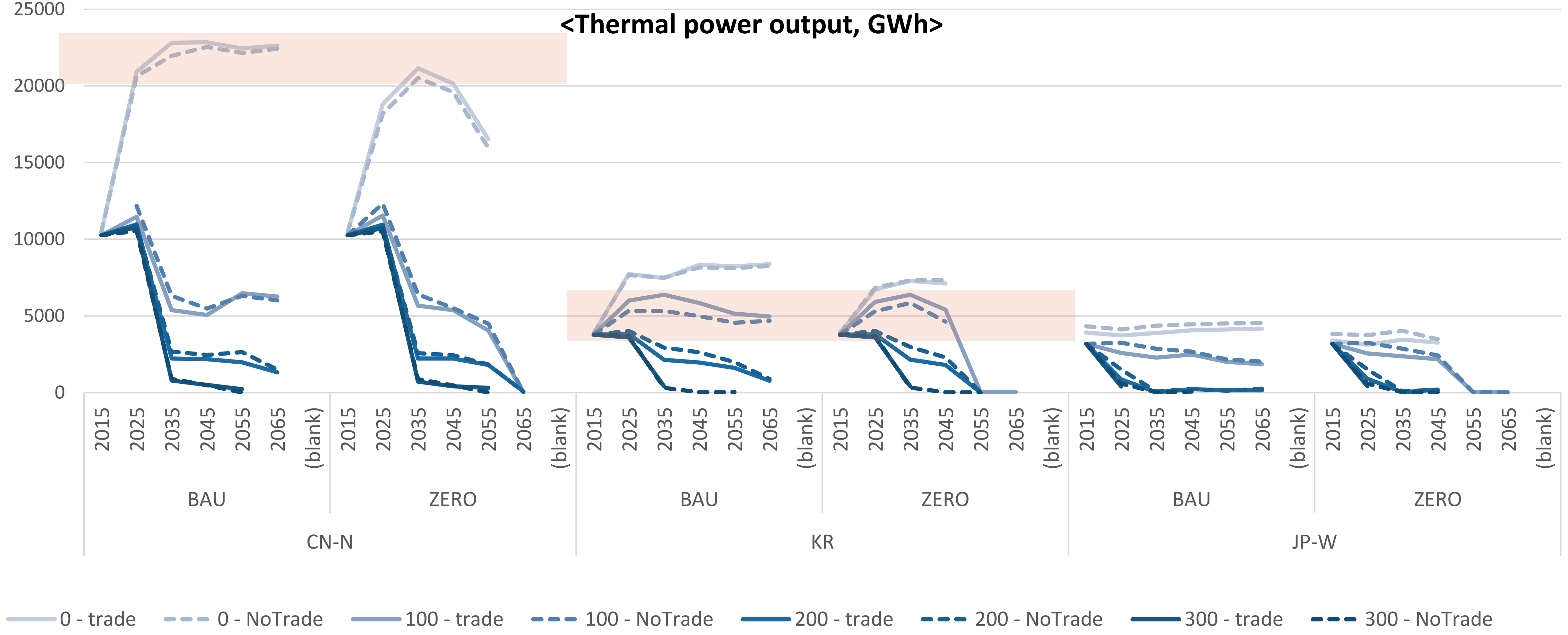
Trade in general further accelerates thermal reductions (gaps in dotted- solid lines at each P level)



Result 3. Decarbonization pathways with trade

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

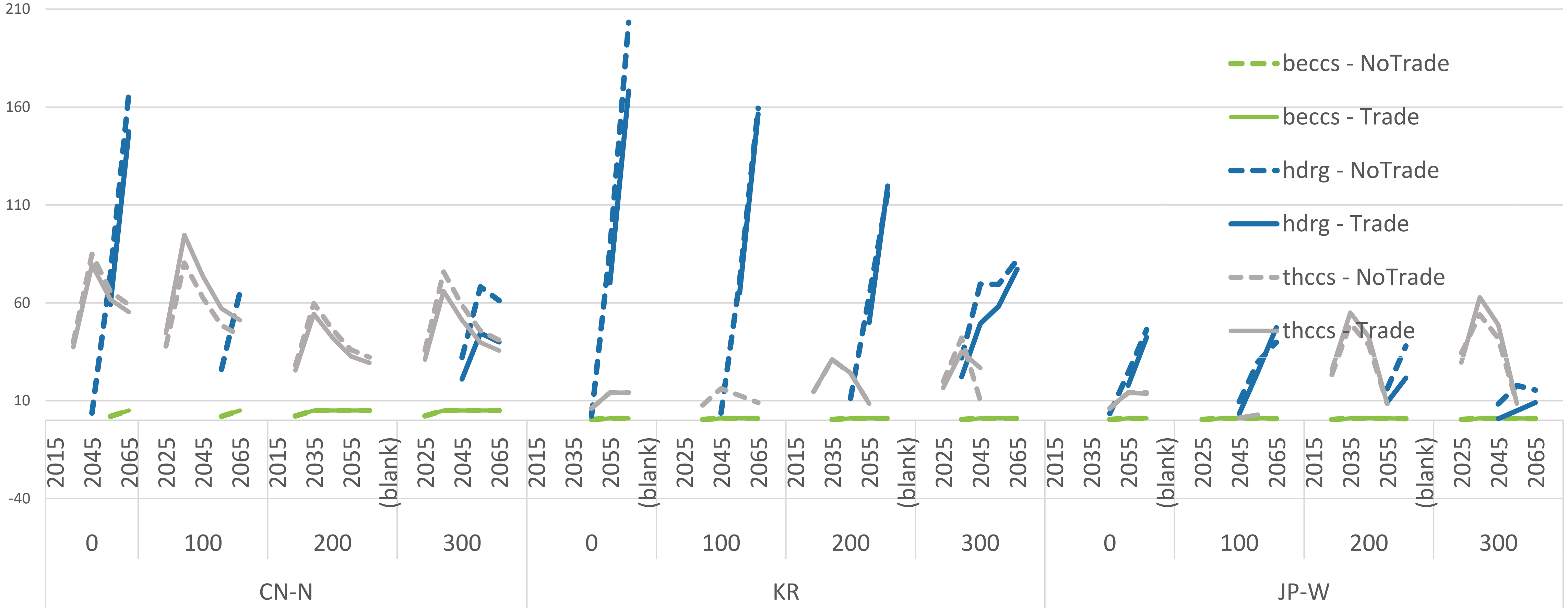
- P0, P100 trade increases CN-N, and KR thermal power output compared to notrade



Result 3. Decarbonization pathways with trade

Beyond solar/wind : Hydrogen, BECCS, thCCS

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



<Capacity development over time (GW)>

Result 3. Decarbonization pathways with trade

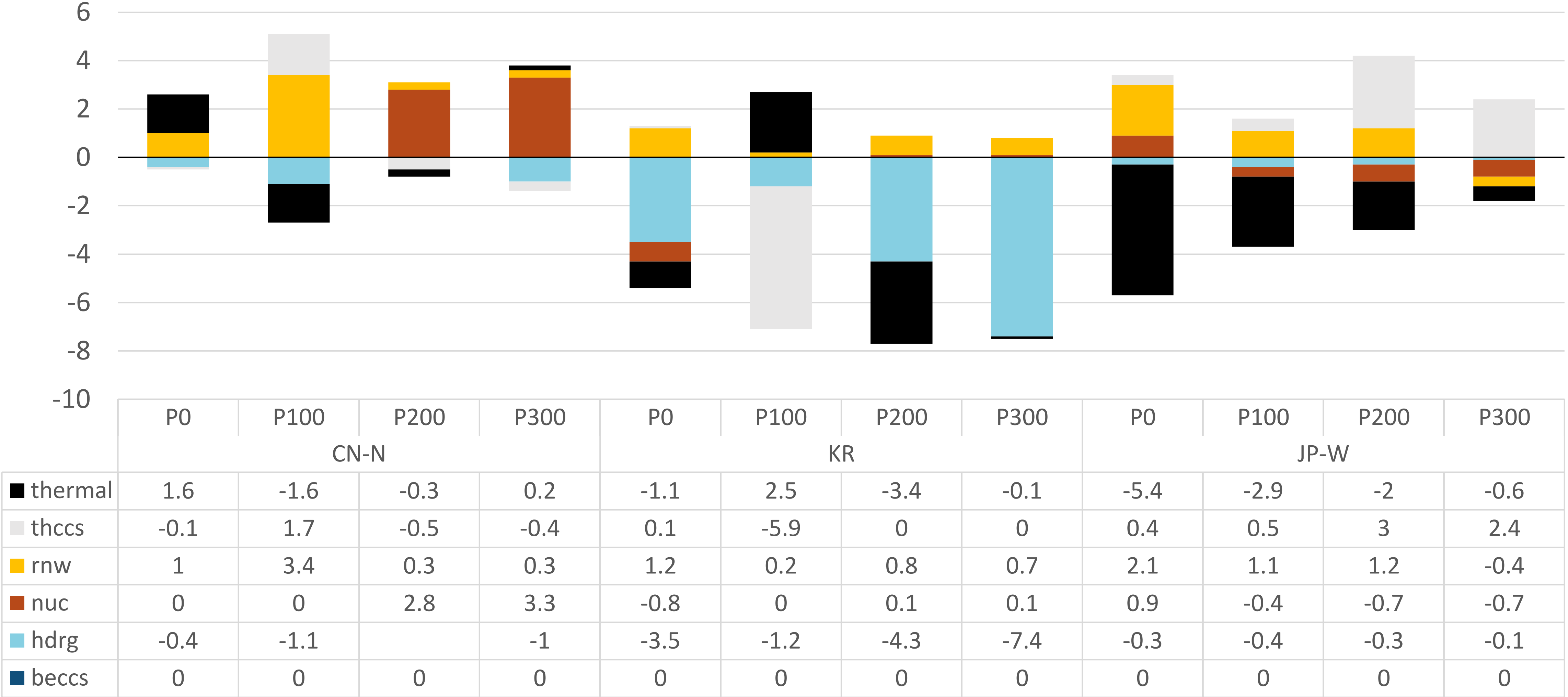
ZERO requires beyond solar&wind: nuclear

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

<Capacity development over time (GW)>

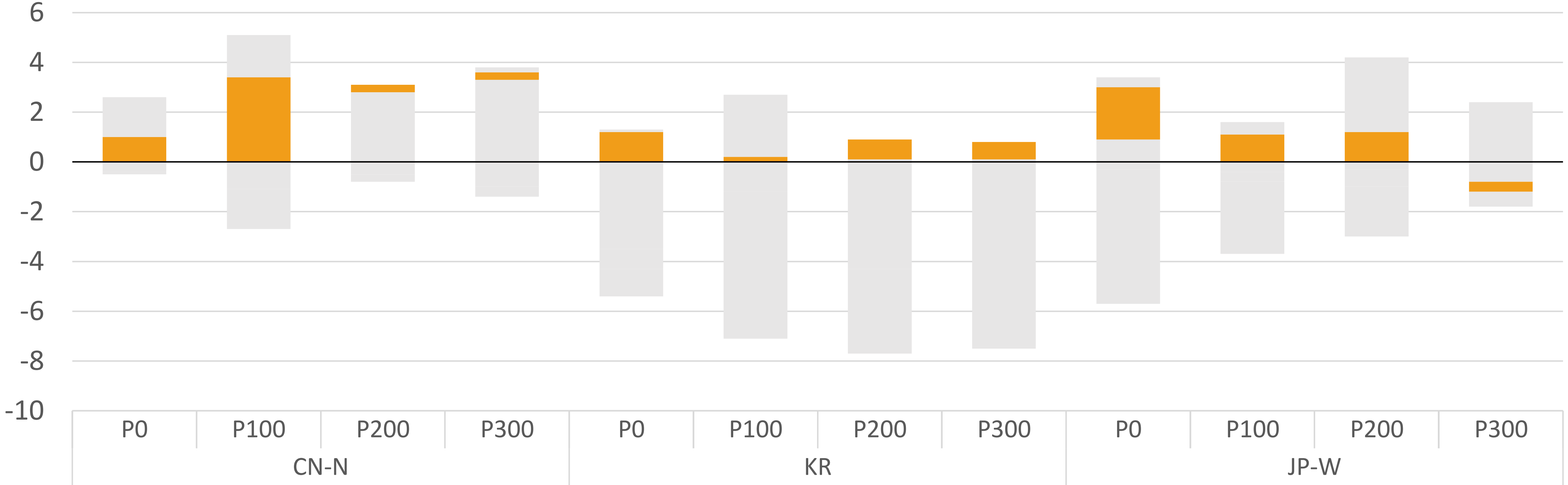
Trade impact on Technology Substitution for Carbon Neutrality

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



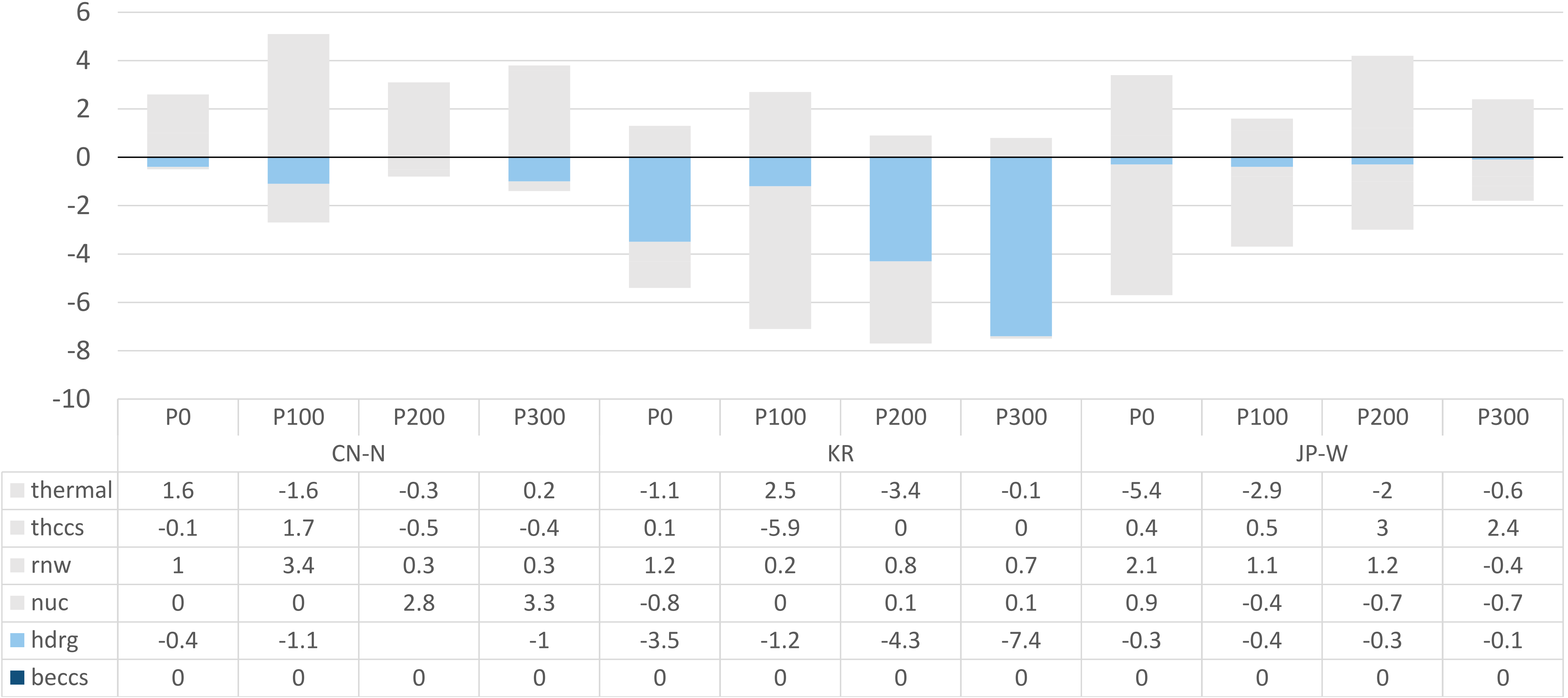
	CN-N				KR				JP-W			
	P0	P100	P200	P300	P0	P100	P200	P300	P0	P100	P200	P300
■ thermal	1.6	-1.6	-0.3	0.2	-1.1	2.5	-3.4	-0.1	-5.4	-2.9	-2	-0.6
■ thccs	-0.1	1.7	-0.5	-0.4	0.1	-5.9	0	0	0.4	0.5	3	2.4
■ rnw	1	3.4	0.3	0.3	1.2	0.2	0.8	0.7	2.1	1.1	1.2	-0.4
■ nuc	0	0	2.8	3.3	-0.8	0	0.1	0.1	0.9	-0.4	-0.7	-0.7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



	P0	P100	P200	P300	P0	P100	P200	P300	P0	P100	P200	P300
	CN-N				KR				JP-W			
⬜ 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

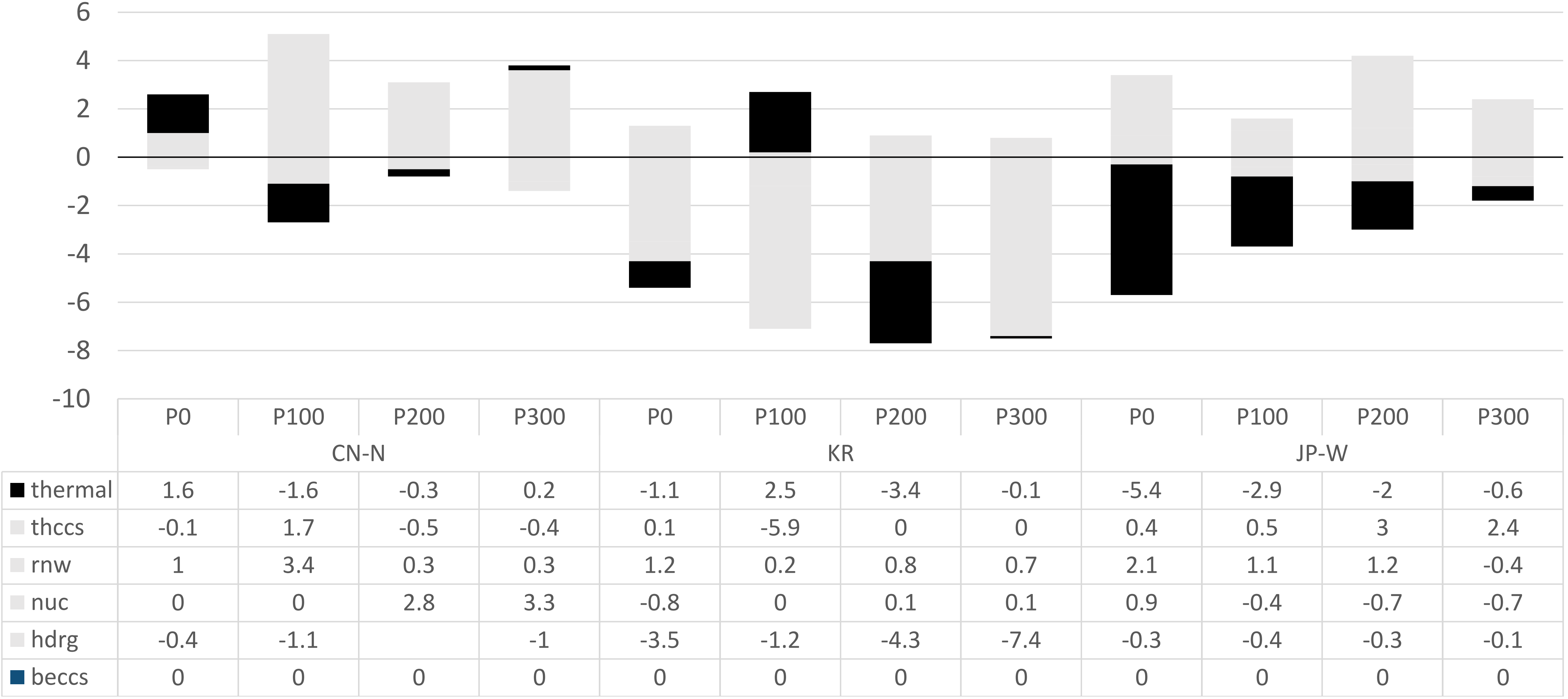


	CN-N				KR				JP-W			
	P0	P100	P200	P300	P0	P100	P200	P300	P0	P100	P200	P300
⬜ thermal	1.6	-1.6	-0.3	0.2	-1.1	2.5	-3.4	-0.1	-5.4	-2.9	-2	-0.6
⬜ thccs	-0.1	1.7	-0.5	-0.4	0.1	-5.9	0	0	0.4	0.5	3	2.4
⬜ rnw	1	3.4	0.3	0.3	1.2	0.2	0.8	0.7	2.1	1.1	1.2	-0.4
⬜ nuc	0	0	2.8	3.3	-0.8	0	0.1	0.1	0.9	-0.4	-0.7	-0.7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

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

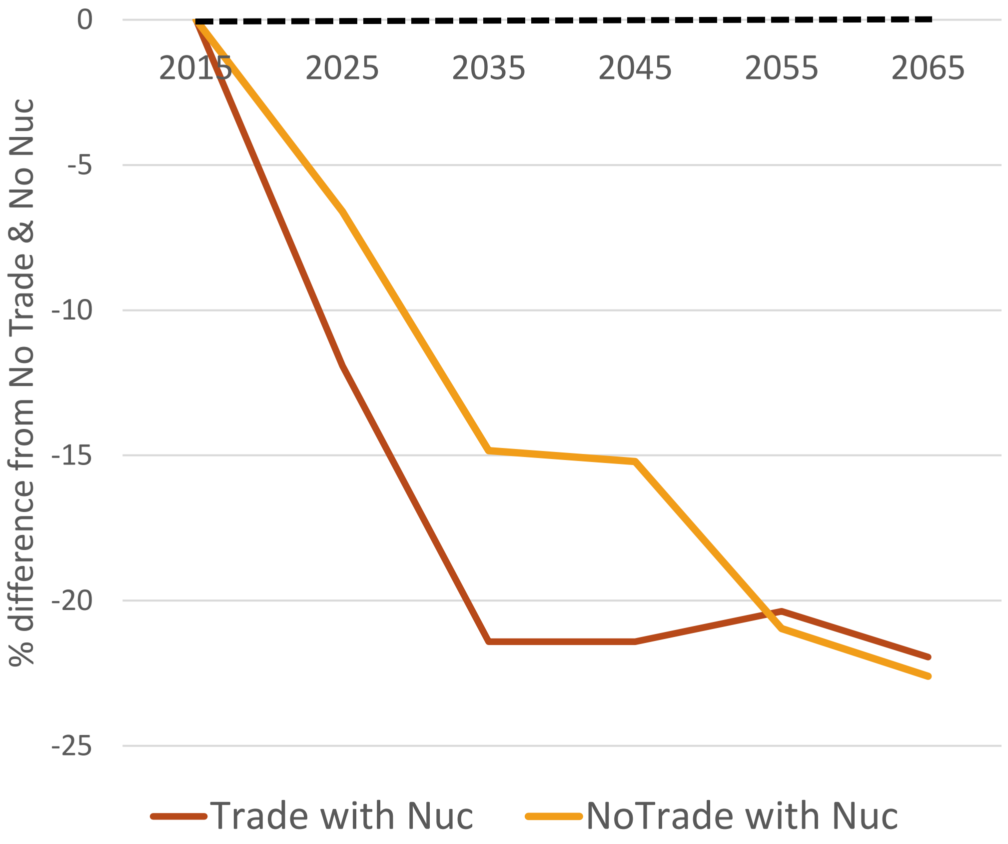


	P0	P100	P200	P300	P0	P100	P200	P300	P0	P100	P200	P300
	CN-N				KR				JP-W			
■ thermal	1.6	-1.6	-0.3	0.2	-1.1	2.5	-3.4	-0.1	-5.4	-2.9	-2	-0.6
■ thccs	-0.1	1.7	-0.5	-0.4	0.1	-5.9	0	0	0.4	0.5	3	2.4
■ rnw	1	3.4	0.3	0.3	1.2	0.2	0.8	0.7	2.1	1.1	1.2	-0.4
■ nuc	0	0	2.8	3.3	-0.8	0	0.1	0.1	0.9	-0.4	-0.7	-0.7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

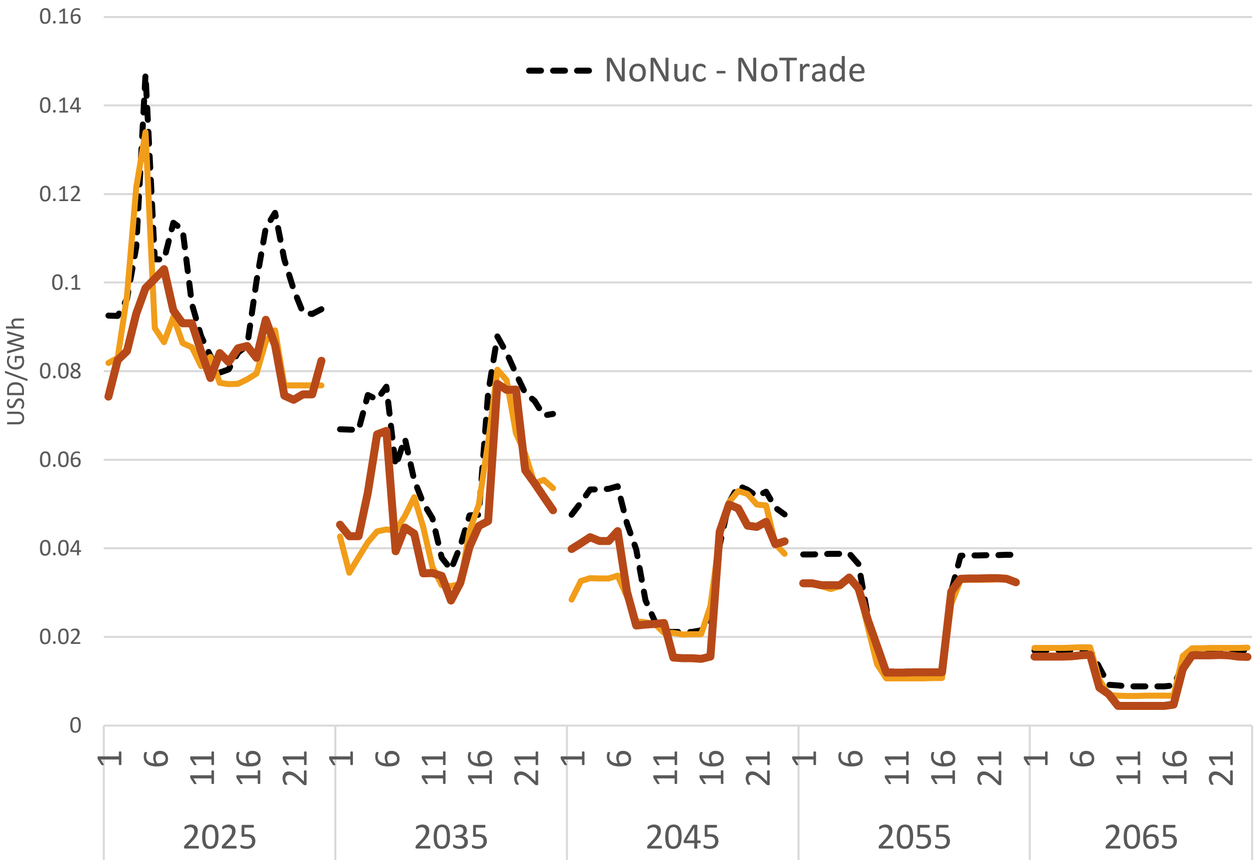
Sensitivity to nuclear deployment (ZERO)- Removing nuc constraint in KR and JP-W

- 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 a lower TC
  - BAU and ZERO trajectory similar above P200
  - Trade accelerates the timing of fossil fuel phase-out

Implications

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

- timely actions for correction of coal prices
  - i.e.) removal of fossil fuel subsidies, reformation of emission trading system

Trade as an incentive for increasing clean electricity generation and reducing shared climate change impact

  - Air quality impacts of interstate power trade

Questions and comments to hkim724@wisc.edu

Accelerating Renewable Transitions of Power Sectors: Options and Challenges

Q&A