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Analysis of Optimal Power Generation Mix in Japan to 2050, using Dynamic Multi-Sector Energy Economic Model

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Table

Background

Background

How to …

- Reduce the global CO_2 emissions?
- Solve the exhaustible resource problems?
- Operate nuclear power plants with citizens?
- Cooperate with countries for energy problems?

→ How to increase our economic, facing energy problems?

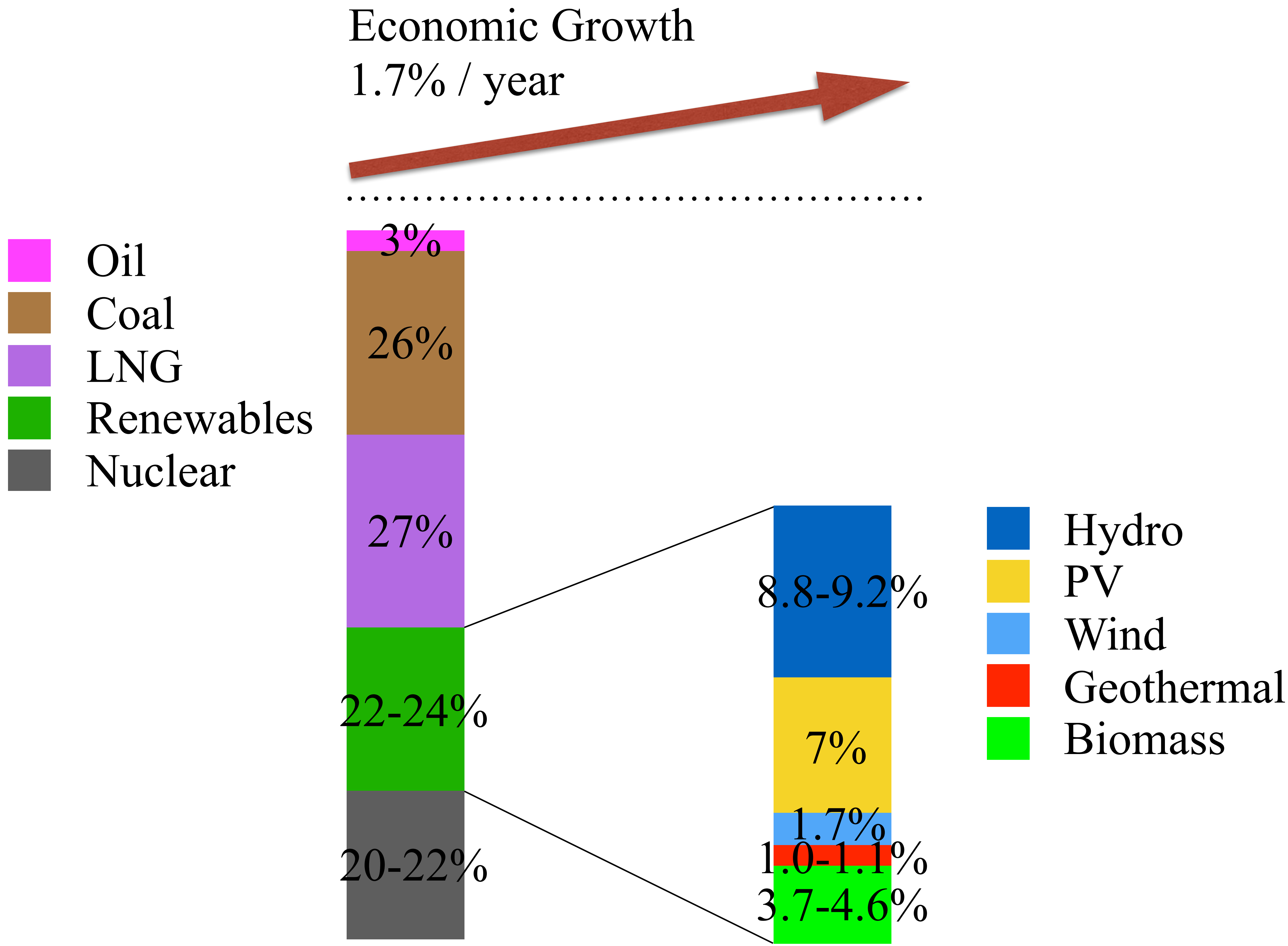


Fig. 1. The best mix of power generation in Japan in 2030, released in 2015 by Minister Economy, Trade and Industry (METI).

Motivation and Purpose

Develop a unique energy economic model,
which can consider inter-industry linkages
between economic multi-sectors including energy sectors

Contribute to framing the best energy/economic policy
for a target region or regions

Fundamental Classification of Energy Models

Table. 1. Characteristics of Bottom-up and Top-down Energy Models.

Bottom-up	Top-down
Optimizing objective functions for a particular system **deductively** with assumptions.	Optimizing objective functions for plural activities **inductively** with some real values.
Good at considering detailed technological constraints with high time/region resolution.	**Good** at considering the competitive relationships between activities logically.
Difficult to analyze the whole system composed of plural activities.	**Difficult** to analyze each activity in detail with high resolution.

Modeling

Dynamic Multi-Sector Energy Economic Model
(DMSEE)

Dynamic Multi-sector Energy Economic Model

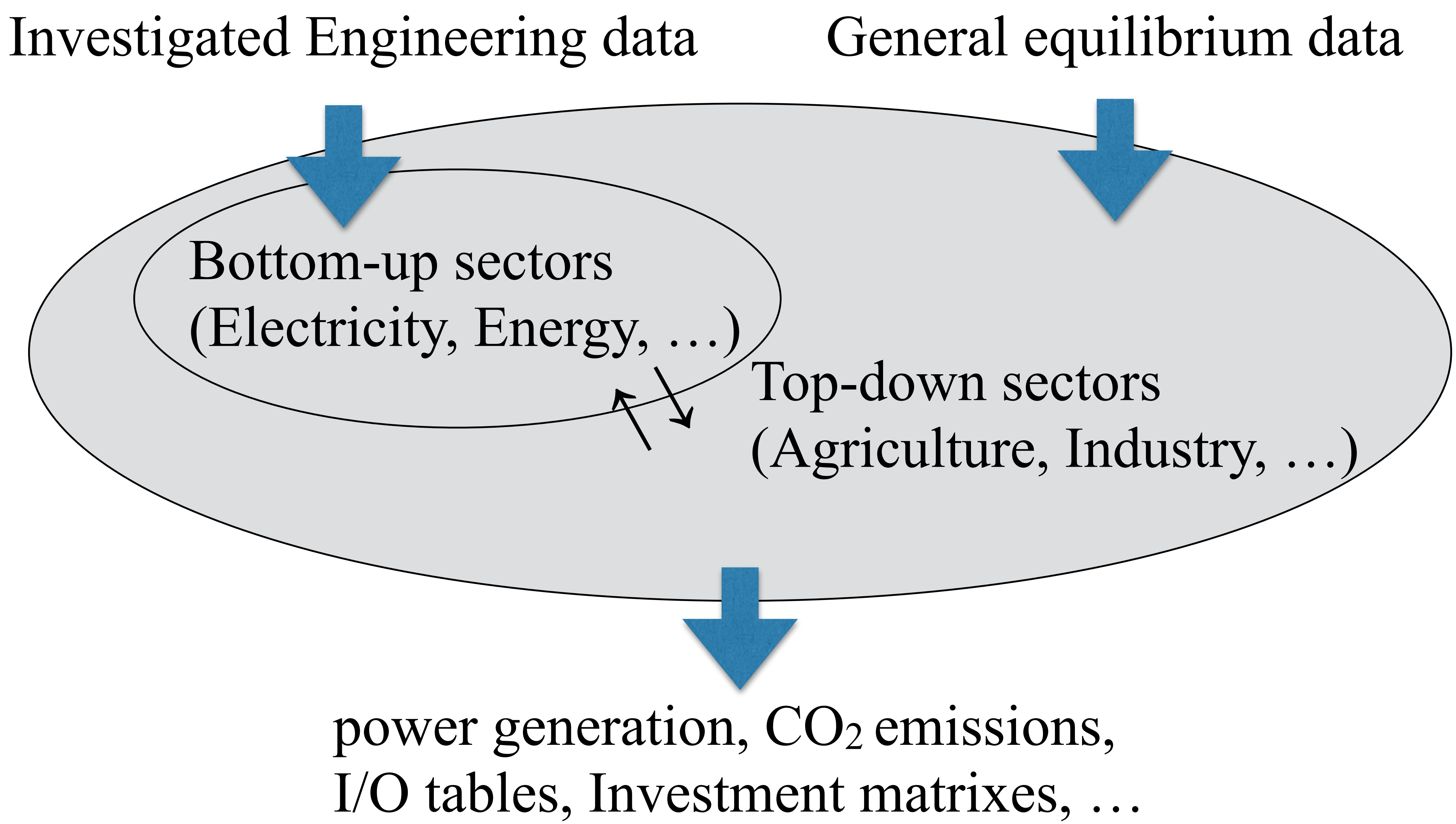


Fig. 2. Overview of the model from inputs to outputs.

Basic Information

Dynamic Multi-sector Energy Economic Model …

- Is a linear programming which maximizes **utility function.**
- Targets **JAPAN**.
- Has **8** time points from **2015 to 2050**.
- Has **24 TD sectors** and **a BU sector** (**Electricity sector**)
- Considers outputs of BU sectors with high resolution, per **1 hour**.
- Considers elasticities of substitutions with **CES (**Constant Elasticity of Substitutions**) function**, including Armington consumption for the process of TD production.

Main Original Points of the Model

- A general equilibrium model elaborating the electricity sector with very high time resolution.
- Not calculated by the link of multiple models, but is completed in one model.
- A new formulate for relationship between investment and facility for Top-down sectors.

Bottom-up side (Electricity)

Power Generation Sectors

NuclearE

CoalE

OilE

GasE

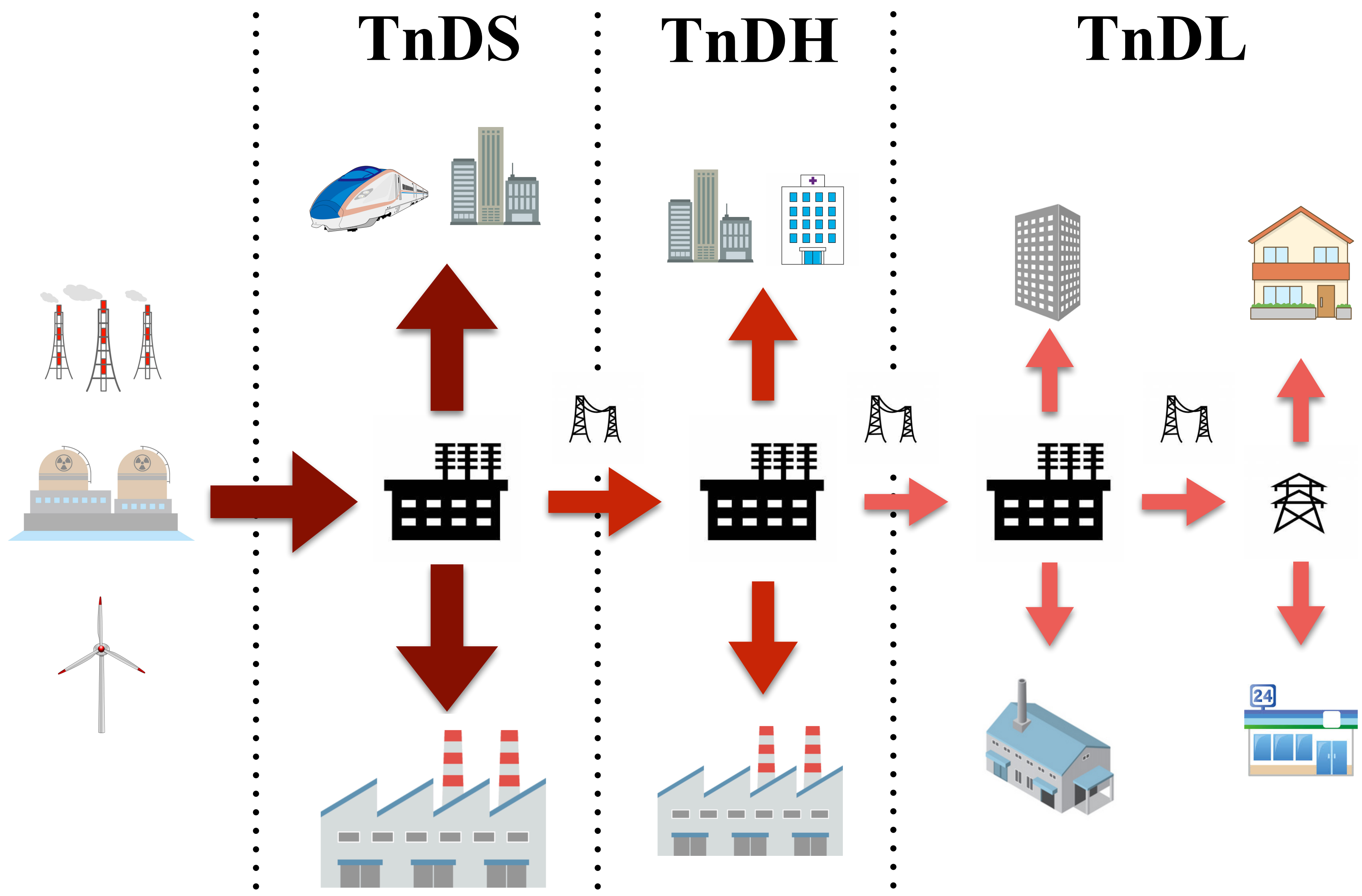
HydroE

WindE

SolarE

OtherE

Transmission/Distribution Sectors



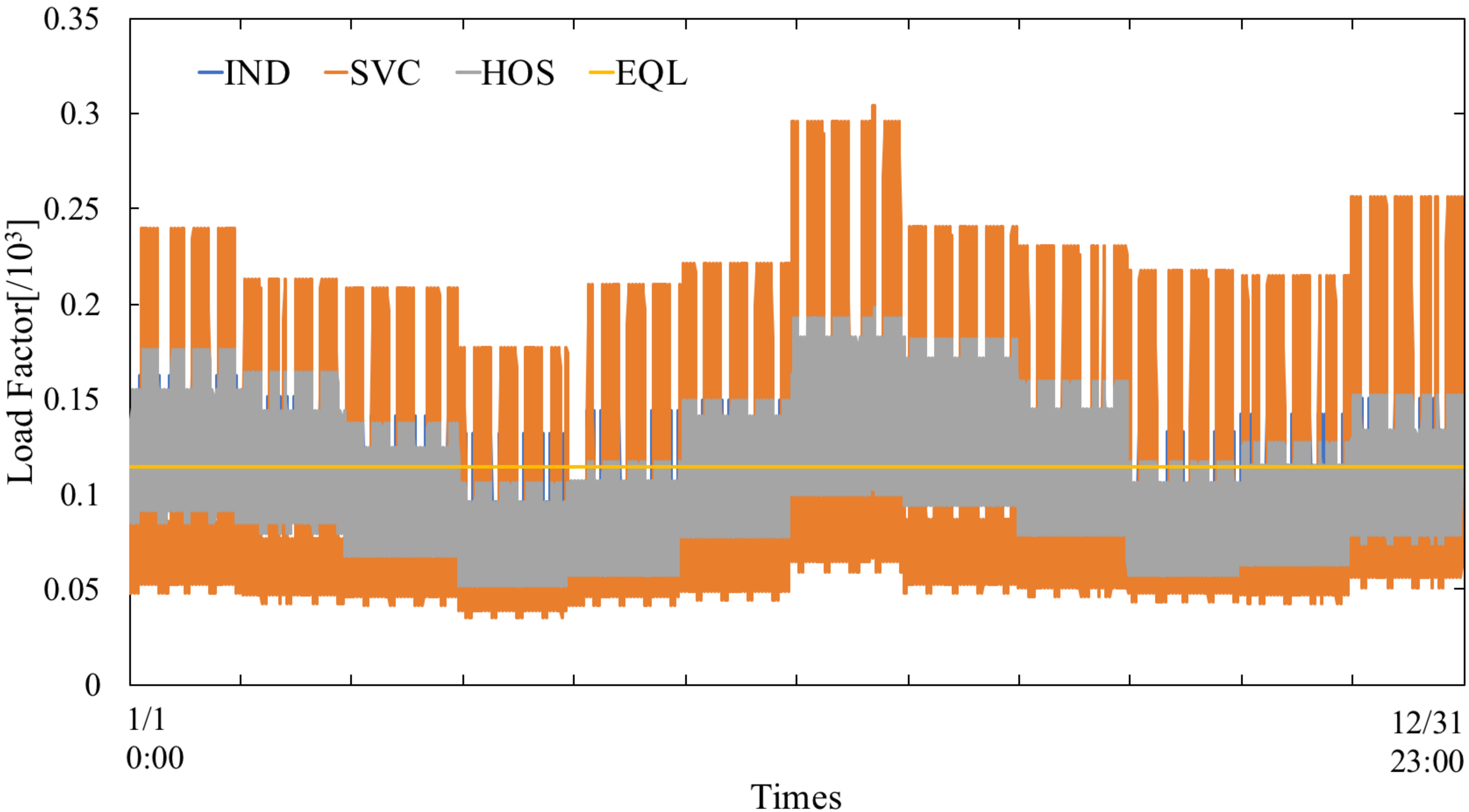


Fig. 3. Hourly Load Curve of each sector.

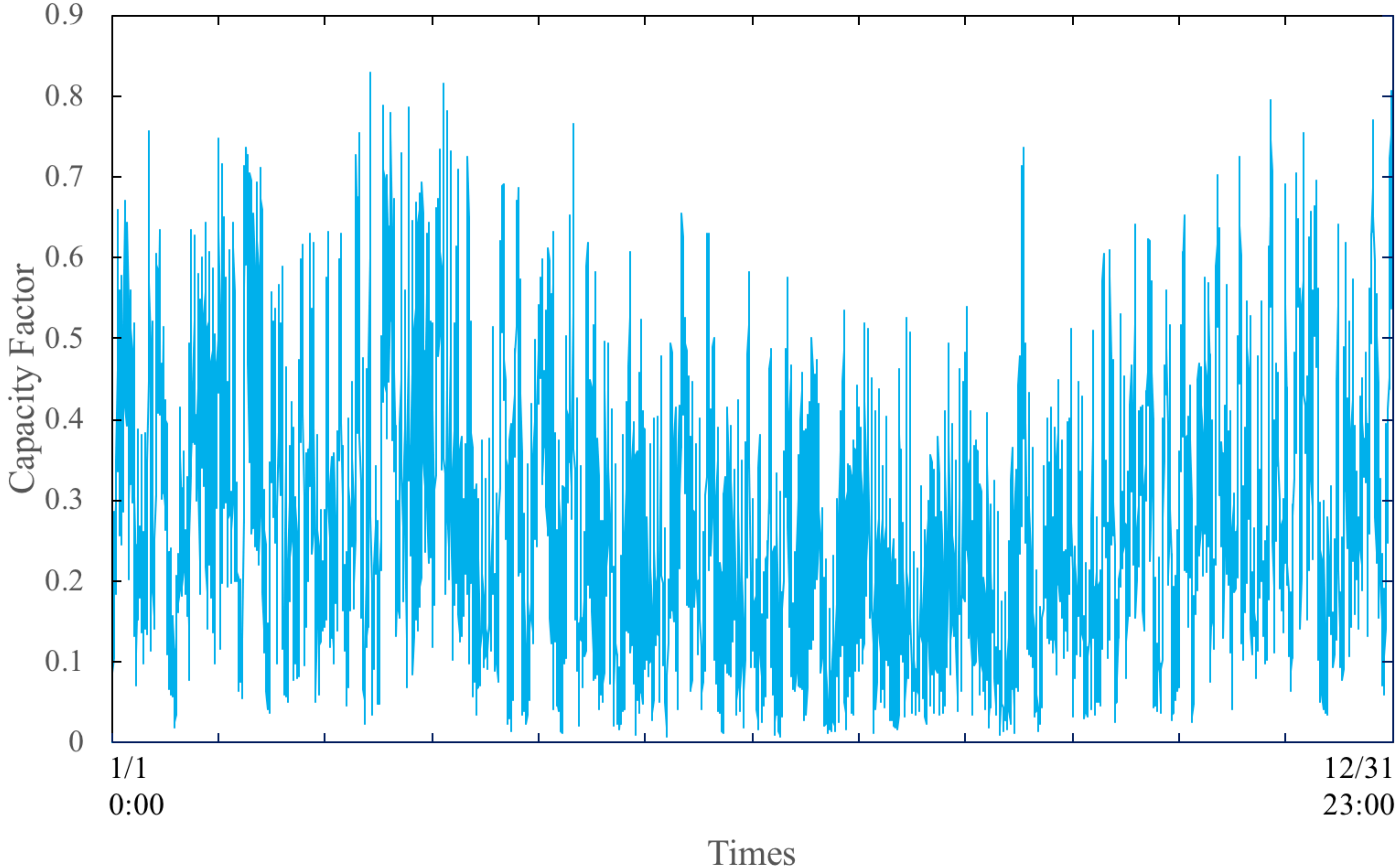


Fig. 4. Wind Hourly capacity factor for 365 days

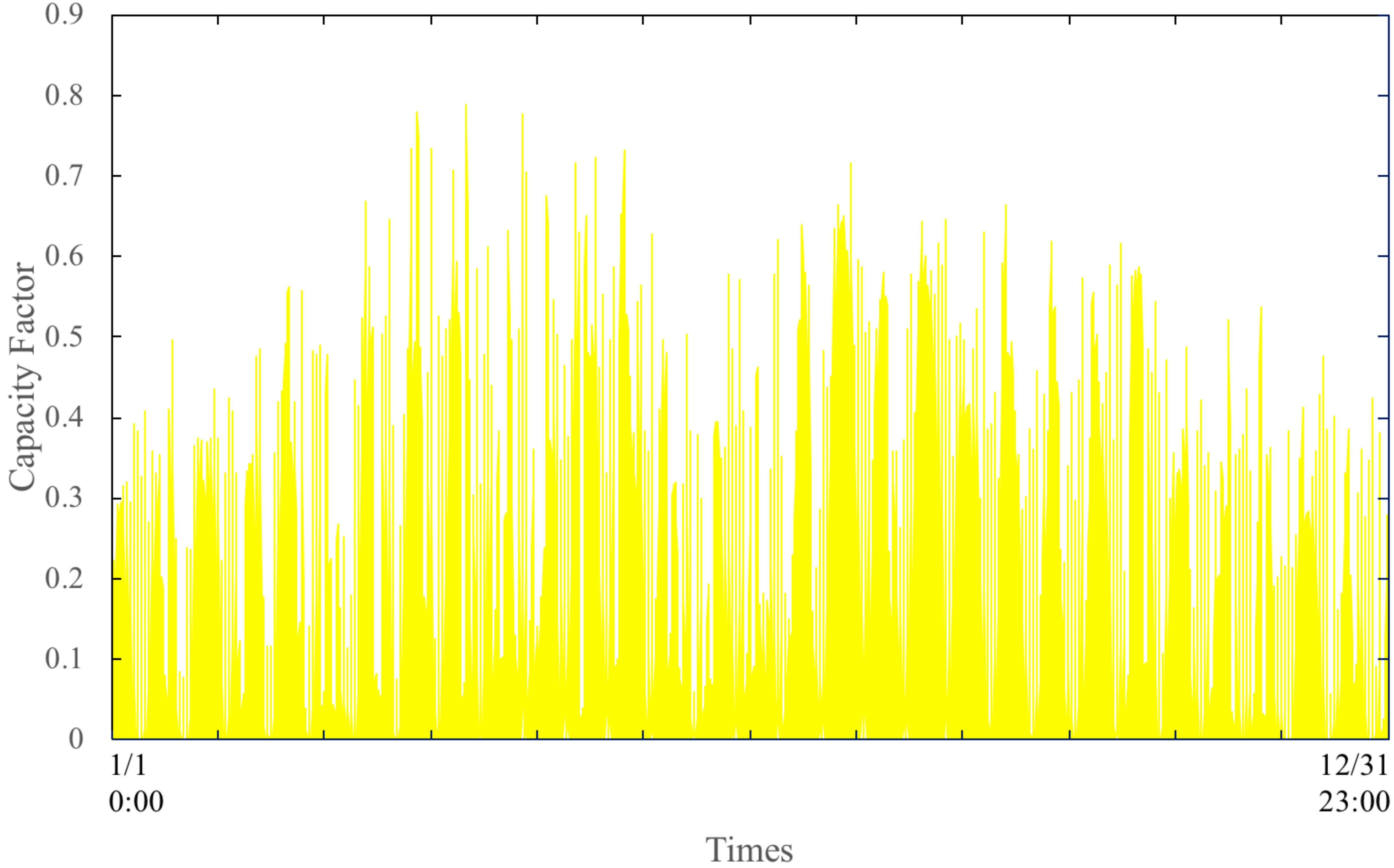


Fig. 5. Solar Hourly capacity factor for 365 days

Top-down side

Nested General CES Production Function is (1).

$$\boldsymbol{z} = \left(\sum_i \boldsymbol{\mu}_i \left(\sum_j \boldsymbol{v}_{i,j} \boldsymbol{y}_{i,j}{}^{\rho_i} \right)^{\frac{\rho}{\rho_i}} \right)^{\frac{1}{\rho}}$$

Approximated, $\beta_{i,j,t} \cdot z_t \leq y_{i,j,t}$ (1)

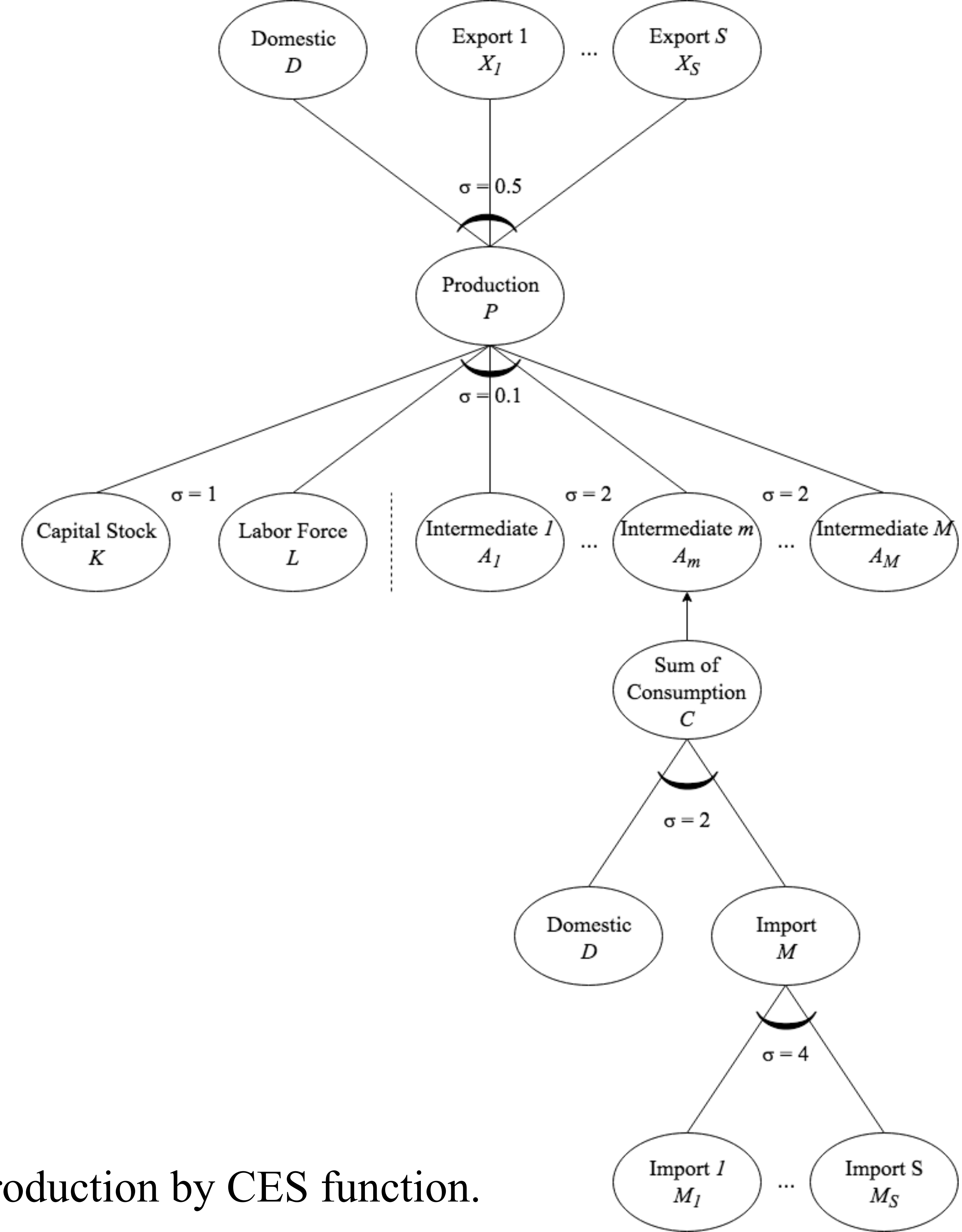


Fig. 4. Tree of production by CES function.

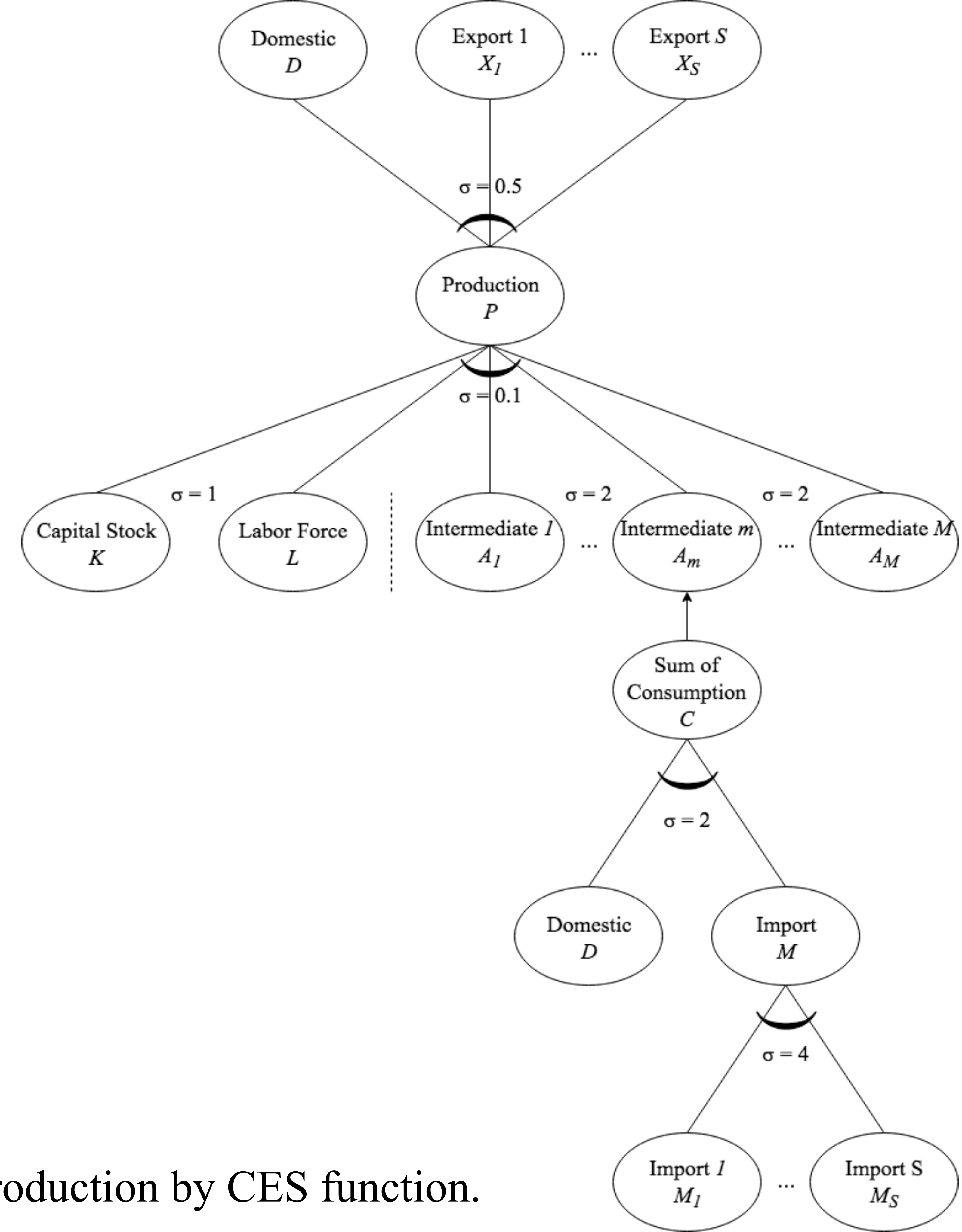


Fig. 4. Tree of production by CES function.

Objective Function

Maximize $$obj = \sum_t \sigma_t \left(util_{\mathrm{H}_t} + util_{\mathrm{G}_t} - tax_t\right) \quad (4)$$

$$\boldsymbol{util}_{\mathrm{H}} = \left(\sum_{m}^{M} \boldsymbol{v}_{\mathrm{H}_m} \boldsymbol{h}_{\mathrm{T}_m}{}^{\rho} + \boldsymbol{v}_{\mathrm{H}_{M+1}} \left(\sum_{e}^{E} \boldsymbol{h}_{\mathrm{B}_e}\right)^{\rho}\right)^{\frac{1}{\rho}} \quad (5)$$

$$\boldsymbol{util}_{\mathrm{G}} = \left(\sum_{m}^{M} \boldsymbol{v}_{\mathrm{G}_m} \boldsymbol{g}_{\mathrm{T}_m}{}^{\rho} + \boldsymbol{v}_{\mathrm{G}_{M+1}} \left(\sum_{e}^{E} \boldsymbol{g}_{\mathrm{B}_e}\right)^{\rho}\right)^{\frac{1}{\rho}} \quad (6)$$

σ: Discount Rate, $util_{\mathrm{H}}$: Household Utility Function, $util_{\mathrm{G}}$: Government Utility Function, *tax*: Tax, *h*: Household Consumptions, *g*: Government Consumptions, *M, E*: The number of TD/BU Commodities, *v*: Calculated coefficients, ρ: Index derived from elasticity of substitutions

y1

Constraints

Balance of demand and supply

$$\boldsymbol{h}_{\mathrm{B}} + \boldsymbol{g}_{\mathrm{B}} + \boldsymbol{a}_{\mathrm{B}} + \boldsymbol{i}_{\mathrm{B}} = \boldsymbol{c}_{\mathrm{B}}$$
$$\boldsymbol{h}_{\mathrm{T}} + \boldsymbol{g}_{\mathrm{T}} + \boldsymbol{a}_{\mathrm{T}} + \boldsymbol{i}_{\mathrm{T}} = \boldsymbol{c}_{\mathrm{T}} \quad (7)$$

Investment and Capacity

$$\boldsymbol{k}_{\mathrm{B}_t} = \boldsymbol{k}_{\mathrm{B}_0} + \sum_{t'=0}^{t} F_{\mathrm{B}_{t,t'}} \eta_{\mathrm{I}_{t'}} \boldsymbol{i}_{\mathrm{B}_{t'}} \quad (8)$$

$$k_{\mathrm{T}_{t+1}} = (1-\delta) k_{\mathrm{T}_t} + i_{\mathrm{T}_t} / RP_n \quad (9)$$

h: Household Consumptions, *g*: Government Consumptions, *a*: Intermediate Consumptions, *i*: Investment, *c*: Sum of Consumptions, *F*: Matrix for investment, η_I: Construction cost, δ: Depreciation Rate,

y1

Constraints

Balance of demand and supply

$$\boldsymbol{h}_{\mathrm{B}} + \boldsymbol{g}_{\mathrm{B}} + \boxed{\boldsymbol{a}_{\mathrm{B}} + \boldsymbol{i}_{\mathrm{B}}} = \boldsymbol{c}_{\mathrm{B}}$$
$$\boldsymbol{h}_{\mathrm{T}} + \boldsymbol{g}_{\mathrm{T}} + \boxed{\boldsymbol{a}_{\mathrm{T}} + \boldsymbol{i}_{\mathrm{T}}} = \boldsymbol{c}_{\mathrm{T}} \tag{7}$$

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y1

Constraints

Production and Capacity

$$\eta \cdot \boldsymbol{p}_{\mathrm{B}} \leq \boldsymbol{k}_{\mathrm{B}}$$
$$\eta \cdot \boldsymbol{p}_{\mathrm{B}_n} \leq Cu_n \cdot \boldsymbol{k}_{\mathrm{B}_n} \quad (n \in \{WindE, SolarE, HydroE\}) \tag{10}$$

Constraints deriving from CES

$$\beta_{i,j,t} \cdot z_t \leq y_{i,j,t} \tag{11}$$

η: Factor to change production to capacity, p: production, Cu: Capacity Factor,
β: Calculated coefficient

y1

Constraints

Reserve Capacity

$$\sum_{pw} \boldsymbol{k}_{\mathrm{B}_{pw}} \geq (1 + 0.05) \cdot \eta \cdot \boldsymbol{MaxLOAD} \tag{12}$$

Load Following Operation

$$\begin{aligned} p_{\mathrm{B}_t} &\leq (1 + MaxLF) p_{\mathrm{B}_{t+1}} \\ p_{\mathrm{B}_t} &\geq (1 + MinLF) p_{\mathrm{B}_{t+1}} \end{aligned} \tag{13}$$

MaxLOAD: Max of electricity demand, *MaxLF*: Max Ratio, *MinLF*: Min Ratio,

y1

Constraints

Maintenance Operation

$$\boldsymbol{ap}_{i,d} + \sum_{m=0}^{3} Ur_{m,d}\boldsymbol{mk}_{m,d} = \boldsymbol{k}_{\mathrm{B}i} \qquad \sum_{m=0}^{3} Ur_{m,d}\boldsymbol{mk}_{m,d} \geq (1 - Up_i)\boldsymbol{k}_{\mathrm{B}i}$$

$$\sum_{m=0}^{3}\sum_{d=0}^{365-1} Ur_{m,d}\boldsymbol{mk}_{m,d}/365 = (1 - Ua_i)\boldsymbol{k}_{\mathrm{B}i} \qquad \eta \cdot \boldsymbol{p}_{\mathrm{B}i,d,t} \leq \boldsymbol{ap}_{i,d} \tag{14}$$

ap: Operation capacity, *Ur*: Maintenance rate, *mk*: Maintenance capacity,
Up: Day max operation rate, *Ua*: Year mean operation rate

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Results

Scenarios and Policy

Consumption Scenario

- Constant household/government consumptions from the initial
- Growth by 1.5% yearly especially for electricity consumptions

CO_2 tax and prohibition of new construction of Nuclear Power Plant (noN)

- Business As Usual case
- 50$/t-$CO_2$ case
- 300$/t-$CO_2$
- 300$/t-$CO_2$ and noN

Today's Results

- Power Generation Mix
- CO_2 Emissions
- GDP

Power Generation in BAU case

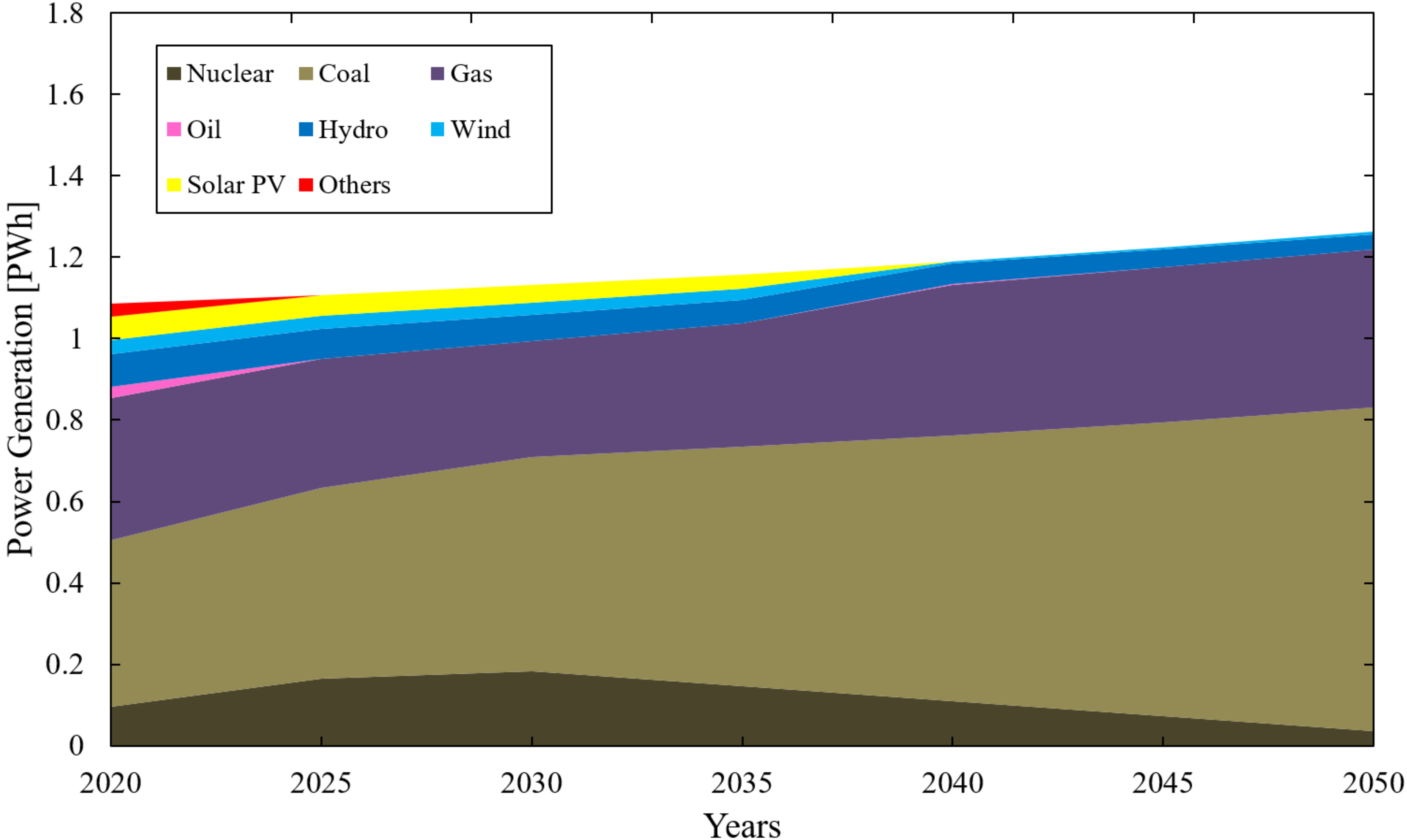

Fig. 6. Power Generation Mix in BAU case

Comparison between Cases for Power Generation

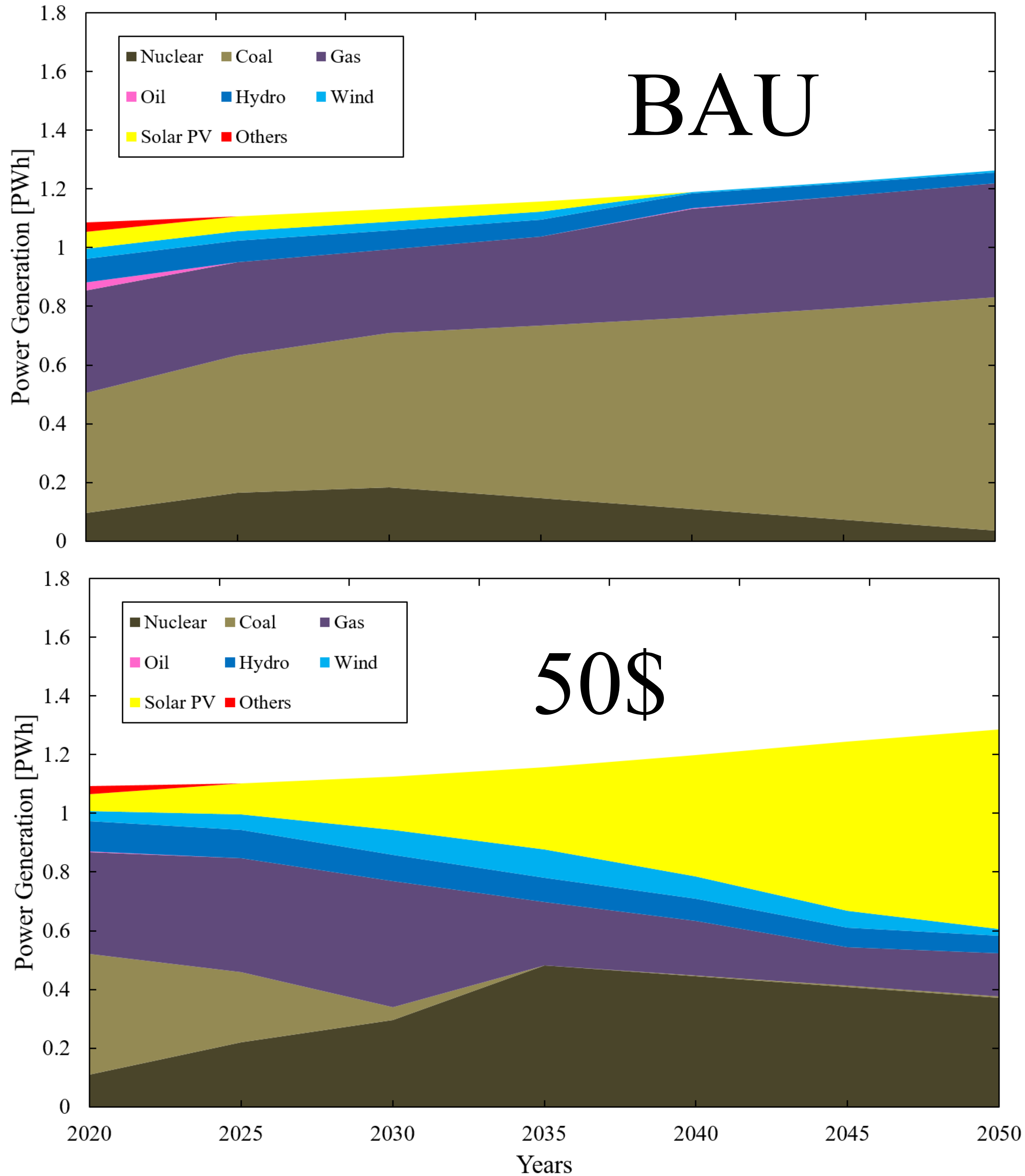

Fig. 7. Power Generation Mix of each case

Comparison between Cases for Power Generation

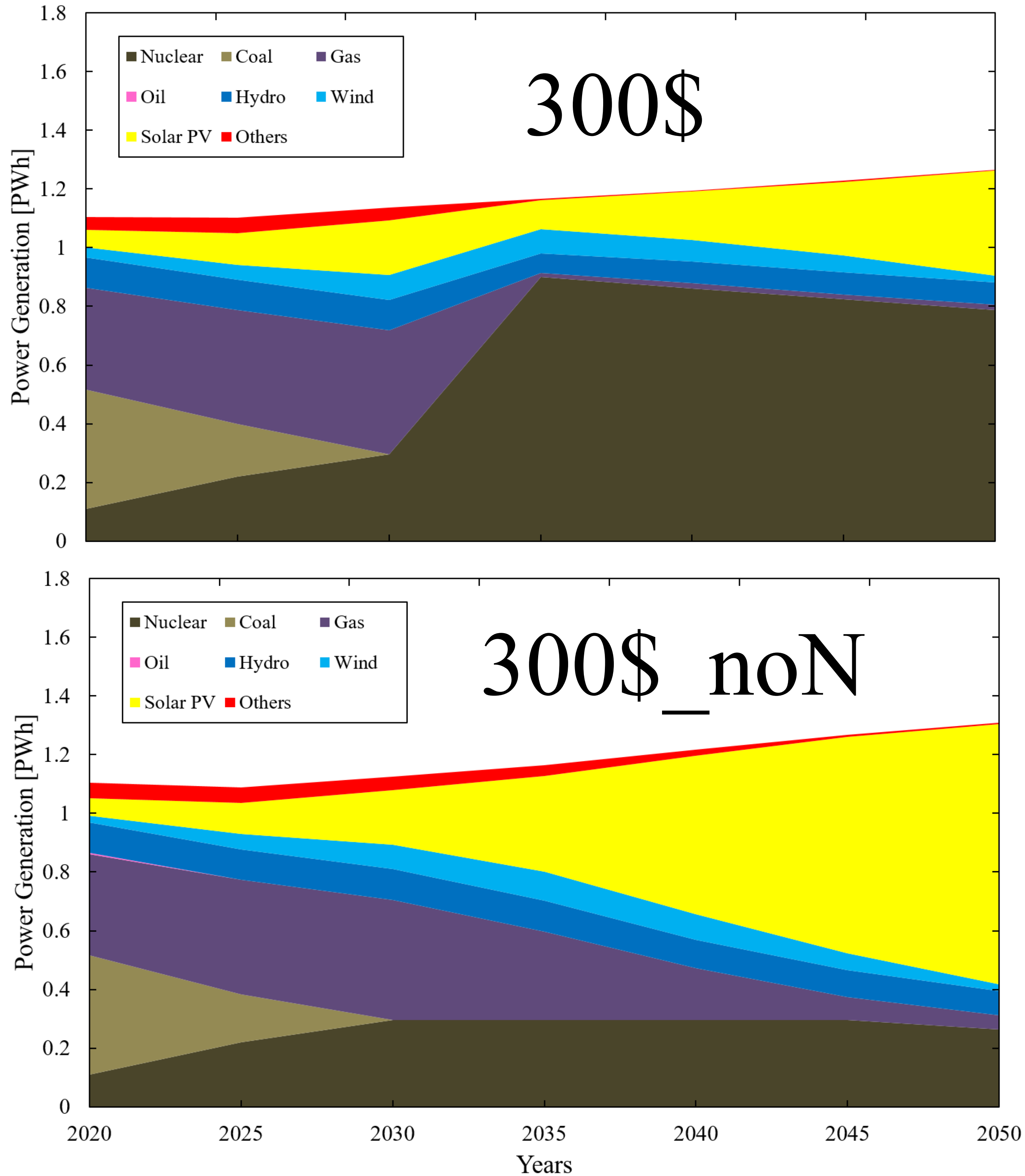

Fig. 8. Power Generation Mix of each case

Power Generation Mix and CO_2 Emissions in 2050

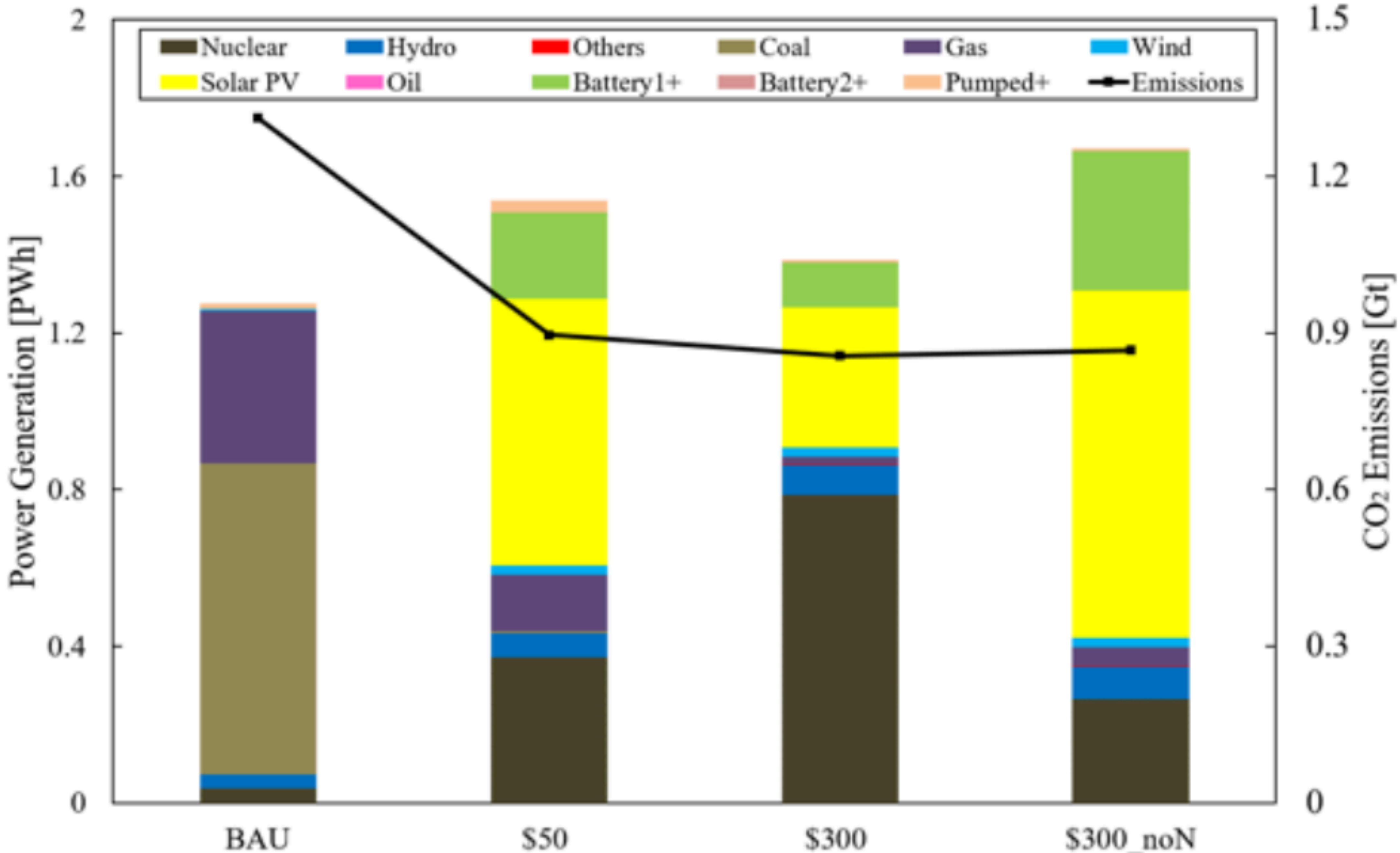

Fig. 9. Power generation mix and CO_2 emissions in 2050.

Power Generation Mix and CO_2 Emissions in 2050

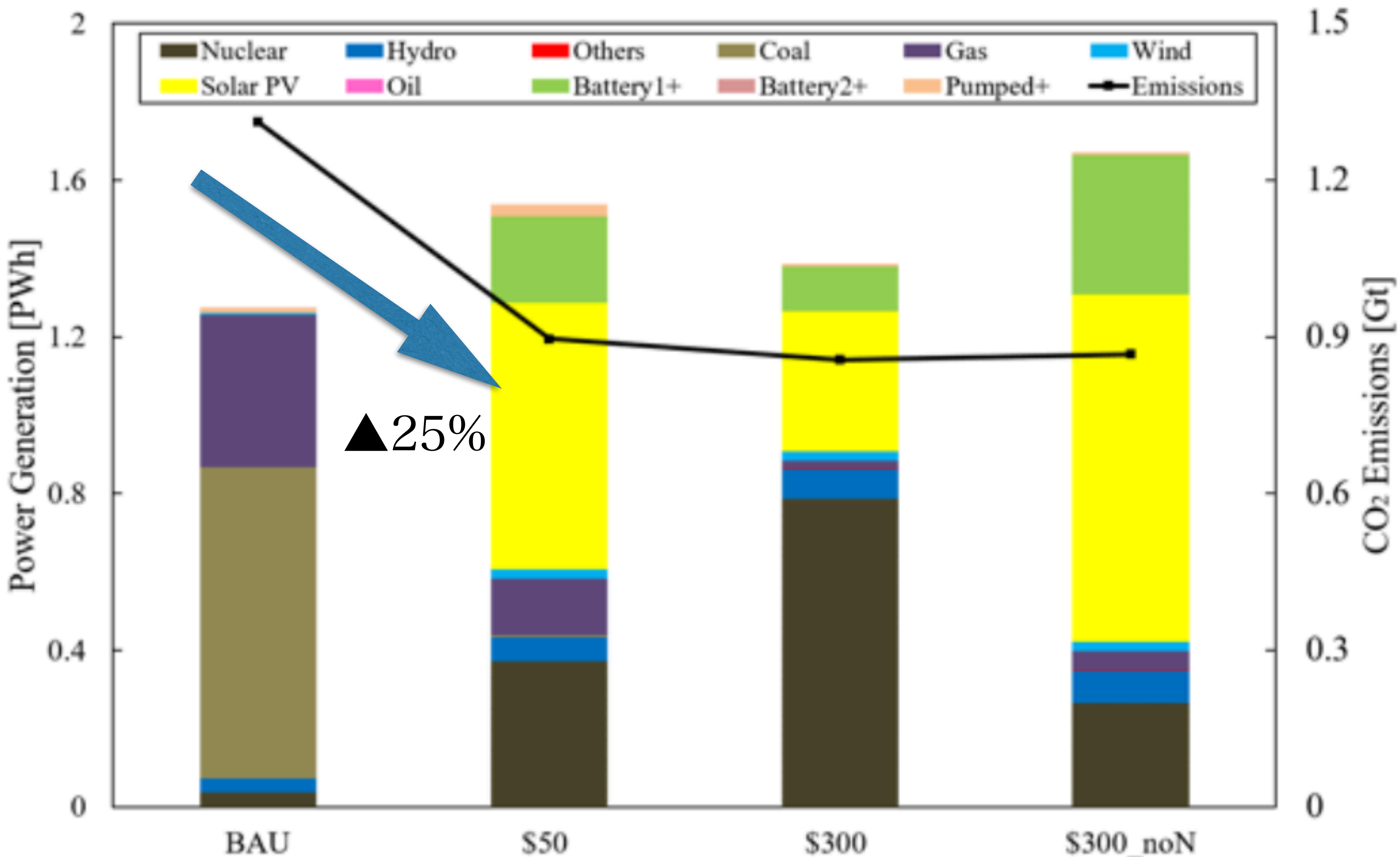

Fig. 9. Power generation mix and CO_2 emissions in 2050.

An Example of Power Generation at any T/D/M/Y

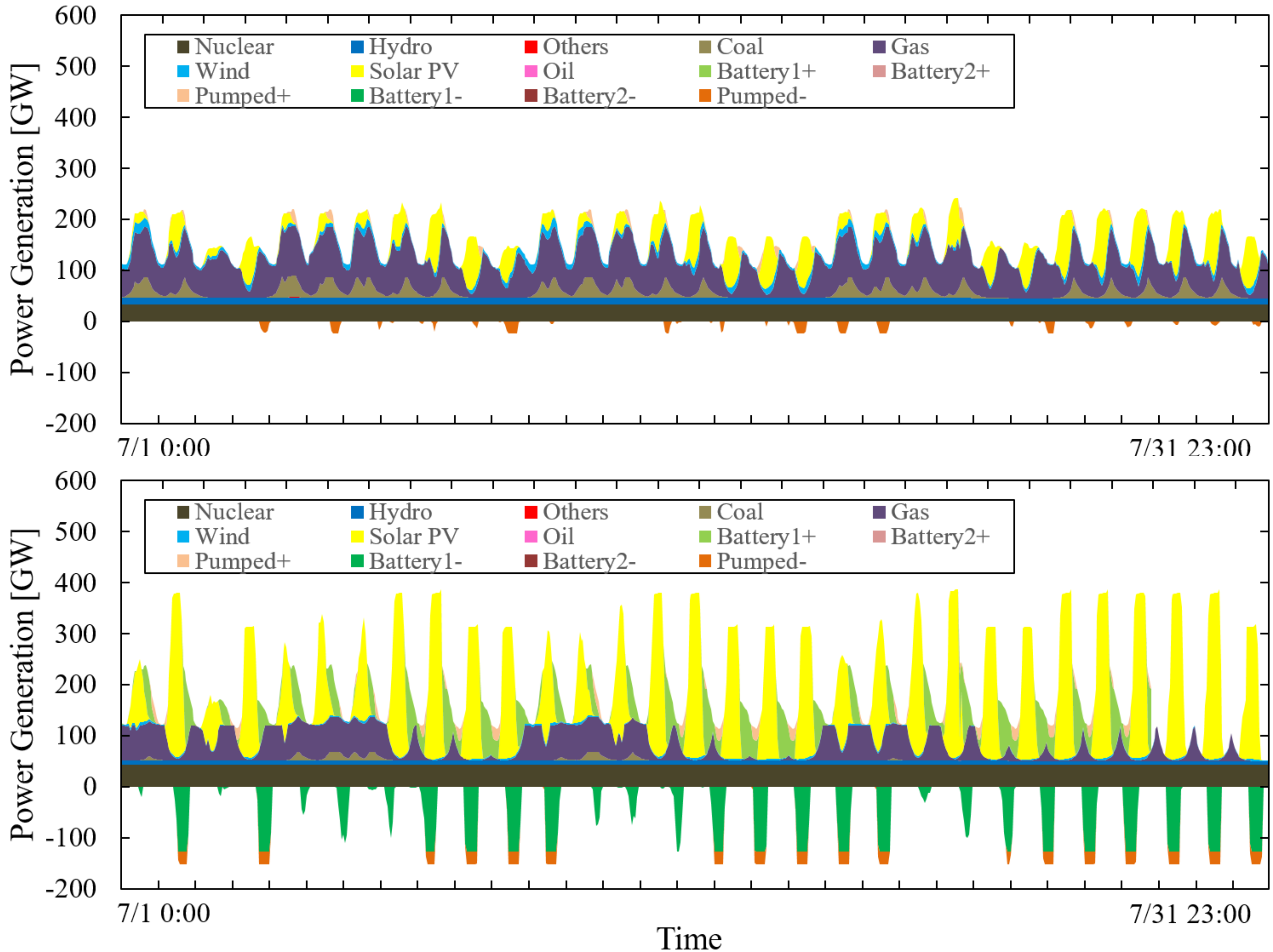

Fig. 10. Power Generation (above: in 2050 ($50), below: in July, 2050 ($300))

GDP growth

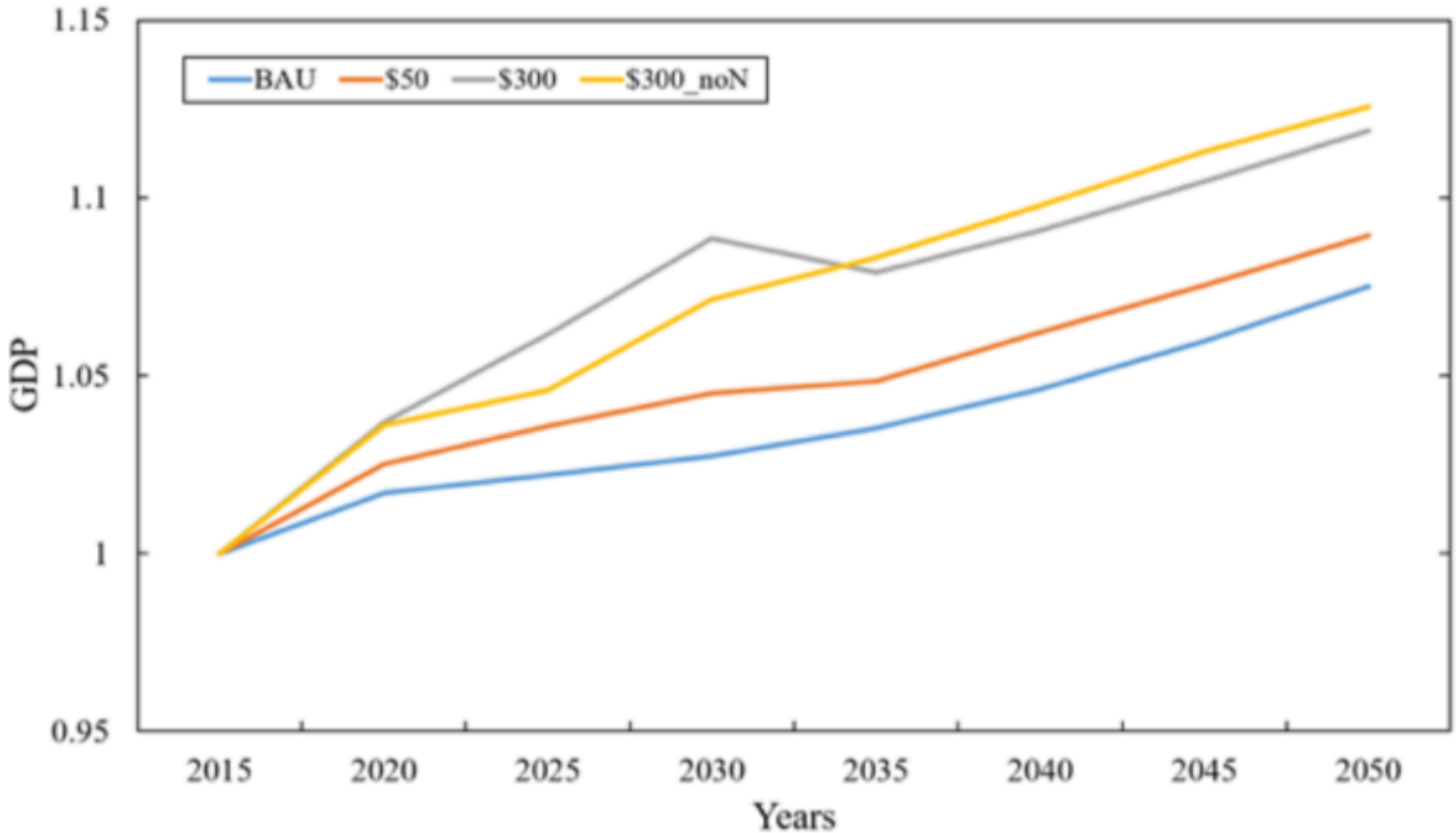

Fig. 11. GDP growth (standardized by value in 2015).

Summary and Future Works

Summary

DMSEE model suggests that…

- Gas-fired and Nuclear power are fundamental in Japan.
- restart and new construction of nuclear power plant are hoped.
- investment especially for PV plays important role to reduce CO_2.
- high CO_2 tax contributes increase of GDP, while utility of consumptions declines, by investment mainly for renewables.

Future Works

I am …

- increasing the number of BU sectors, such as other energy sectors and material sectors in order to consider electrification technologies.
- introducing new energy-saving technology, such as CCS and EV.

Thank you for your attention!