PCCC-8

Session 5C - Heat Pumps & Thermal Integration
Wednesday, Sep 17, 2025, 15:50 - 17:30
Track 3 Stockholm & Rome Stream C

Profitability analysis of flexible operation of thermal power with CO_2 capture in future electricity market

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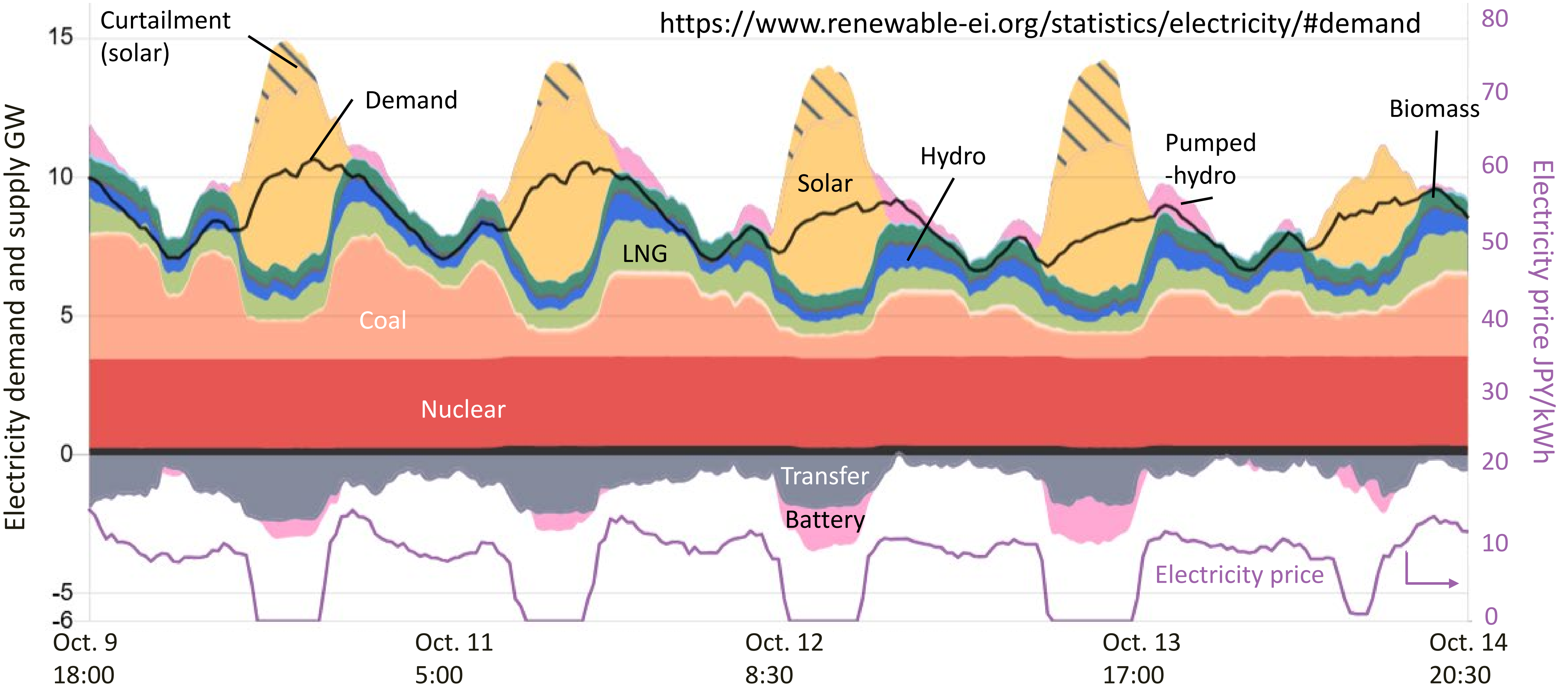
Power generation and electricity prices with increased VRE

Electricity supply and demand and electricity price chart in Kyushu area in Japan (October 9–14, 2024)



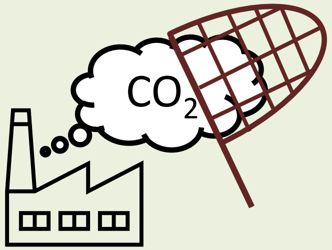
Increasing variable renewable energy (VRE) ⇒flexible operation of LNG and coal and fluctuation of electricity price

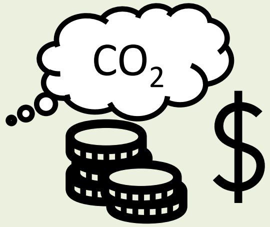
Necessity of profitability analyses

What situation makes CCS economically viable?

Requirement 1

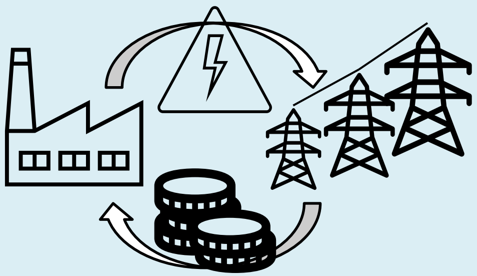
CO_2 avoided cost [USD/t-CO_2] < **Carbon prices [USD/t-CO_2]**





Requirement 2

Net present value or annual profits [USD/year] > 0



Comparison of CO_2 avoided cost and profitability

	CO_2 avoided cost [USD/t-CO_2]	**Profitability (i.e., net present value or annual profits) [USD/year]**
Popularity of the indicator	High	Low
Assumption of capacity factor of plant	Fixed (and often high (≥85%))	Calculated based on electricity market
Does electricity price affect the result?	No	Yes

Given flexible operation of thermal power plant and fluctuation of electricity price, profitability evaluation is also important.

Research purpose and methodology

Purpose of presentation

Profitability evaluation for thermal power plants with CCS in electricity market via mathematical model, aiming at

- sensitivity analysis of key external factors (e.g., electricity price, fuel price, capacity factor)
- validation of a novel process (power to heat PCC)

Methodology: ①National-level scenario analysis→②Plant-level profitability assessment

①NE_Japan model

Objective function	Energy system costs in Japan
Decision variables	Installed capacity of power sources, generated power, etc.
Constraints	Electricity balances, net-zero in 2050, CO_2 storage potential, etc.

Output：Electricity prices (8760 h/year), Marginal abatement cost (=Carbon price)

②Single plant model

NGCC: Natural gas combined cycle

Objective function	Annual operation profit for an NGCC plant (with CCS)
Decision variables	Commitment status (i.e., on or off) and fractional load
Constraints	Minimum load, ramp up/down rate, etc.

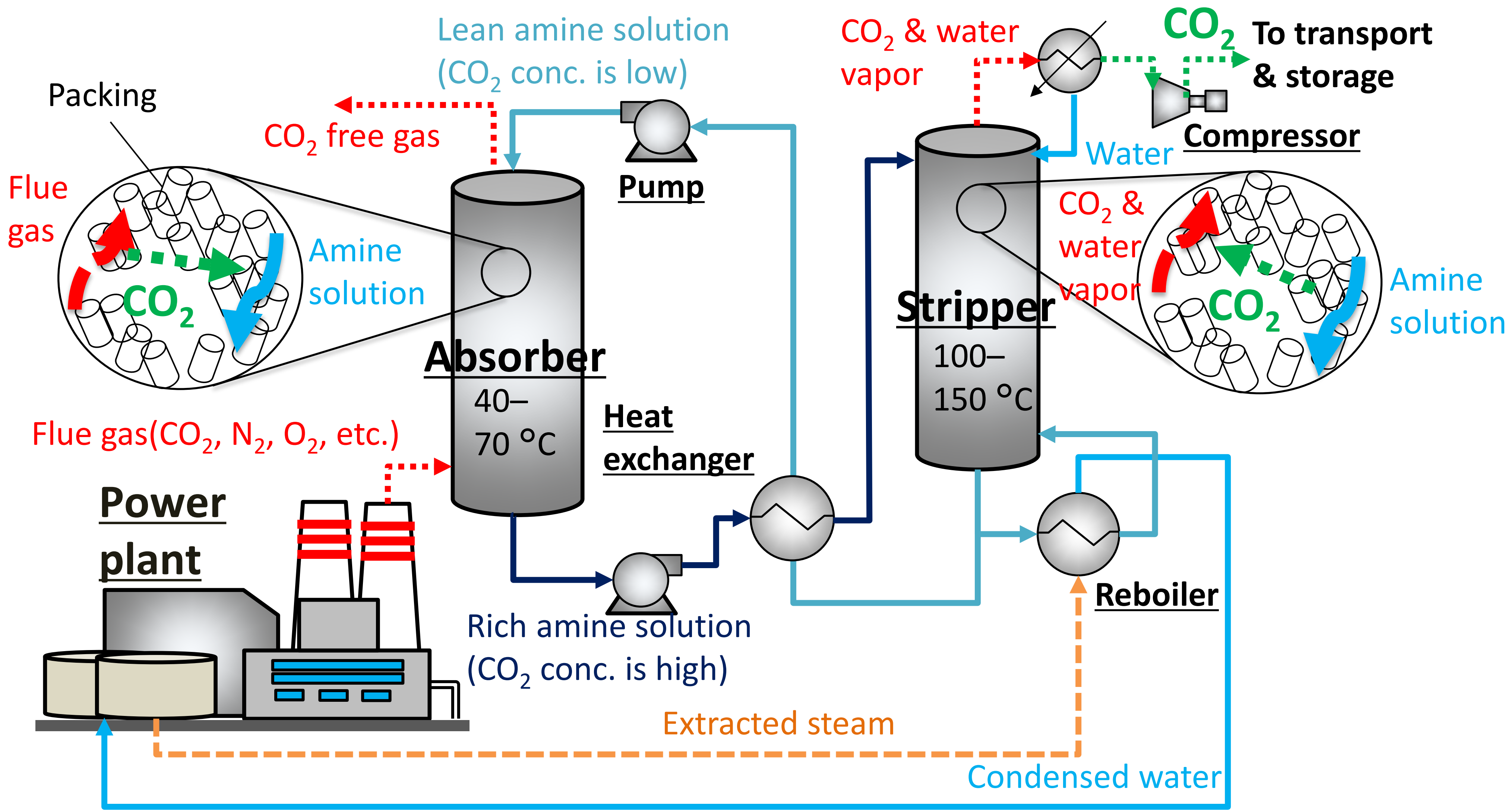
Output: Annual operation profit

CAPEX: Capital expenditure
OPEX: Operational expense

Evaluation index: Annual profits ⇐ Annual CAPEX and fixed OPEX

Conventional amine-based PCC

PCC: Post combustion CO_2 capture

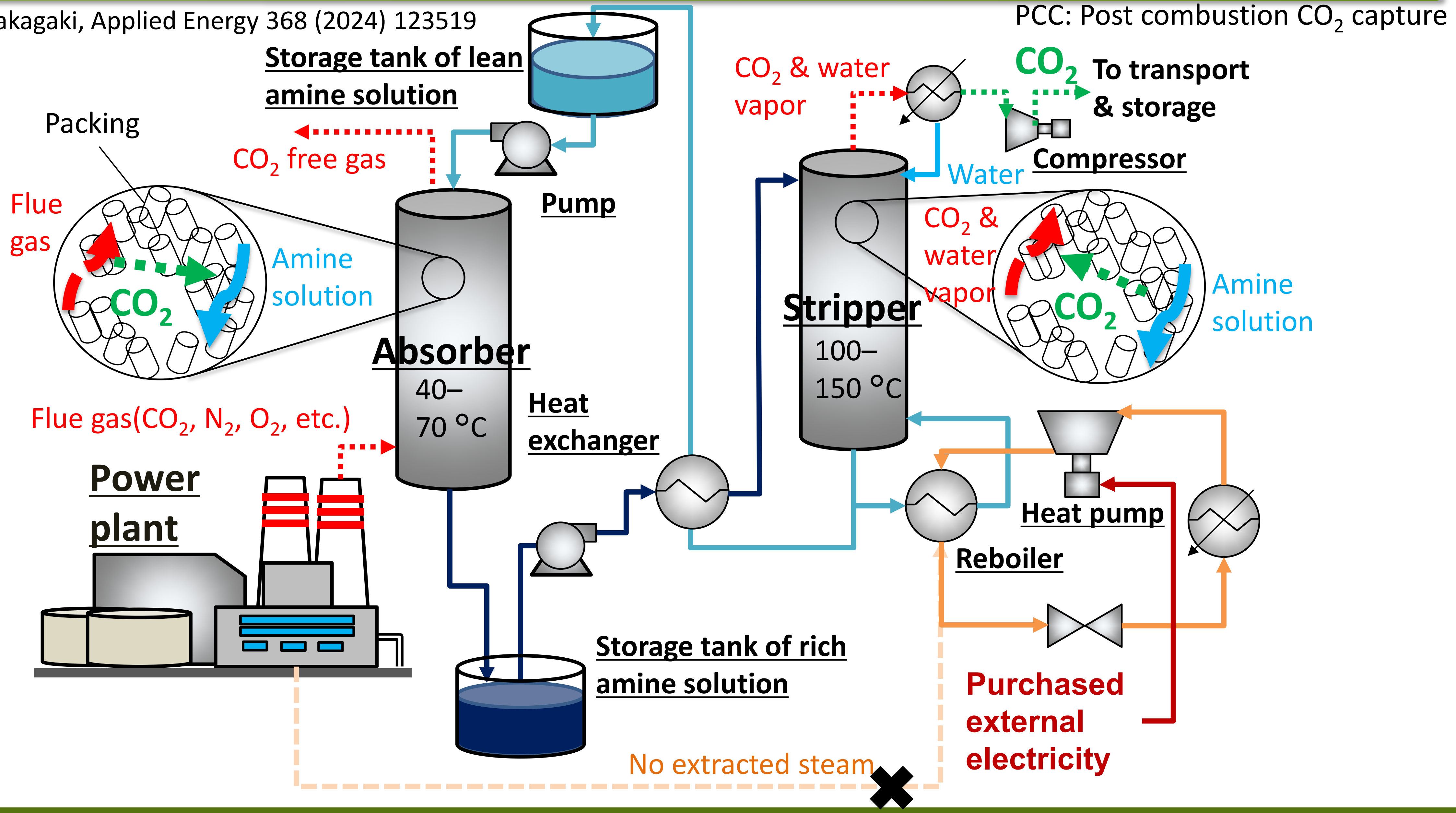


Steam extraction ⇒ Power generation↘ ⇒ Revenue↘

Power to heat (P2H) amine-based PCC*

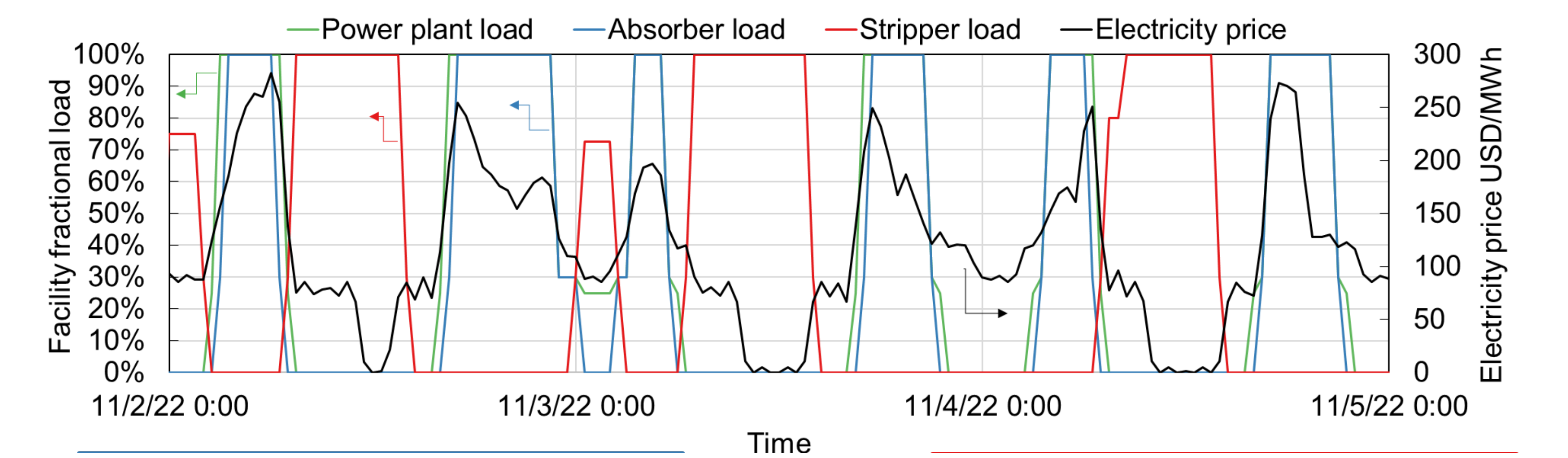
*Isogai and Nakagaki, Applied Energy 368 (2024) 123519

PCC: Post combustion CO_2 capture



Operation of P2H amine-based PCC

*Isogai and Nakagaki, Applied Energy 368 (2024) 123519



Applied Energy 368 (2024) 123519

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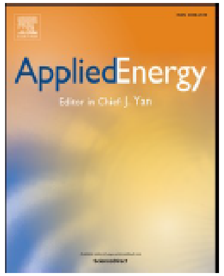

Power-to-heat amine-based post-combustion CO_2 capture system with solvent storage utilizing fluctuating electricity prices

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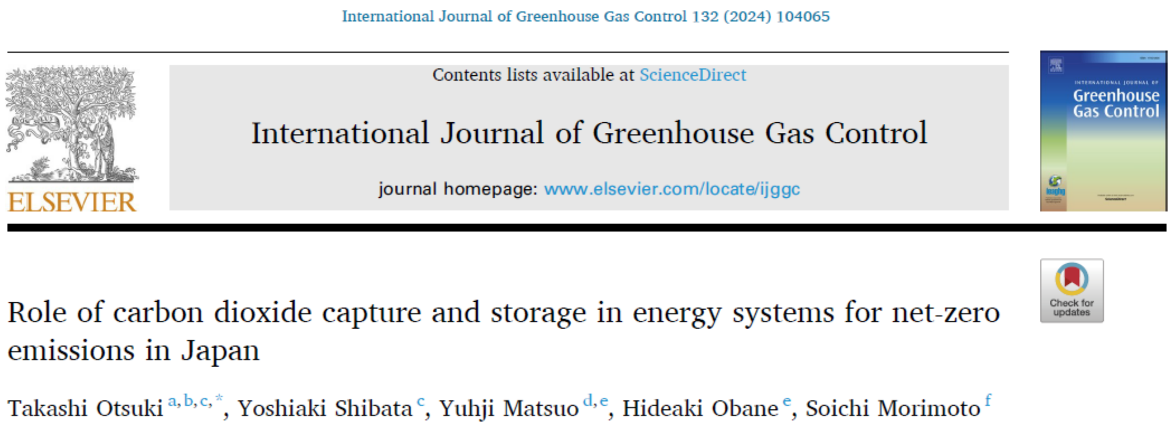
Environmental Research Centre, Waseda University, 1011 Nishitomida, Honjo-shi, Saitama 367-0035, Japan

①NE_Japan model: Overview


International Journal of Greenhouse Gas Control 132 (2024) 104065

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International Journal of Greenhouse Gas Control

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Role of carbon dioxide capture and storage in energy systems for net-zero emissions in Japan

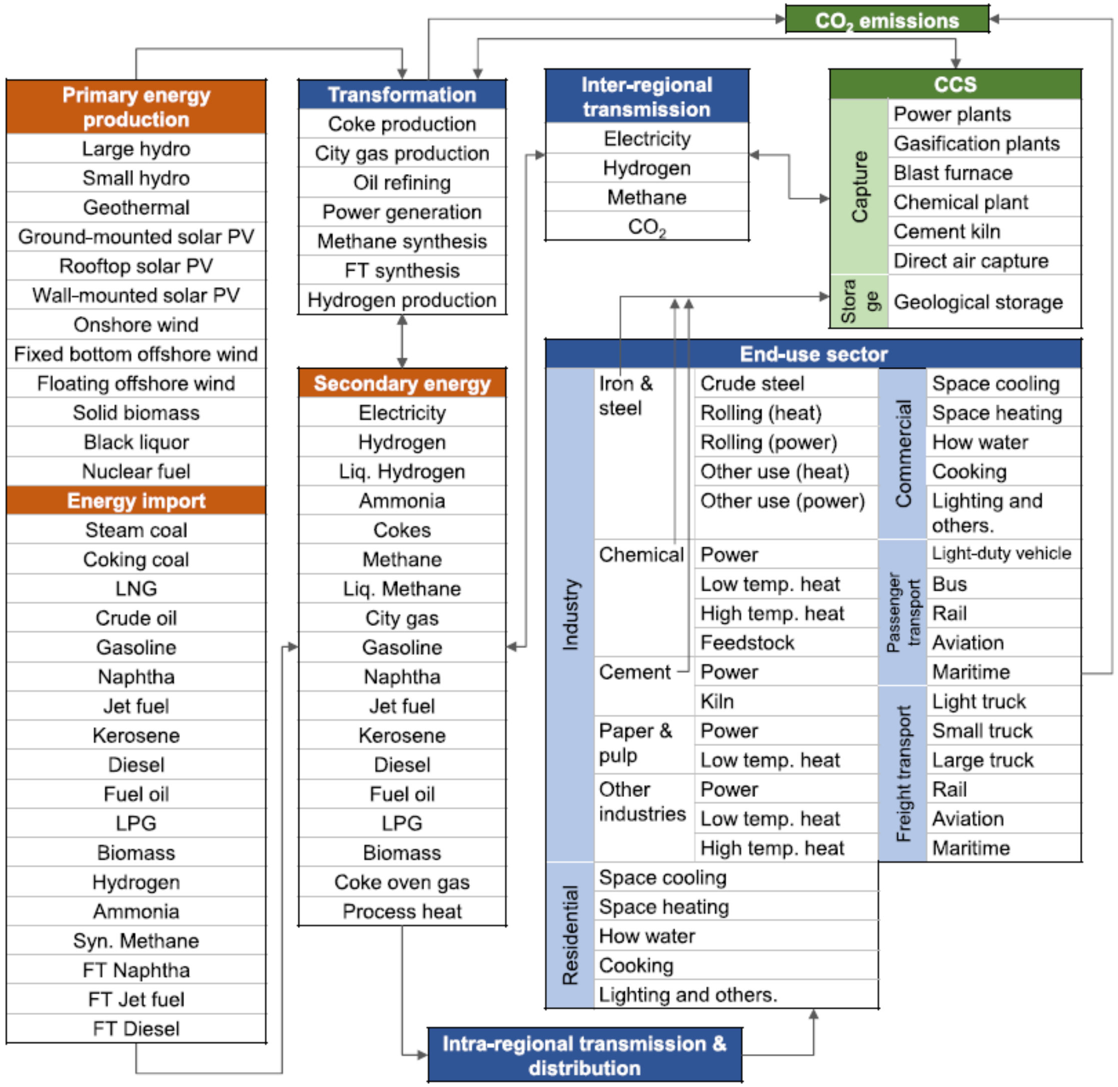
Takashi Otsuki[a,b,c,*], Yoshiaki Shibata[c], Yuhji Matsuo[d,e], Hideaki Obane[e], Soichi Morimoto[f]

- Bottom-up model minimizing the discounted total system cost
- Optimization solver: FICO's Xpress
- Analysis period: 2015–2080*
- Five areas (Hokkaido, Tohoku, Kanto, West Japan, Kyushu)
- Long-distance transmission capacity
- CO_2 storage potentials: Table below

Year	2030	2040	2050
Potential Mt/y	0	66.6	200

*Supply and demand in 2015, 20, 30, 40, 50, 65, and 80 years are calculated as representative points in time

Energy system modelled in NE_Japan model



Otsuki et al., International Journal of Greenhouse Gas Control 132 (2024) 104065

Graduate School of Creative Science and Engineering, Waseda University

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①NE_Japan model: Main assumptions

- Based on the study by Otsuki et al.[*1]
- Update of specification and cost for CO_2 capture system based on recent reports[*2] (Tables below)

*1: Otsuki et al., International Journal of Greenhouse Gas Control 132 (2024) 104065

*2: Rochelle et al., International Journal of Greenhouse Gas Control 132 (2024) 104040

Main parameters of the CO_2 capture technology

		Pre-combustion CO_2 capture	Post-combustion CO_2 capture	Direct air capture			
	Units	2020–2050	2020–2050	2020	2030	2040	2050
Decrease in power generation due to steam extraction	kWh/t-CO_2	-	249	-	-	-	-
Power consumptions	kWh/t-CO_2	288	37	1535	1458	1385	1316
Variable operating costs for consumables	JPY/t-CO_2	-	659	6656	6656	6656	6656
Plant lifetime	Year	40	40	30	30	30	30
CO_2 capture rate	-	90%	90%	-	-	-	-

Assumptions on CAPEX and global installed capacity of CO_2 capture technology

		Units	2020	2030	2040	2050
Pre-combustion CO_2 capture	CAPEX	JPY/(t-CO_2/year)	48842	42503	41127	39796
	Installed capacity	Million t-CO_2/year	36.79	870	1840	3890
Post-combustion CO_2 capture	CAPEX	JPY/(t-CO_2/year)	24704	19869	19398	18938
	Installed capacity	Million t-CO_2/year	3.2	455	785	1355
Direct air capture	CAPEX	JPY/(t-CO_2/year)	106778	26756	22307	18598
	Installed capacity	Million t-CO_2/year	0.01	90	298	985

Calculation methods are detailed in Isogai et al., Journal of Japan Society of Energy and Resources, Vol. 46, No. 4 (2025).

②Single plant model: Objective function

Constructed using General Algebraic Modelling (GAMS) optimization software with reference to previous research[*1]

Objective function

$$\Pi_{\mathrm{o}} = \sum_{\forall t}\left(P_t^{\mathrm{e,f}} x_t^{\mathrm{net}} \tau - C_t^{\mathrm{SUp}} - C_t^{\mathrm{SDown}} - C_t^{\mathrm{fuel}} - C_t^{\mathrm{CO_2}} - C_t^{\mathrm{p,O\&M}} - C_t^{\mathrm{sol}} - C_t^{\mathrm{cau}} - C_t^{\mathrm{waste}} - C_t^{\mathrm{capwat}} - C_t^{\mathrm{T\&S}} - C_t^{\mathrm{capramp}}\right)$$

Each symbol of the objective function

Symbol	Description	Note
Π_{o}	Annual operation profits	Objective variable
$P_t^{\mathrm{e,f}}$	Pseudo-forecasted electricity price	Linear interpolation of outlier and smoothing via a Savitzky–Golay polynomial filter
x_t^{net}	Net power output	cf. Appendix of our study[*2]
τ	Time step	Assumed to be 1 hour
C_t^{SUp}	Startup cost	18239.9 USD/startup, cf. Appendix of our study[*2]
C_t^{SDown}	Shutdown cost	0 USD/shutdown, cf. Appendix of our study[*2]
C_t^{fuel}	Fuel cost	Mentioned later, cf. Appendix of our study[*2]
$C_t^{\mathrm{CO_2}}$	CO_2 emission cost	Equal to the marginal abatement cost calculated by NE_Japan model
$C_t^{\mathrm{p,O\&M}}$	Variable operating cost for thermal plant	Excluding fuel cost, cf. Appendix of our study[*2]
C_t^{sol}	Amine solution cost	7.12 USD/kg-amine, cf. Appendix of our study[*2]
C_t^{cau}	Caustic makeup cost	2.44 USD/kg-NaOH, cf. Appendix of our study[*2]
C_t^{waste}	Reclaimer waste disposal cost	0.436 USD/kg-waste, cf. Appendix of our study[*2]
C_t^{capwat}	Cost for additional water used for CO_2 capture facility	0.233 USD/m^3, cf. Appendix of our study[*2]
$C_t^{\mathrm{T\&S}}$	CO_2 transport and storage cost	29.56 USD/t-CO_2, cf. Appendix of our study[*2]
C_t^{capramp}	Cost for ramping CO_2 capture facilities	Costs for additional generation losses due to load changes in the capture facilities

*1: Cohen et al., International Journal of Greenhouse Gas Control, 8 (2012), pp.180–195, *2: Isogai and Nakagaki, Applied Energy 368 (2024) 123519

②Single plant model: Main assumptions

- Power plant: NGCC with J class (1600 °C) gas turbine
- PCC: Typical amine-based PCC or P2H-PCC

Power plant specifications without PCC

	Units	Value
Rated power output	MW	982.1
CO_2 emissions intensity	t-CO_2/MWh	0.314
Plant efficiency	-	62.6%
Plant heat rate	MMBtu/MWh	5.541

Specifications of amine-based PCC

	Units	Value
Maximum CO_2 capture rate	%	90
Specific reboiler duty	GJ/t-CO_2	2.5
Reduction in power output due to steam extraction	GJ/t-CO_2	0.897*
COP of heat pump (w/ P2H-PCC)	-	3.0

*Calculated using Aspen Plus®; COP: Coefficient of performance

Decision variables

	Power plant	Absorber	Stripper
Commit-ment status	u^{p}	u^{a}	u^{s}
Fractional load	y^{p}	y^{a}	y^{s}

u=1: on, u=0: off

Major constraints

	w/o PCC	w/ PCC	w/ P2H-PCC
Minimum y^{p}	25%	25%	25%
Maximum capacity factor	85%	85%	85%
Ramp rate for $y^{\mathrm{p}}, y^{\mathrm{a}}, y^{\mathrm{s}}$[/h]	100%	100%	100%
Minimum $y^{\mathrm{a}}, y^{\mathrm{s}}$	30%	30%	30%
Relationship between y^{a} and y^{s}	N/A	$y^{\mathrm{a}} = y^{\mathrm{s}}$	N/A
Tank size	N/A	N/A	$0 \leq l_t^{\mathrm{l}} \leq \overline{l^{\mathrm{l}}}$ $\overline{l^{\mathrm{l}}} = l_t^{\mathrm{l}}@15:00$

Note

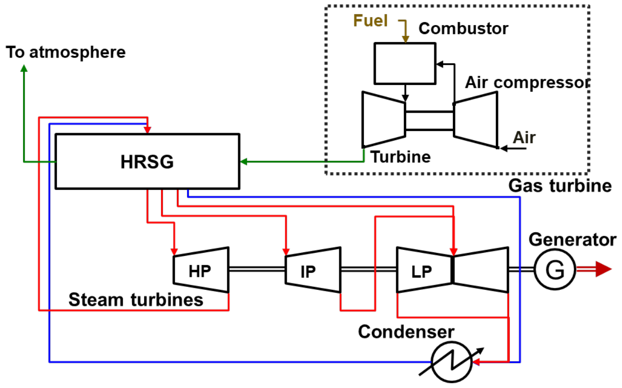
When purchasing electricity in the P2H-PCC case, basic charge of 423.39 JPY/month per kW and metered charge of 91.00 JPY/kWh*1 were considered as a wheeling charge; thus, the model is calculated as a mixed integer quadratic programming problem (MIQP). Otherwise, mixed integer linear programming problem (MILP).

*1: https://www.tepco.co.jp/pg/consignment/notification/pdf/takusou_yakkan20241001.pdf

Calculation methods are detailed in Isogai and Nakagaki, Applied Energy 368 (2024) 123519.

②Single plant model: Target of evaluation

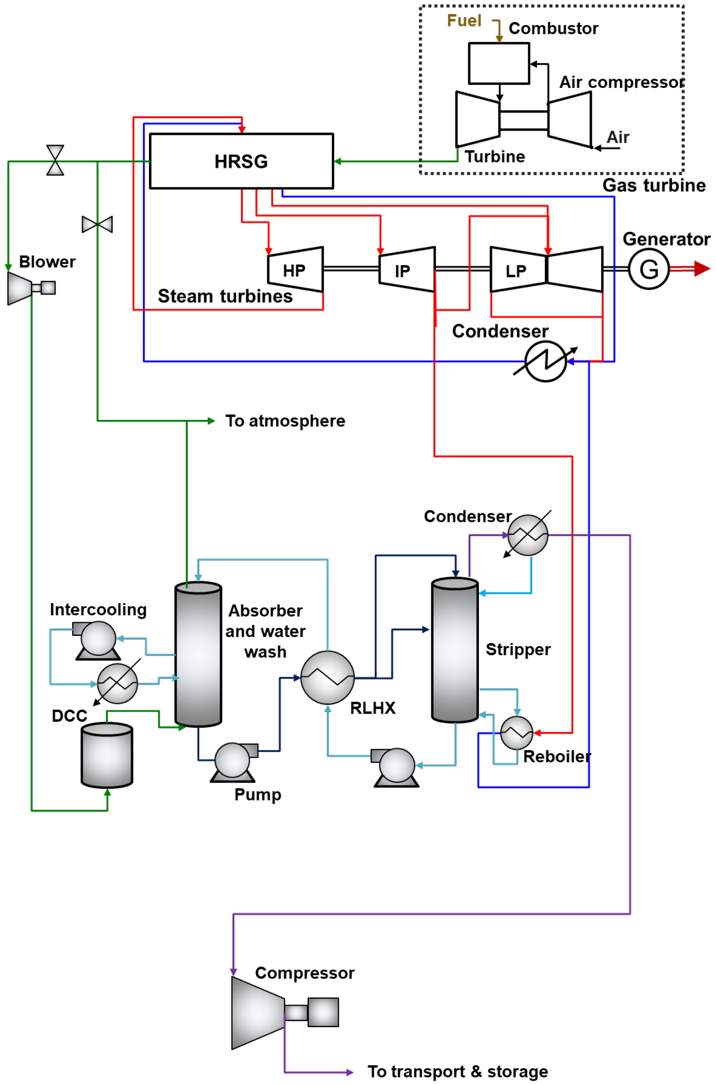
w/o PCC (MILP)



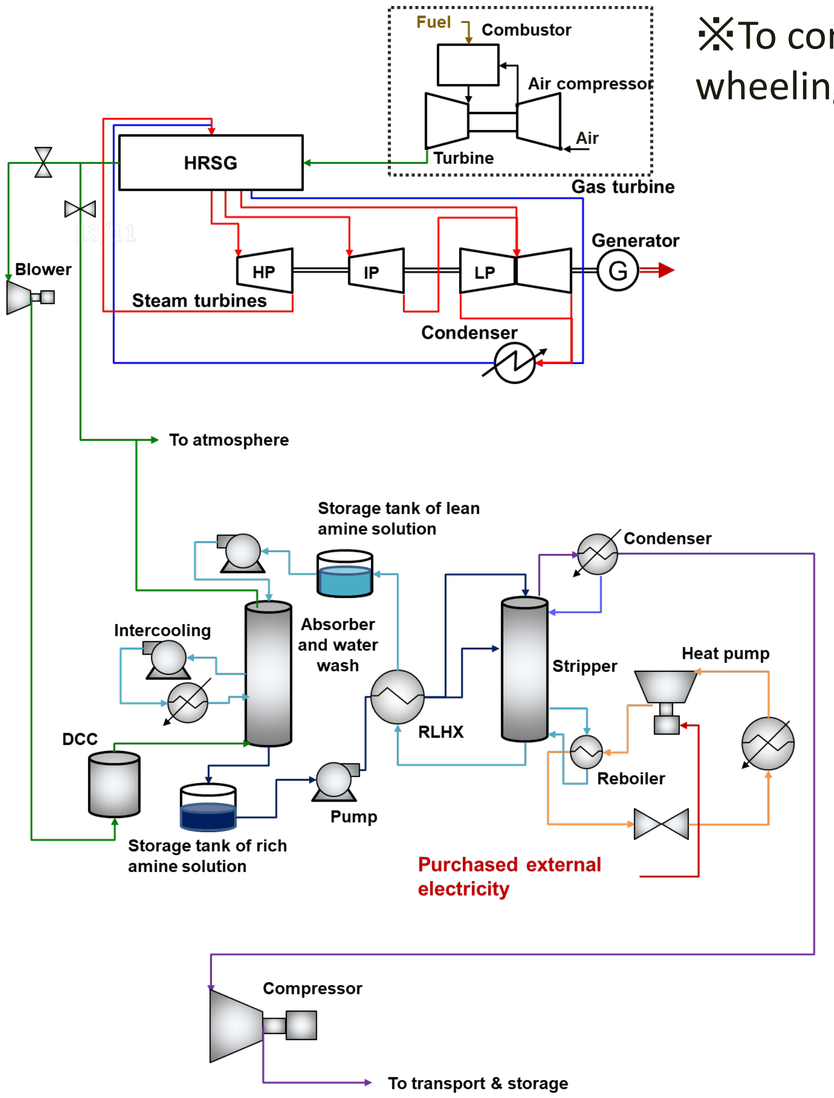
MILP: mixed integer linear programming problem
MIQP: mixed integer quadratic programming problem

Arranged from Isogai and Nakagaki, Applied Energy 368 (2024) 123519

w/ PCC (MILP)



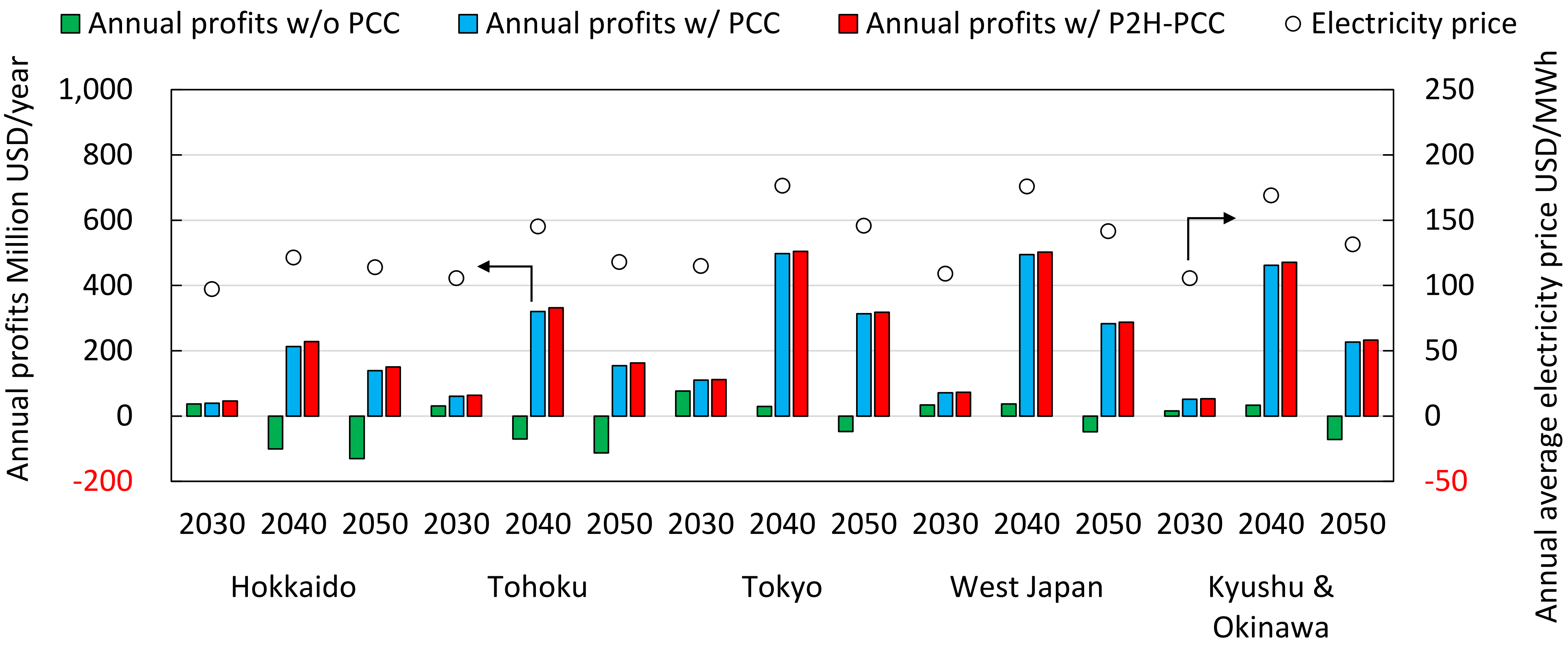
w/ P2H-PCC (MIQP)※



※To consider a wheeling charge

Rich amine solution — Lean amine solution — CO_2 — Flue gas — Water — Steam — Air — Fuel — Refrigerant — Electricity

Results: Annual profits

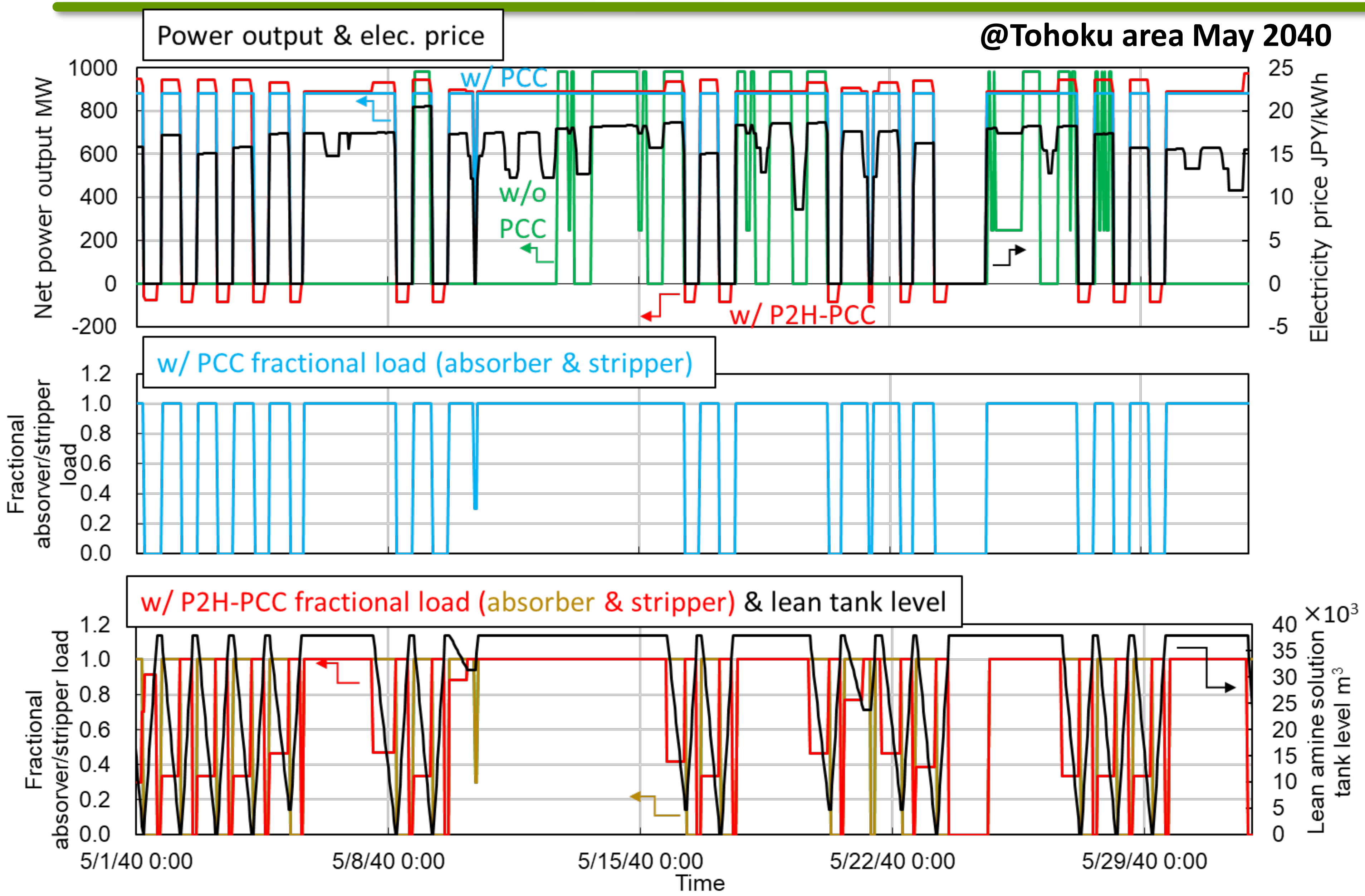


- w/o PCC: Annual profits ⤵ ⇒ Function of carbon price ◎
- w/PCC -> w/ P2H-PCC: Annual profits 1–17%⤴ ⇒ Validating effects of P2H

Marginal abatement cost (=carbon price) calculated via NE_Japan model

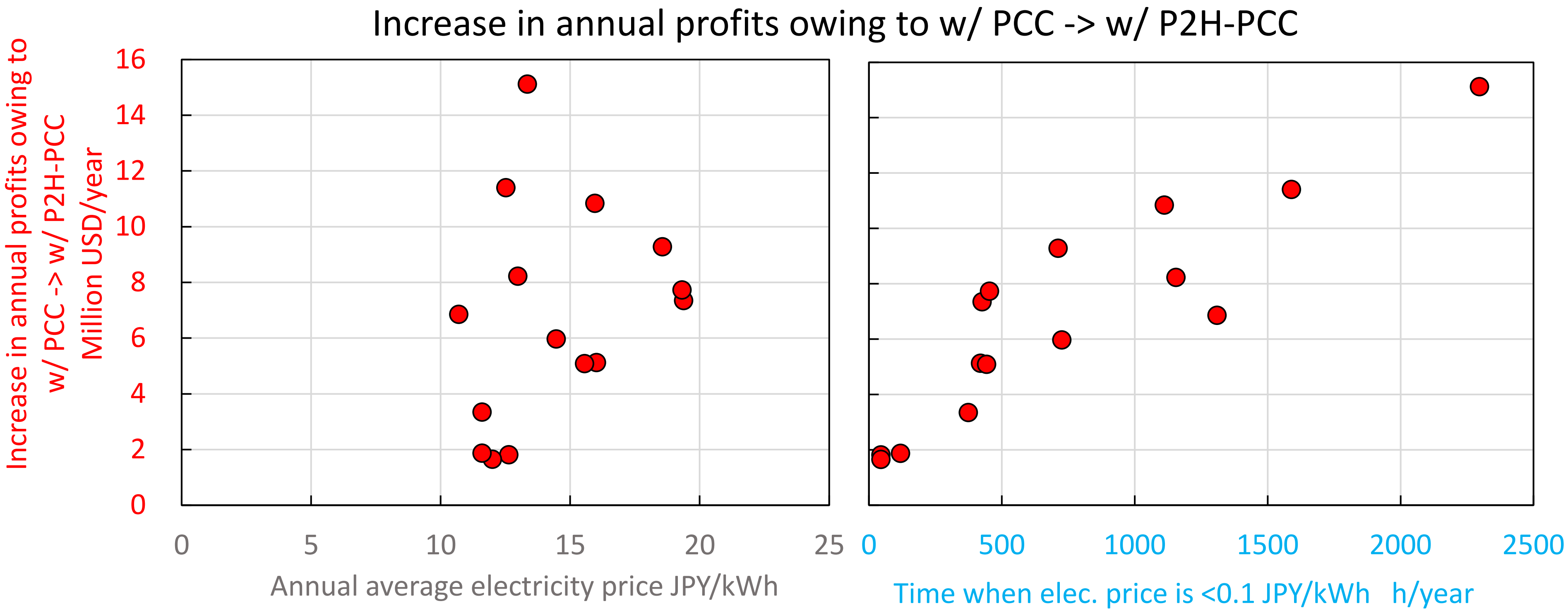
Year	2030	2040	2050
Marginal abatement cost JPY/t-CO_2	16279	44727	50962

Ex. Operation behavior in single plant model



- w/o PCC: hardly operational (∵ carbon tax > profit from electricity sales)
- P2H-PCC: timing shift of CO_2 stripping ⇒ power generation ⤴ when electricity prices volatile
- w/ PCC and w/ P2H-PCC: full load of PCC facility reduces the output by -10% ⇒efficiency improvement of PCC operation only has a limited effect on revenues.

Impacts of electricity prices on P2H's profitability



Correlation: period of extremely cheap electricity price⤴ ⇒ Increase in annual profits⤴

⇩

In the future, period of extremely cheap electricity price⤴(∵ VRE expansion)

∴P2H-PCC is a proper CO_2 capture system in harmony with VRE expansion.

Principal assumptions of sensitivity analyses

Principal assumptions in each scenario

	Units	Value			
Scenario name		Base	High fuel price	Low capacity factor (CF)	Low specific reboiler duty (SRD)
Net power output of NGCC	MW	981.1			
Specific reboiler duty (SRD) of amine-based PCC	GJ/t-CO_2	2.5	2.5	2.5	1.25
Fuel price (2030/2040/2050)	USD/MMBtu	6.2/5.8/5.3	9.4/8.7/8.0	6.2/5.8/5.3	6.2/5.8/5.3
Maximum carbon capture rate	%	90			
Maximum capacity factor of NGCC	%	85	85	42.5	85
MAC	USD/t-CO_2	See table below			

Fuel prices are based on actual import prices in the Ministry of Finance Trade Statistics*1 and price trends in the IEA*2.

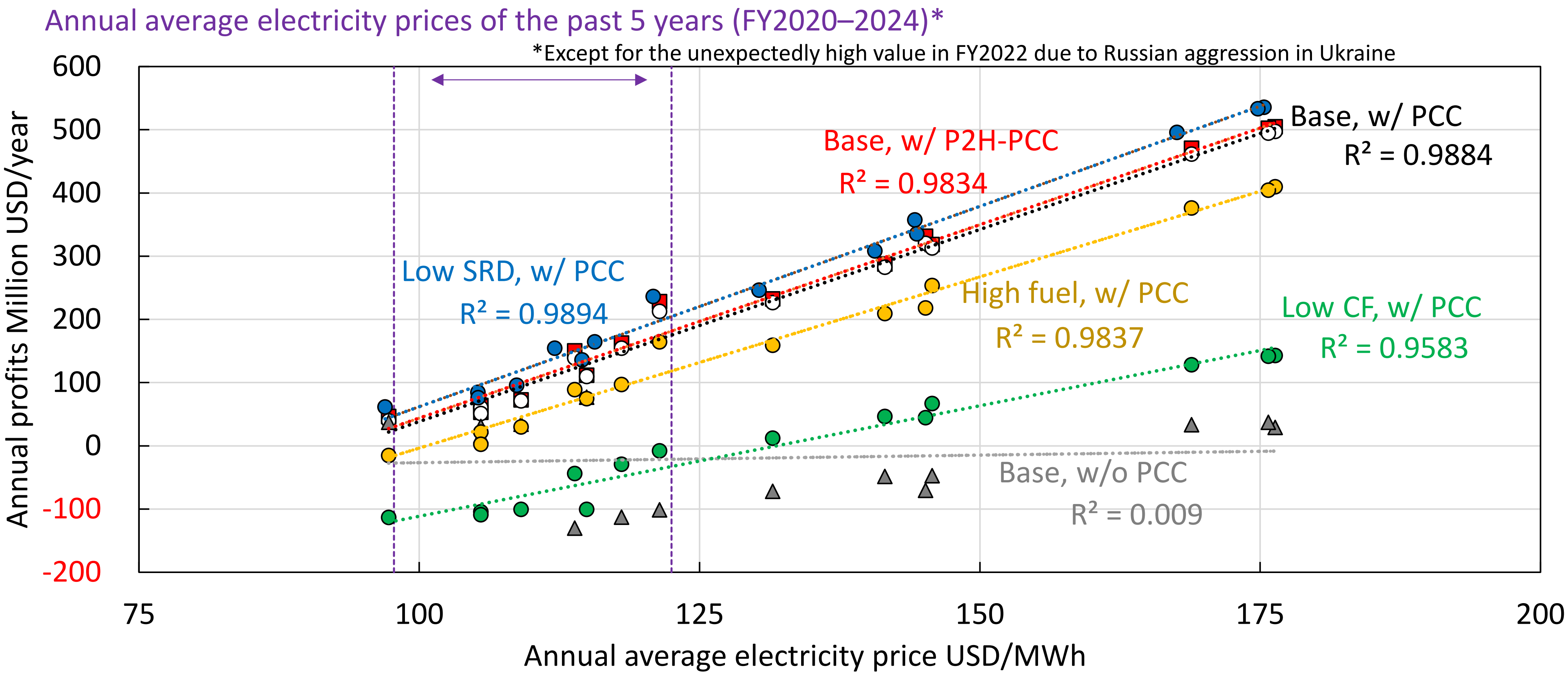
*1: https://www.customs.go.jp/toukei/info/ (Last access: 2024.11.19)

*2: International Energy Agency; World Energy Outlook 2022, (2022), p.110.

Marginal abatement cost (=carbon price) calculated by NE_Japan model

Year		2030	2040	2050
Marginal abatement cost USD/t-CO_2	Base & low CF scenario	148.16	407.05	463.80
	High fuel price scenario	157.30	405.87	475.95
	Low SRD scenario	145.99	405.25	474.38

Results of sensitivity analyses



- Average annual electricity price is the most dominant factor for annual profit (∵R^2>0.95).
- Thermal power with PCC is economically feasible depending on given conditions.
- Profit is increased by reduction in SRD and adoption of P2H, but these impacts are limited.
- Low CF will significantly reduce profit.

Conclusions and key takeaways

This study evaluated the profitability of thermal power plants with post-combustion CO_2 capture in future electricity market via mathematical modelling and calculation of CAPEX and fixed OPEX. The key takeaways are:

- External factors (electricity price, fuel price, capacity factors, etc.) dominantly affects annual profits. Depending on these factors, thermal power plants with PCC is possibly, economically feasible even with current PCC specifications.
- Profitability evaluation should be conducted more and more in accordance with various scenarios.
- Carbon price successfully motivates CCS implementation.
- w/PCC -> w/ P2H-PCC: Annual profits 1–17% ⤴
- P2H-PCC is in harmony with future VRE expansion.

Acknowledgement

This study was supported from the Sumitomo Foundation (FY2024 Environment Research Grant No.2442006).

Appendix.

CAPEX and fixed OPEX

CAPEX of main component

Component	Reference
NGCC	Power generation cost verification WG[*1]
Capture facility	Estimation of DOE's FEED project[*2]
Heat pump	200 €/kW_{th}[*3]

Fixed OPEX

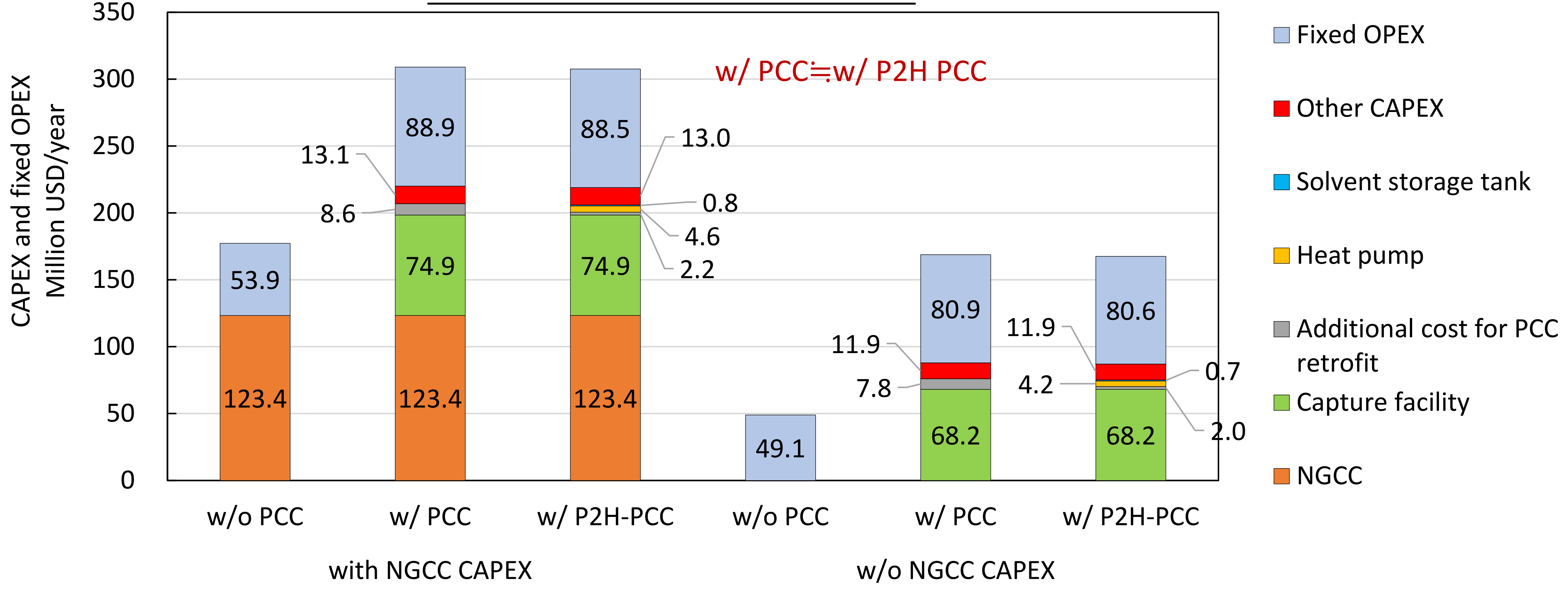
Calculated maintenance and other costs using total plant cost and then adding labour costs.

*1:https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/2021/data/08_06.pdf

*2: Rochelle et al., International Journal of Greenhouse Gas Control 132 (2024) 104040

*3: Meyers et al., Solar Energy 173 (2018) 893–904

Calculated CAPEX and fixed OPEX

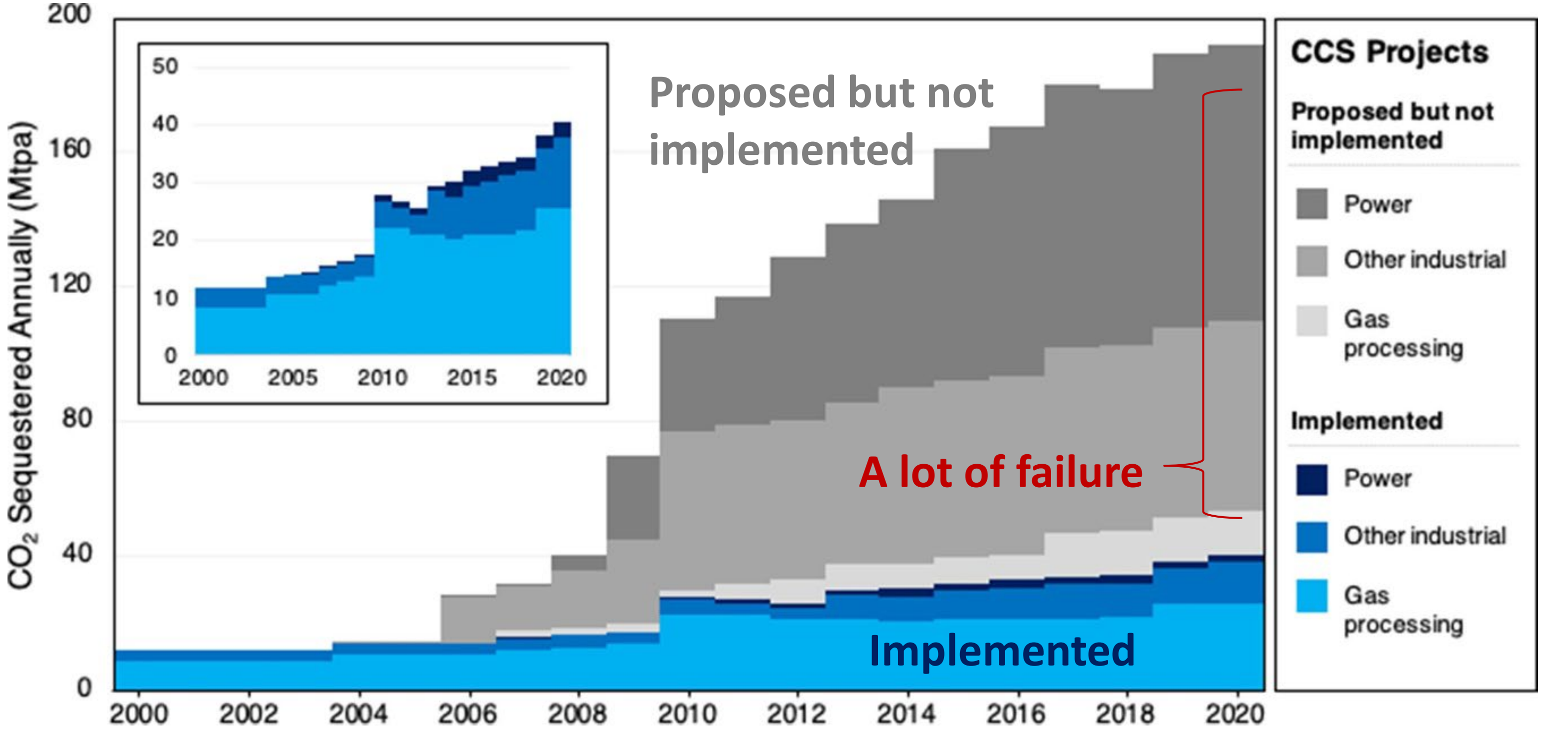


Calculation conditions

- Lifetime: 40 years
- Interest rate: 8%.
- Base year: 2021
- Assumed area: Japan

Failure of CCUS projects mainly due to cost

Global proposed vs. implemented annual CO_2 sequestration (main figure), and global implemented annual CO_2 sequestration by type (inset)*



*Abdulla et al., Environ. Res. Lett. 16 (2021) 014036

Key factors for project outcome*

1. Capital cost
2. Technology readiness level
3. Credibility of project revenues

‘Firm’ (or dispatchable) power resources

Review of 40 electricity deep decarbonization studies*

*Jenkins et al., Joule 2 (2018) 2487–2510

Authors	Year	Publication	Geographic Scope	Firm Resources Considered (Selected in Lowest CO_2 Cases)
Akashi et al.	2014	Climatic Change	Global	bio, bio CCS, coal, coal CCS, gas, gas CCS, nuc, oil, oil CCS
Amorim et al.	2014	Energy	Portugal	coal, gas, res. hydro (existing), oil, bio
Bibas and Méjean	2014	Climatic Change	Global	bio CCS, coal, coal CCS, gas, gas CCS, nuc, oil
Heuberger et al.	2017	Comp. & Chem. Eng.	UK	coal CCS, gas, gas CCS, nuc
Jacobson et al.	2014	Energy	California	geo, res. hydro (existing)
Sepulveda et al.	2018	Joule	New England, Texas	bio, gas CCS, nuc
:	:	:	:	:

res. hydro: reservoir hydro-power; nuc: nuclear power

20/40 studies: Cost optimization considering ‘firm’ (or dispatchable) resources

➔ All these studies include a substantial share of ‘firm’ resources in their lowest cost scenarios.