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Integration of Computable General Equilibrium Model with Power Sector Optimization models for Net Zero Scenario Analyses

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Micro vs. Macro Impacts

- **Micro abatement costs and macro system impacts**
  - ✓ Impacts on the whole economic system ≠ sum of costs to individuals
    - ➢ The expense borne by one individual = income gained by another
    - ➢ No single indicator for system costs
      - ▪ Welfare loss (EV/CV) in theory but real GDP in practice
      - ▪ GDI or Household consumption change might be better
- **Methodologies**
  - ✓ **Micro-economic cost for individuals** via optimization model (Bottom-up) to minimize cost with detailed description of technologies
  - ✓ **Economy-wide impacts** via general equilibrium model (Top-down)
  - ✓ Integrated Top-down/Bottom-up Models provides both
    - ➢ more tractable as the computation capacity improves

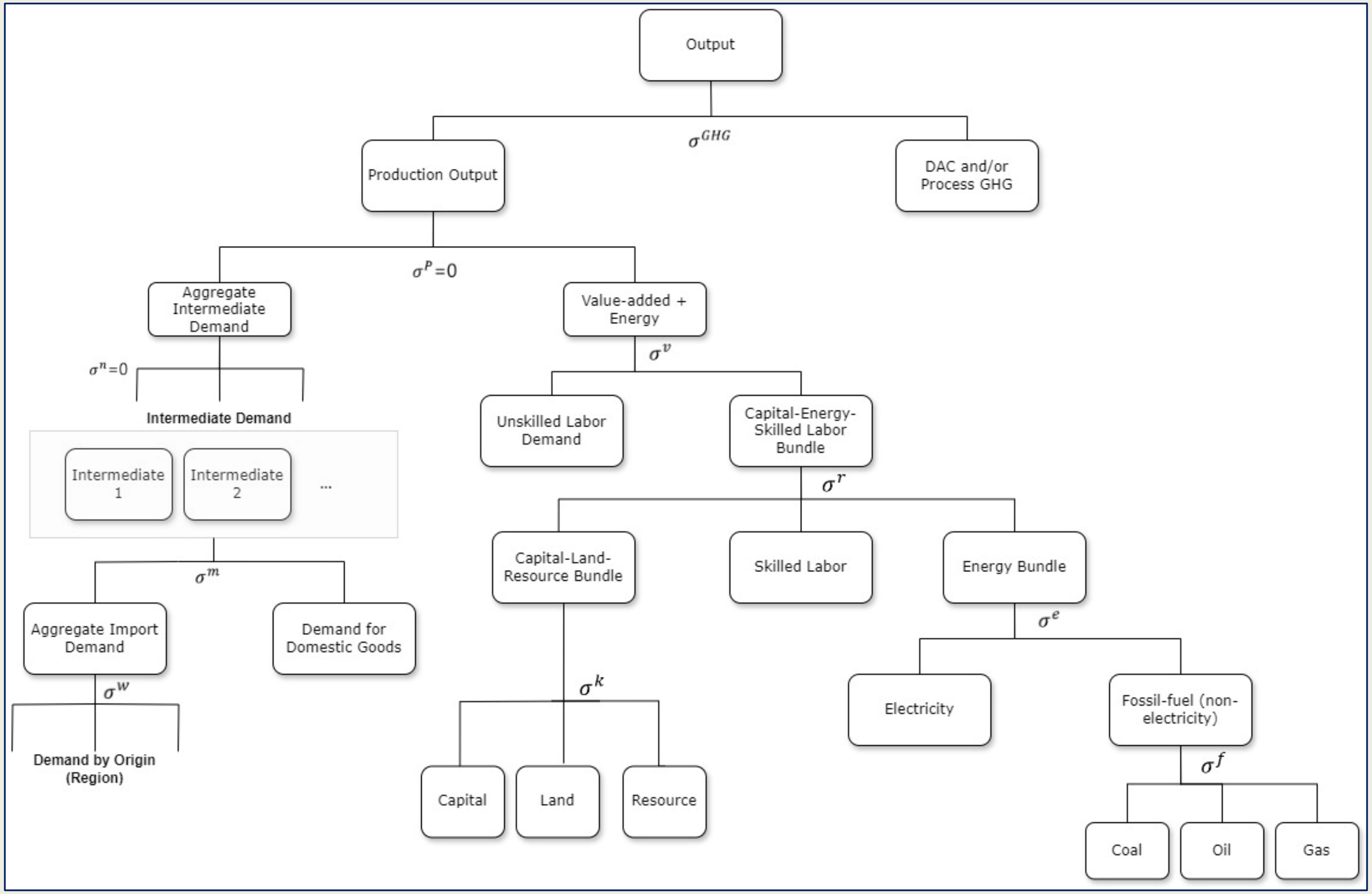
Integration of TD-BU models

- **CGE model + Power sector optimization for Korea**
  - ✓ UNICON-K-v1
    - Based on the model developed through “Climate Change R&&D” sponsored by MOE/KEITI
  - ✓ Hybrid SAM combining SAM (Korean IOT) and Power DB (KPX) with a reconciliation procedure
  - ✓ Linking by decomposition algorithm (Bohringer & Rutherford, 2009)
    - Transform the bottom-up optimization model from cost minimization (LP) to social surplus maximization (QP)
  - ✓ Hydrogen and DAC sector with Learning Curve
  - ✓ New algorithm for improving consistency between TD & BU models and convergence for ETS scenarios
    - Simultaneous reproduction of GDP and power sector forecast

CGE model

- **Simultaneous Equation system: CNS/MCP/NLP formulations**
  - ✓ Supply-demand balance, zero profit condition, budget constraints (household, government), current account balance, capital stock dynamics equation
- **Nested CES (Constant Elasticity of Substitution) for production technologies**
  - ➢ $\boldsymbol{Output = \left[\sum_i Share_i\, Input_i^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \; \sigma = -\frac{\partial\left({Input_i}/{Input_j}\right)/\left({Input_i}/{Input_j}\right)}{\partial\left({Price_i}/{Price_j}\right)/\left({Price_i}/{Price_j}\right)}}$: constant elasticity of substitution
  - ➢ CES, LES, CDE, AIDADS for final demands, Armington model (CET) for exports
- **DAC modeling via additional nest on the top**
  - ✓ Following Hyman et al. (2002)
- **Learning curve:** $IC = IC_0 \times \left(\frac{CC}{CC_0}\right)^{-b}$
  - ✓ CC: Cumulative capacity (CC_0: cumul. Capacity by 2019)
  - ✓ $LR = 100 \times (1 - 2^{-b})$
  - ✓ Graham, Hayward and Foster (2024)

CGE Model (Nested CES)



Output

σ^{GHG}

Production Output

DAC and/or Process GHG

$\sigma^{P}=0$

Aggregate Intermediate Demand

Value-added + Energy

$\sigma^{n}=0$

Intermediate Demand

Intermediate 1

Intermediate 2

...

σ^{m}

Aggregate Import Demand

Demand for Domestic Goods

σ^{w}

Demand by Origin (Region)

σ^{v}

Unskilled Labor Demand

Capital-Energy-Skilled Labor Bundle

σ^{r}

Capital-Land-Resource Bundle

Skilled Labor

Energy Bundle

σ^{k}

Capital

Land

Resource

σ^{e}

Electricity

Fossil-fuel (non-electricity)

σ^{f}

Coal

Oil

Gas

Power sector optimization model

➢ Capacity Expansion Model (LP)

✓ Minimize : $\sum_{t=0}^{T} df^{t} \sum_{k}([INV_{k,v,t} + FOM_{k,v,t}]N_{k,v,t} +$
$$\sum_{v,r}[VOM_{k,v,t} + \sum_{f} FC_{f,k,v,t} + \sum_{gas} Tax_{gas} EmiCoef_{gas,k,v,t}]P_{k,v,t,r})$$

k: technology (s: storage technology), v: vintage year, t: period, r: load region, $N_{k,v,t}$:running capacity, $P_{k,v,t,r}$:generation, F_k: Self consumption rate, L_k:lifetime, $UR_{k,t,r}$:capacity factor, $INV_{k,t}$: investment cost, FOM/VOM: O&M cost, FC: Fuel cost; df: discount factor, CR_k: Capacity credit, $S_{s,t,r}$: Stored power, SL_s: Storage loss, l: storage block

❖Capacity constraint: $P_{k,t,r} \le UR_{k,t,r} \sum_{v=t-L_k}^{t} CR_k N_{k,v}, \ \forall\, k, v, t, r$

❖Demand constraint: $\sum_k (1 - F_k) P_{k,t,r} - \sum_s S_{s,t,r} \ge Demand_{t,r}, \ \forall\, t, r$

❖Reserve margin: $\sum_k CR_k \sum_{v=t-L_k}^{t} N_{k,v} \ge Demand_{t,r} + Buffer_t,$
$\forall\, t, r$=peak

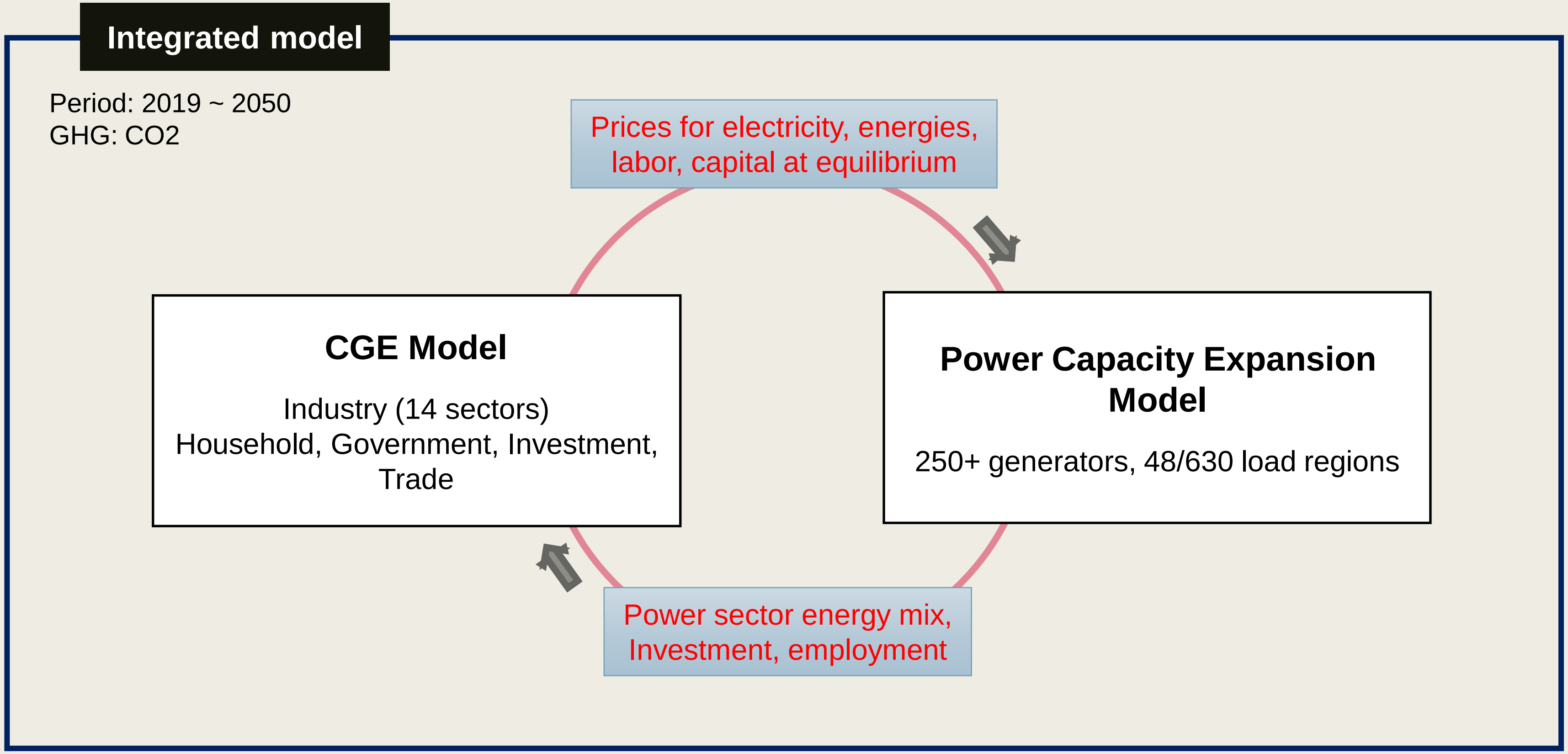
❖Storage constraint: $\sum_{r \in l} \sum_s P_{s,t,r} \le \sum_{r \in l} \sum_s (1 - SL_s) S_{s,t,r}, \ \forall\, s, l$

✓ Storage constraint2: $\sum_{r' \le r} \sum_s P_{s,t,r'} \le \sum_{r' \le r} \sum_s (1 - SL_s) S_{s,t,r}, \ \forall\, s, r$

❖Emission constraint: $\sum_{t \in cp} \sum_{k,r} ECoef_{gas,k,v,t} P_{k,t,r} \le ECap_{gas,cp}, \ \forall\, cp, gas$

❖Renewable capacity constraint for piecewise linear cost, RPS, RE100, ...

Decomposition algorithm



Integrated model

Period: 2019 ~ 2050
GHG: CO2

Prices for electricity, energies, labor, capital at equilibrium

Power Capacity Expansion Model

250+ generators, 48/630 load regions

Power sector energy mix, Investment, employment

CGE Model

Industry (14 sectors)
Household, Government, Investment, Trade

TD-BU Linking Algorithm

- **Transformation of BU model formulation**
  - ✓ Revision of Decomposition Algorithm by Boeringer & Rutherford (2009)
  - ✓ BU Objective function : LP => QP
    - ➢ Minimize $\sum_{t=0}^{T} df^t \{ \sum_k \Big([\overline{P_K^t} INV_{k,v,t} + \overline{P_L^t} FOM_{k,v,t}] N_{k,v,t} + \sum_{v,r} \Big[\overline{P_{Ser}^t} VOM_{k,v,t} + \sum_f \overline{P_f^t} FC_{k,v,t} + \sum_{gas} Tax_{gas} EmiCoef_{gas,k,v,t} \Big] P_{k,v,t,r} \Big) - \overline{P_e^t} Q_e^t \left[1 - \frac{Q_e^t - 2\overline{Q_e^t}}{2\epsilon \overline{Q_e^t}} \right] + \mu^t Q_e^t \}$
      - $\overline{P_e^t} Q_e^t \left[1 - \frac{Q_e^t - 2\overline{Q_e^t}}{2\epsilon \overline{Q_e^t}} \right] = \int P_e^t(Q_e^t) dQ_e^t, \;\; Q_e^t(P_e^t) = \overline{Q_e^t} \left[1 - \in \left(\frac{P_e^t}{\overline{P_e^t}} - 1 \right) \right]$
      - Calibration of μ^t to reproduce power demand scenario
  - ✓ Modified demand constraint
    - ➢ $\sum_k (1 - F_k) P_{k,t,r} - \sum_s S_{s,t,r} \geq \left(\frac{Q_e^t}{\sum_{r'} Demand_{t,r'}} \right) Demand_{t,r}, \;\; \forall\, t, r$

Baseline (BAU) Scenario

- **Population and real GDP projection for Korea from 2050 LEDS scenario**
  - ✓ Annual average population growth rate of 0.1%('17~'40), -0.5%('40~'50)
  - ✓ Average real GDP growth rate of 2.0%('17~'40), 1.0%('40~'50)
  - ✓ Electricity demand grow from 526.9 in 2019 to 1,054.5 TWh in 2050
- **Calibration of TFP to reproduce real GDP projection**
  - ✓ Electricity demand growth projection has been reproduced with the calibration of BU objective function

Key assumptions for power technology

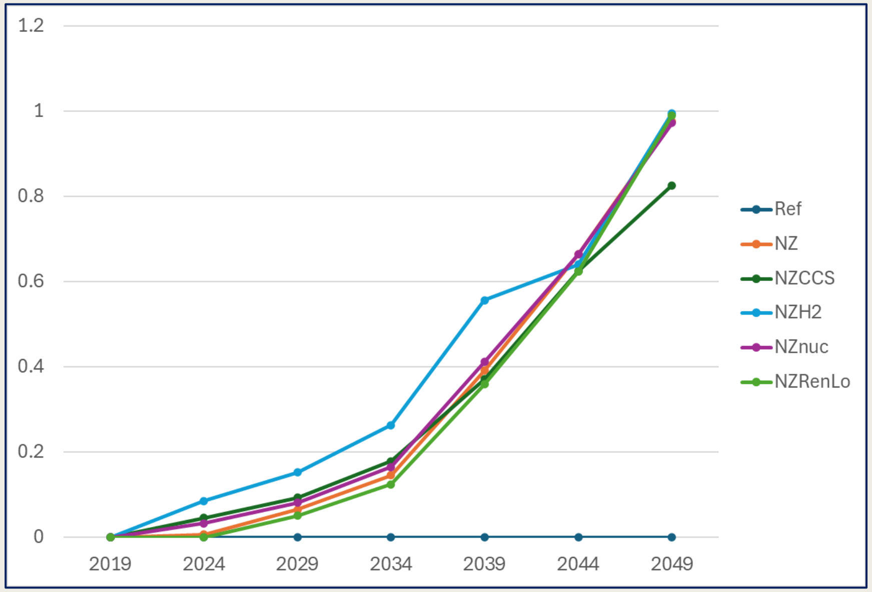
- **No more nuclear/coal (after Sinhanwool 3,4)**
  - ✓ Nuclear capacity factor of 87%, life of 60 yrs
- **Cost of solar PV (1MW, 15.4%) and wind power (20MW, on-shore 23%/off-shore 38.5%) from KEEI(2022)**
  - ✓ Cost reduction (CAPEX) over 2020~2050 (NREL NTB 2022 ‘Advanced’ scenario)
    - ➢ 65% for PV, 64% for On-whore Wind, 43% for Off-shore Wind
  - ✓ Grid connection cost from OECD & NEA(2012): $9.65/MWh for on shore wind, $26/MWh for off shore wind, $14.57/MWh for solar PV
  - ✓ Piece-wise linear cost function base on technical/economic potential (KECO, 2022)
- **ESS (4-hr duration Li ion battery) from Wesley & Frazier (NREL, 2020)**
  - ✓ 393 $/kWh in 2019, 156 $/kWh in 2050, O&M(2.5%), lifetime of 15 yr, roundtrip efficiency of 85%
- **Assumptions for hydrogen gas turbine from AGORA(2020), electrolysis from IRENA(2020)**
- **CCS cost follows EIA(2021)**
  - ✓ CCS for NGCC with 90% capture rate
- **Max Capa (GW/yr): Pump hydro 1, Solar PV 20, on shore wind 1, off shore 2**

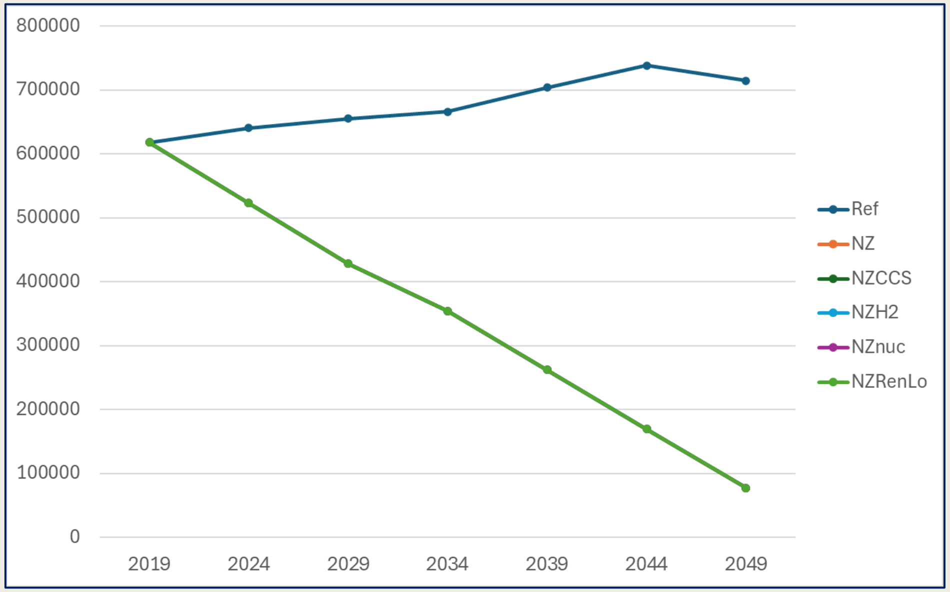
Policy scenarios for carbon pricing

- **Net Zero Scenario (‘NZ’)**
  - ✓ 59.1 MtCO2 of energy-related CO2 emission in 2050
    - ➢ Remaining emission corresponding to net sink in AFOLU (21.6) and foreign credit utilization (37.5m)
  - ✓ Carbon pricing to meet emissions constraints
    - ➢ Carbon tax recycling towards labor tax cut
- **4 Variants of NZ Scenario**
  - ✓ NZCCS: DAC learning rate from 10% to 15%
  - ✓ NZH2: Import price of hydrogen decreased by 50%
  - ✓ NZnuc: Additional nuclear by 2.8GW in 2037
  - ✓ NZRenLo: Lower cost reduction of PV and Wind
    - ➢ From ‘Advanced’ to ‘Conservative’ scenario of NREL NTB (2022)
      - ▪ CAPEX reduction by 2050: 43% for PV, 38% for On-shore Wind and 24% for Off-shore Wind

Carbon prices and CO2 emissions

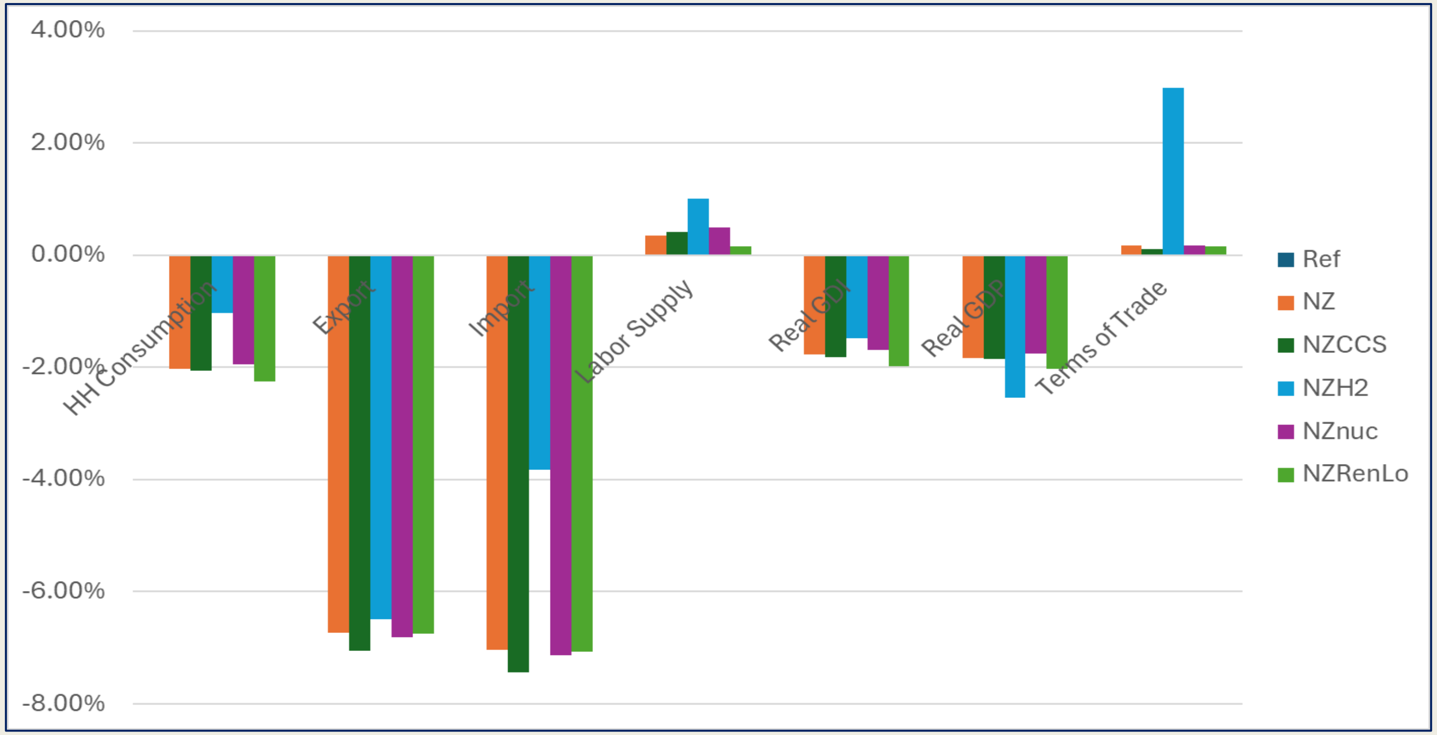
- **Carbon price (Left panel, Million Korean Won(₩)/tCO2) and CO2 emissions for Korea (Right, 1000 tCO2)**
  - ✓ 826~996 Thousand ₩/tCO2 of carbon price required for CO2 reduction towards 77.6 MtCO2 in 2049
    - ➢ The lowest carbon price of 826 Thousand ₩/tCO2 in NZCCS and the highest of 996 Thousand ₩/tCO2 in NZH2





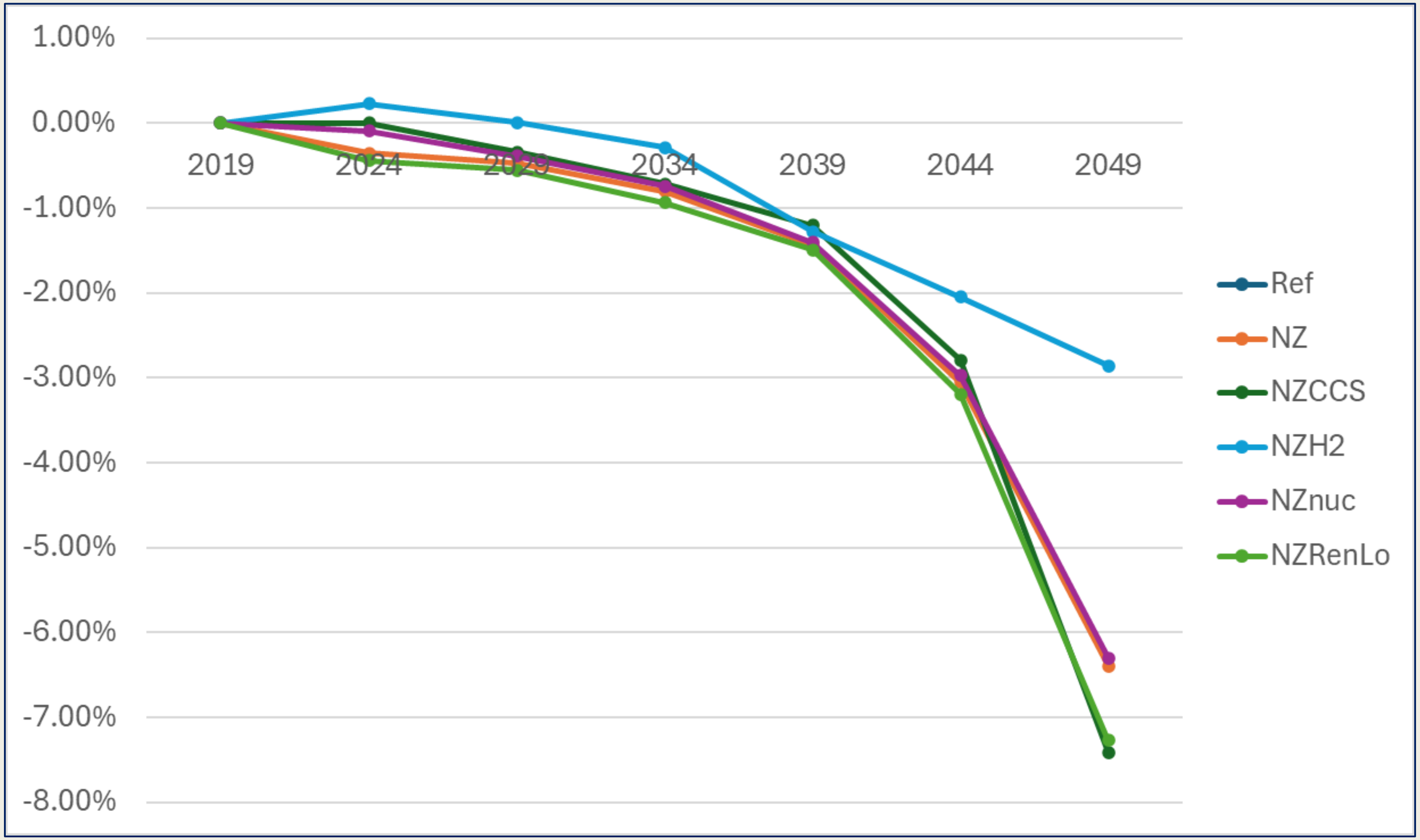
Macro economic impacts

- **[2019~2049, average % change from BAU] Real GDP, GDI and household consumption impacts of around -2%**
  - ✓ With slight gains for labor supply



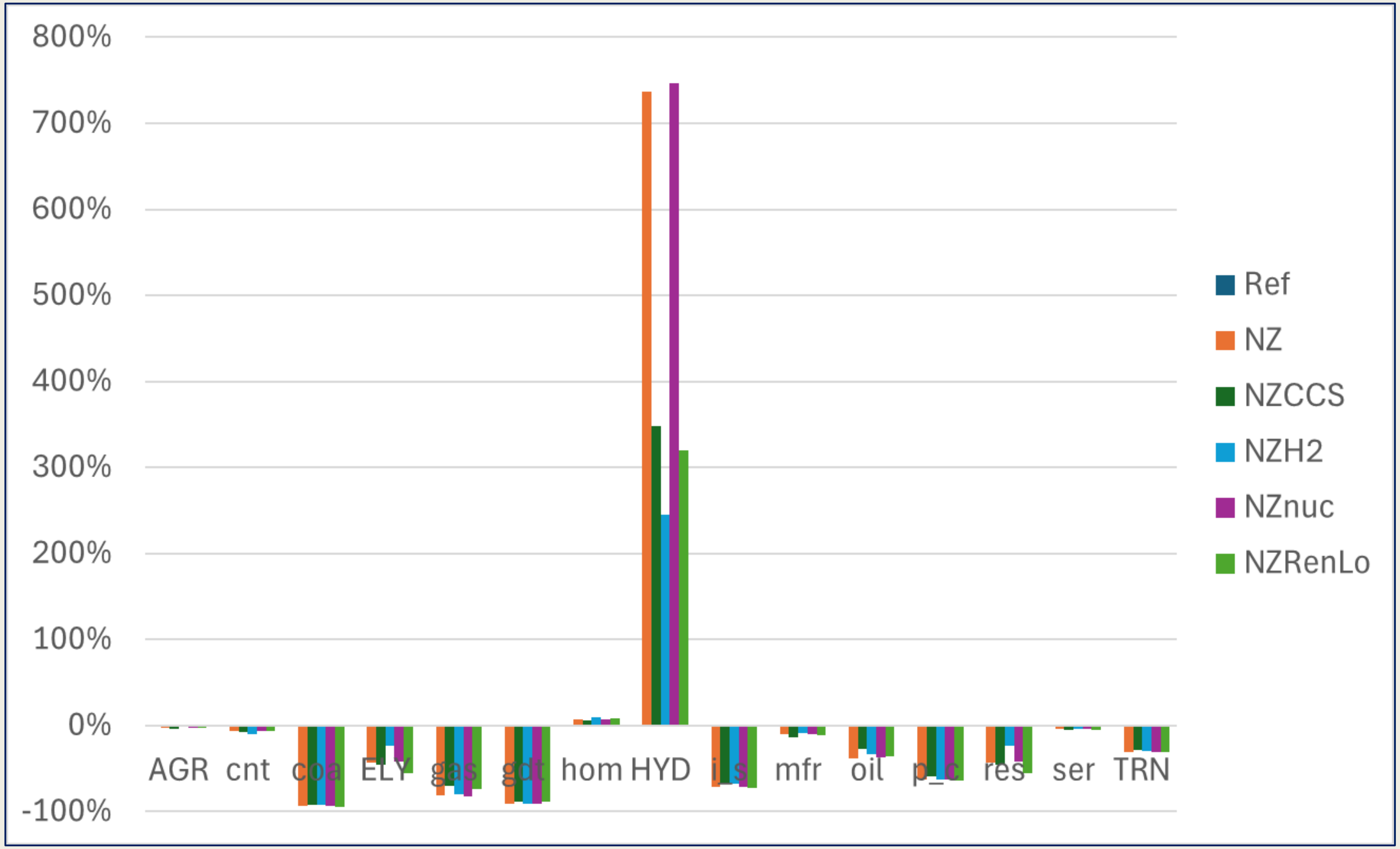
Macro economic impacts

❖ Trends of Real Household Consumption



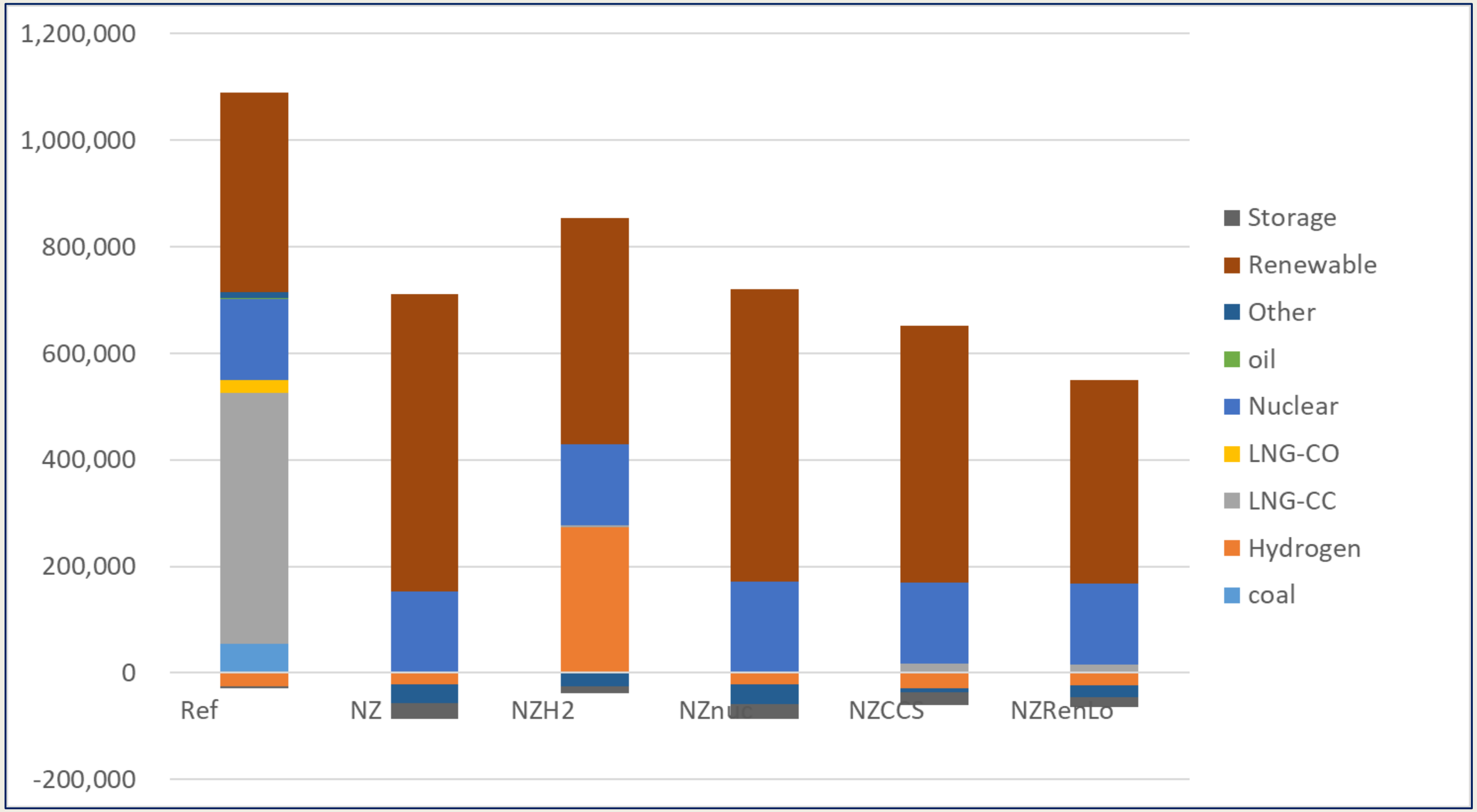
Macro economic impacts

- **Significant growth of hydrogen industry output (2049, % from Ref)**



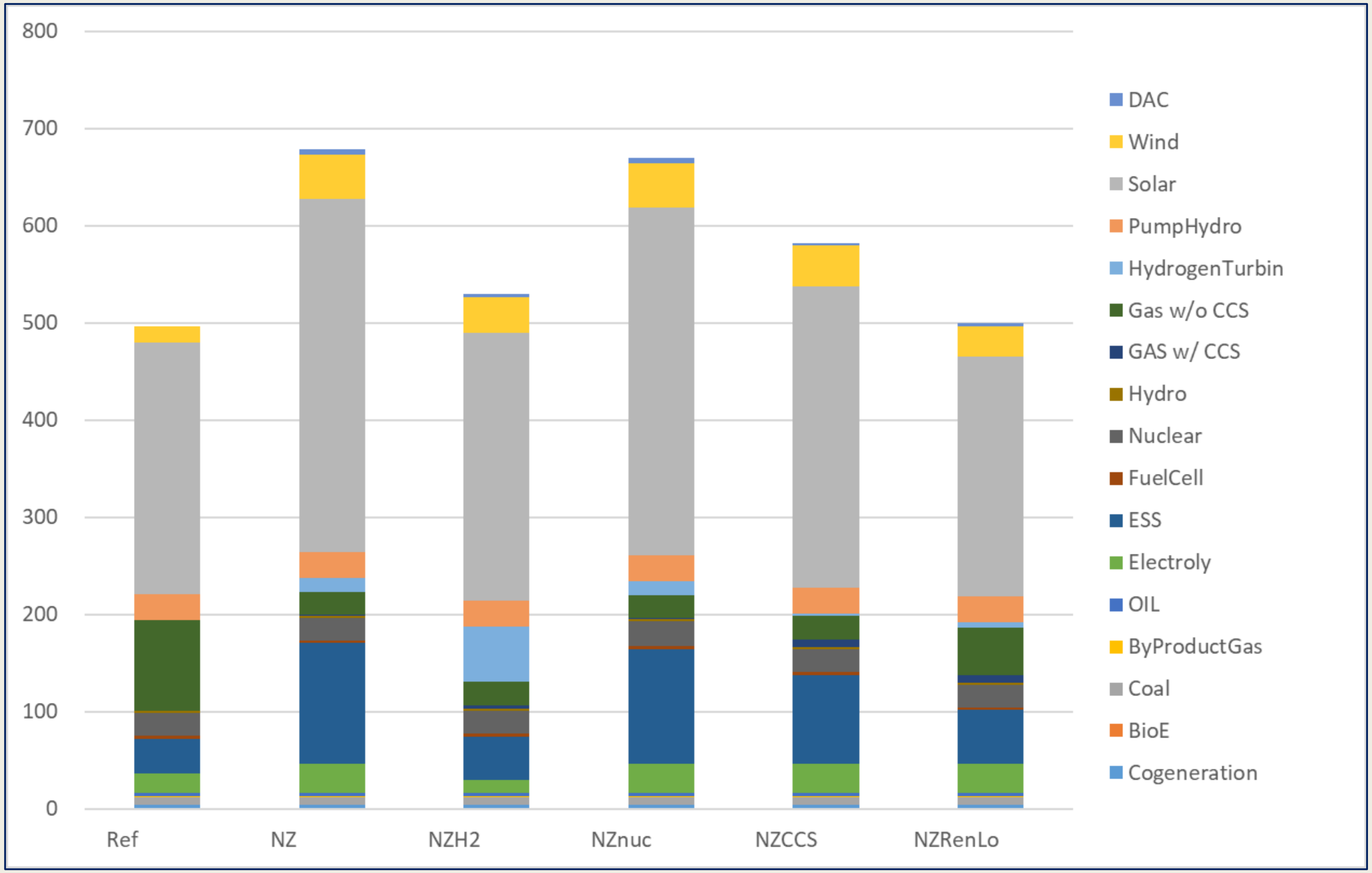
Power generation mix (GWh, 2049)

- Renewable energies dominate, supported by storage system



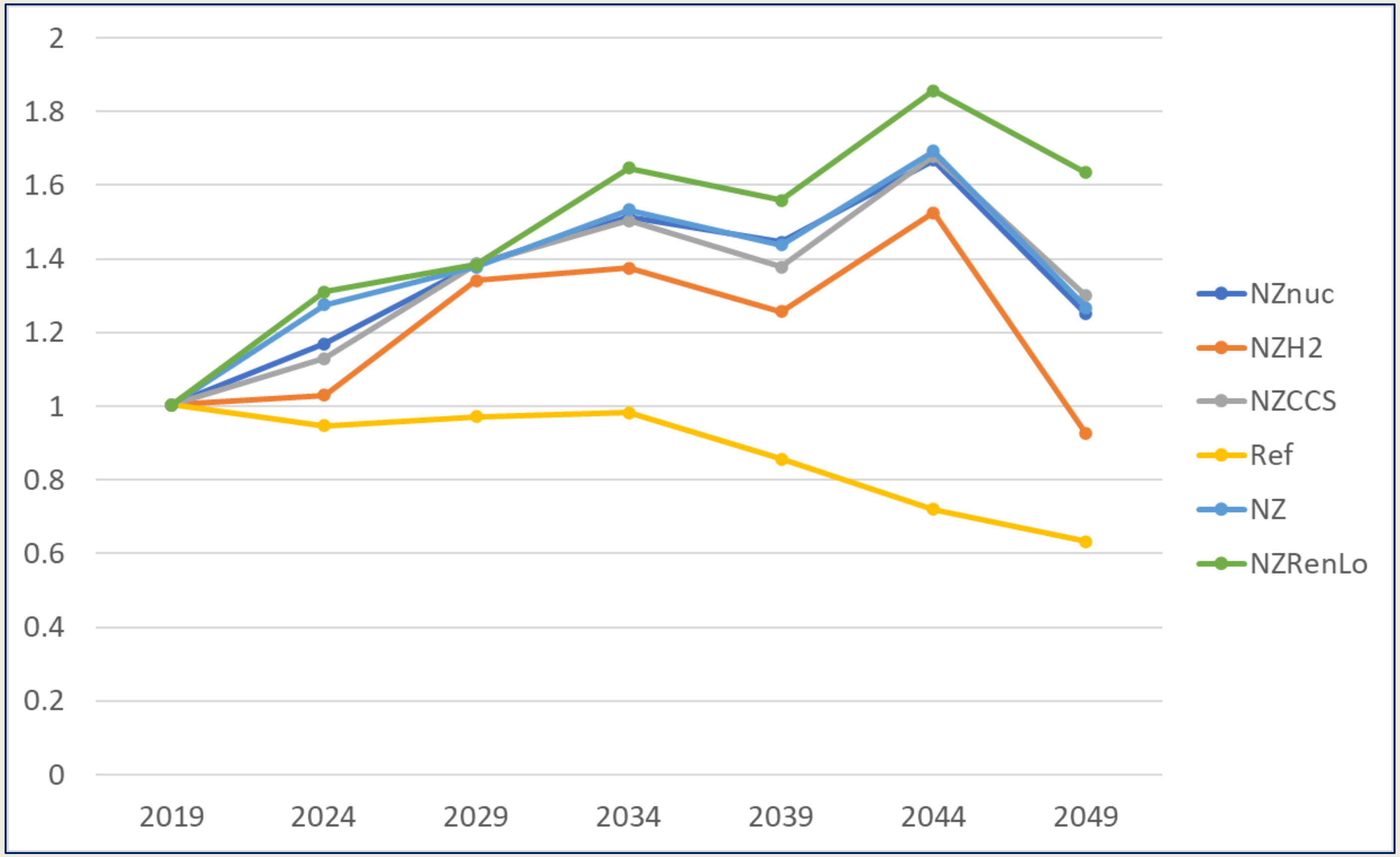
Capacity Mix (GW, 2049)

- **Dominant role of solar PV**



Price Impacts

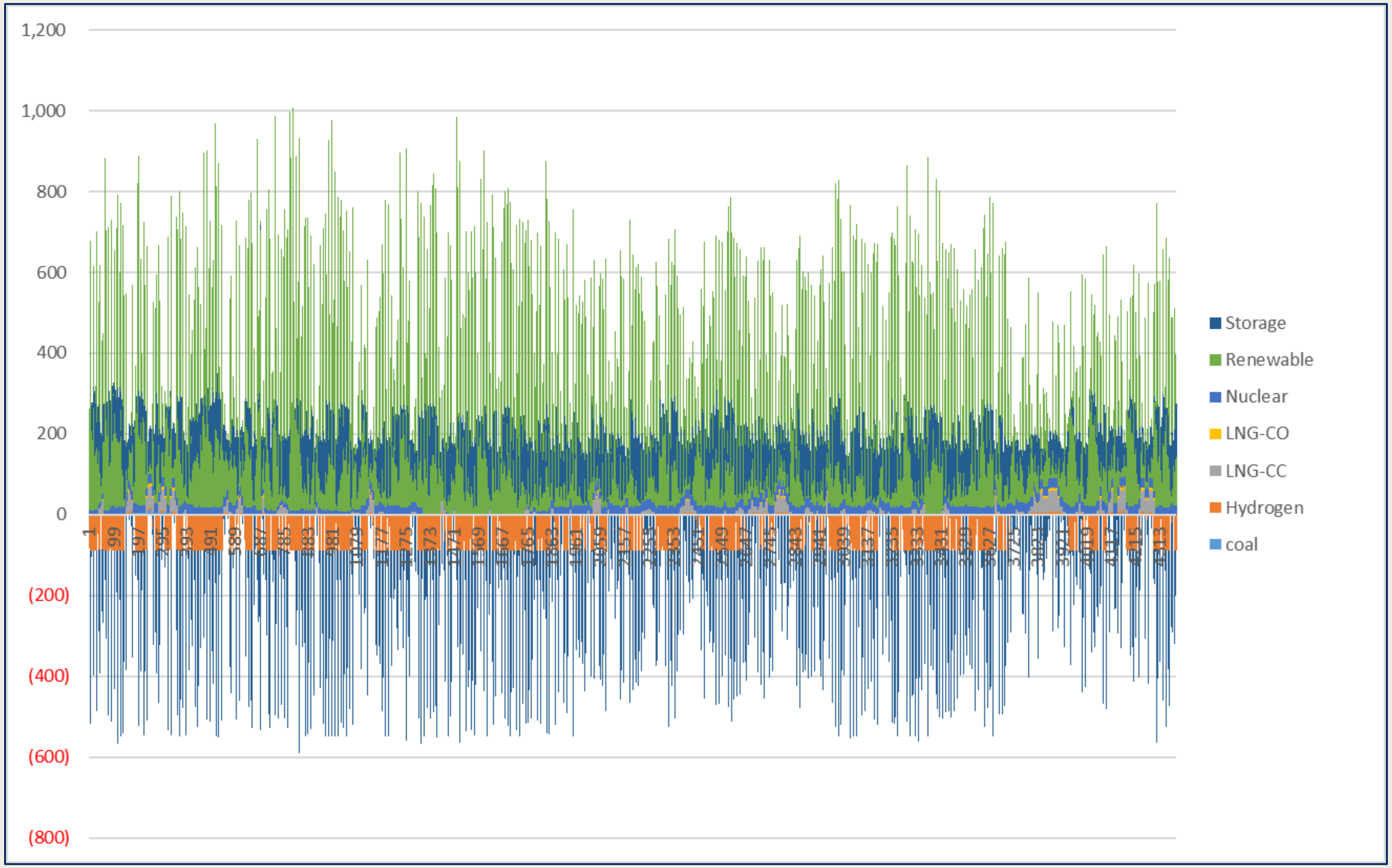
❖ Trends of Electricity Price



Unit commitment model

- **Mixed Integer Programming (MIP) Model for 2050**
  - ✓ To accommodate start-up/shut-down cost and minimum output ratio with high resolution of time (every 2 hour)
  - ✓ Minimum duration for operation/shut-down, quick-start/spinning reserve constraints
- **Greater demands for storage system**
  - ✓ ESS capacity requirement increases up to 252.7 GW
  - ✓ Electrolysis capacity (for hydrogen production) requirement also grows to 184.7 TWh
  - ✓ Bigger renewables curtail reaching 93.3 TWh
  - ✓ Old coal plants find a role for load balancing, supplying 1.9 TWh
- **Need for combining capacity expansion model and unit commitment model for informed decisions**

Hourly generations from MIP



Policy implications

- **Steep increase of marginal abatement costs near net-zero target may necessitates flexibility measures such as international market mechanism (IMM)**
  - ✓ Or aggressive utilization of innovative technologies such as DAC
  - ✓ A slight allowance for residual emissions could significantly limit the economic impact
- **Least negative impacts from the Low Hydrogen Price scenario**
  - ✓ Lowest carbon price, minimum loss of real GDI, consumption, exports and imports; Biggest benefit of employment and terms of trade
    - ➢ But hardest hit on real GDP
  - ✓ Maximized potential of hydrogen turbines
    - ➢ With minimal use of ESS and electrolysis
  - ✓ Need for proactive investment in foreign suppliers
- **Support for GHG-dependent industries for just transition**
  - ✓ Compensation of stranded asset, re-education of unemployed

Thank You!

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