March 6, 2024

(The Japanese version: January 24, 2024)

Development of Transition Roadmaps for Net-zero Emissions (2023 Edition)

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Motivation and aim of developing transition roadmaps

- It is necessary to strengthen measures in each sector to achieve the 2℃ and 1.5℃ long-term targets of the Paris Agreement and carbon neutrality early in the second half of the 21st century.
- On the other hand, there is a wide range of transitions that can lead to emission reductions. Even if they are consistent with the global CN, the emission reduction pathways for each industrial sector differ from sector to sector in terms of the life span of existing infrastructure and the difficulty level of emission reduction measures. Uniform emission reductions may increase the cost of measures and make emission reductions more difficult to achieve.
- In general, however, the pathways to consistent emission reductions, including technologies, are not always well understood, and there is a need for quantitative information to make judgments about the appropriateness of investments. Therefore, the NGFS and other organizations are developing emission reduction scenarios using integrated assessment models that allow for quantitative analysis. On the other hand, these models do not provide sufficient information on emission reduction pathways for each sector.
- The Government of Japan has developed transition roadmaps for FY2021-2022 to provide specific transition directions toward achieving carbon neutrality, with an intention to utilize these for transition financing. While the roadmaps provide useful information, these were developed on a sector-by-sector basis, thus, there is a need to improve the accountability in terms of consistency with the overall 2℃ and 1.5℃ emission reduction pathways.
- Therefore, we have developed sectoral transition roadmaps using the bottom-up global assessment model for energy and climate change, the DNE21+, that allows for consistent analysis among countries, regions, and sectors.

Remarks of existing scenarios/pathways that are widely referenced internationally:

- **The ICMA report indicates the issues regarding the consideration of regional and industrial characteristics for the SBTi, TPI, and IEA, which are listed as scientifically based references in the ICMA Basic Guidelines. When formulating the roadmap, it is necessary to select technologies based on the characteristics of Japan, while referring to the above.**
- **In addition, the NGFS scenarios that have been used in the financial industry have estimated values by country and sector, but it is assumed that they will be adjusted on their own when used.**

Remarks of existing scenarios/pathways that are widely referenced internationally:

Organizations	Remarks
IEA	• The IEA presents pathways for emissions from energy use by country/region or by energy sector/industry, so regional and industrial characteristics are taken into account, but no pathways are presented that take into account both (country and industry), simultaneously.
SBTi	• The Absolute Contraction Approach requires the same reduction rate for all actors and does not take into account regional and industry characteristics. • The Sectoral Decarbonization Approach (SDA) shows pathways based on the 2DS and B2DS scenarios in the IEA-ETP, but regional characteristics are not taken into account except for current emissions and production.
TPI	• The sectoral approach used by SBTi is utilized by referring to the IEA-ETP, etc., but does not take into account regional characteristics.
NGFS	• The NGFS scenarios are disaggregated by country and industry, but there are issues with the accuracy of industry (final consumption) estimates, and industry-specific data based on regional characteristics need to be adjusted to reflect the characteristics of each country in detail.

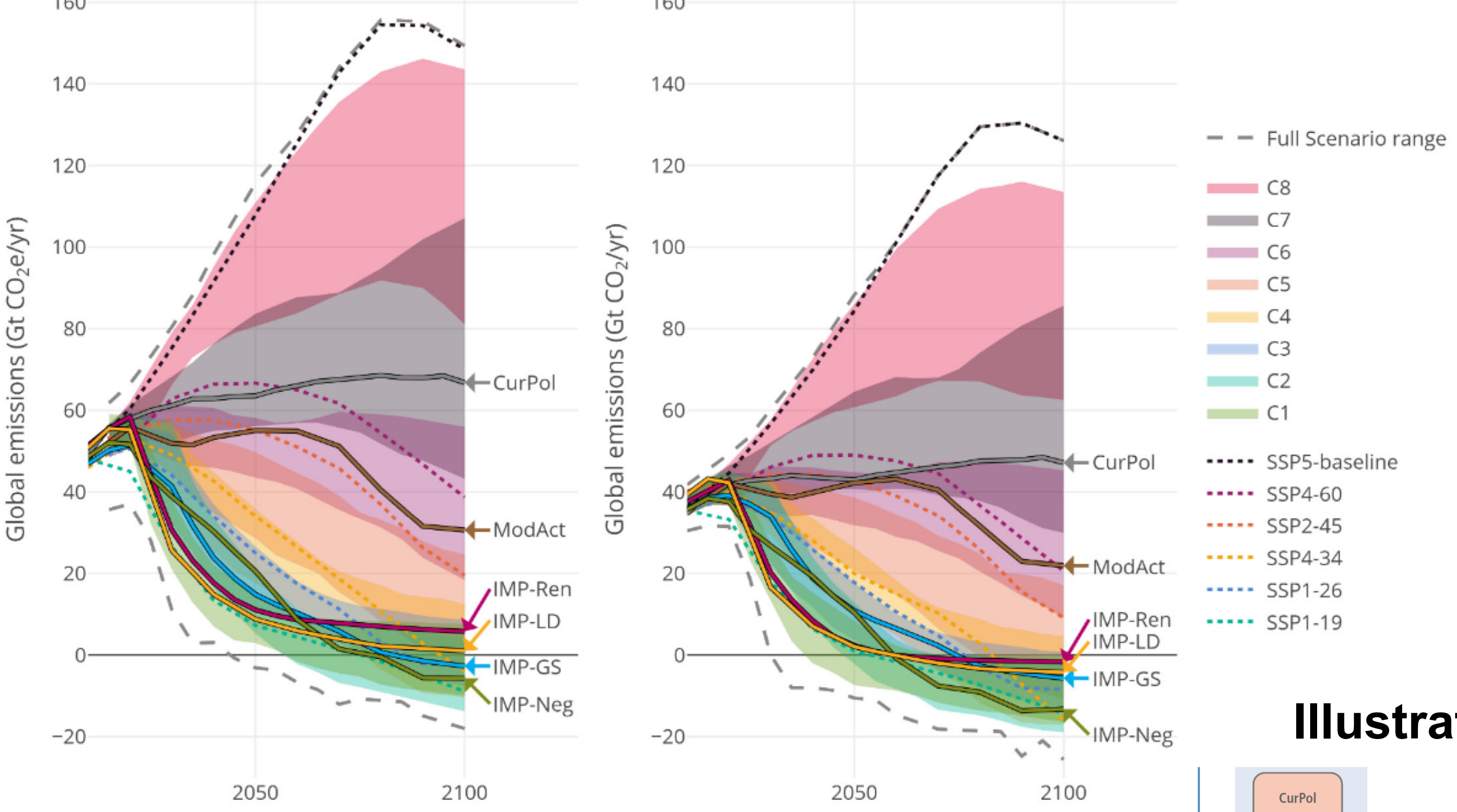
(Source) Based on the ICMA Overview and Recommendations for Sustainable Finance Taxonomies and materials by each organization

1. Examples of Existing Scenarios

IPCC Scenarios

Classification of emissions scenarios and illustrative pathways of the AR6 of IPCC

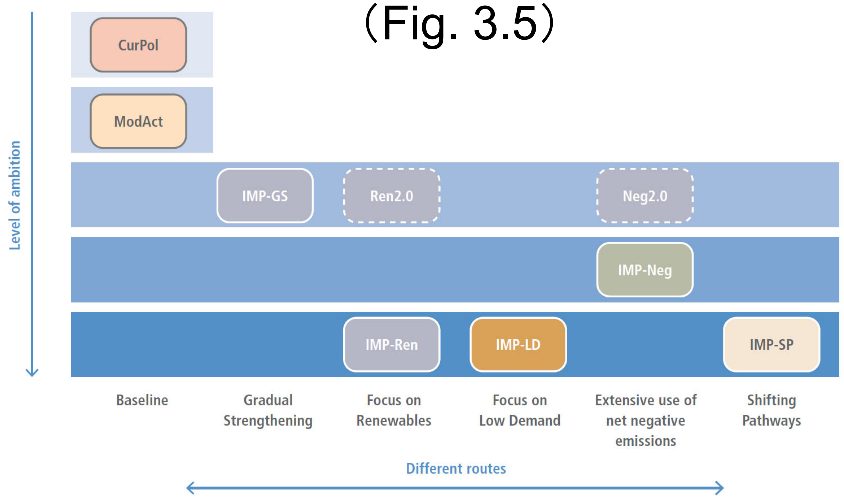
Emission pathways (Fig. 3.10)



C8	＞4℃
C7	4℃
C6	3℃
C5	2.5℃
C4	2℃（＞50%）
C3	2℃（＞67%）
C2	1.5℃-high overshoot
C1	1.5℃-no/limited overshoot

Illustrative Pathways (IPs)

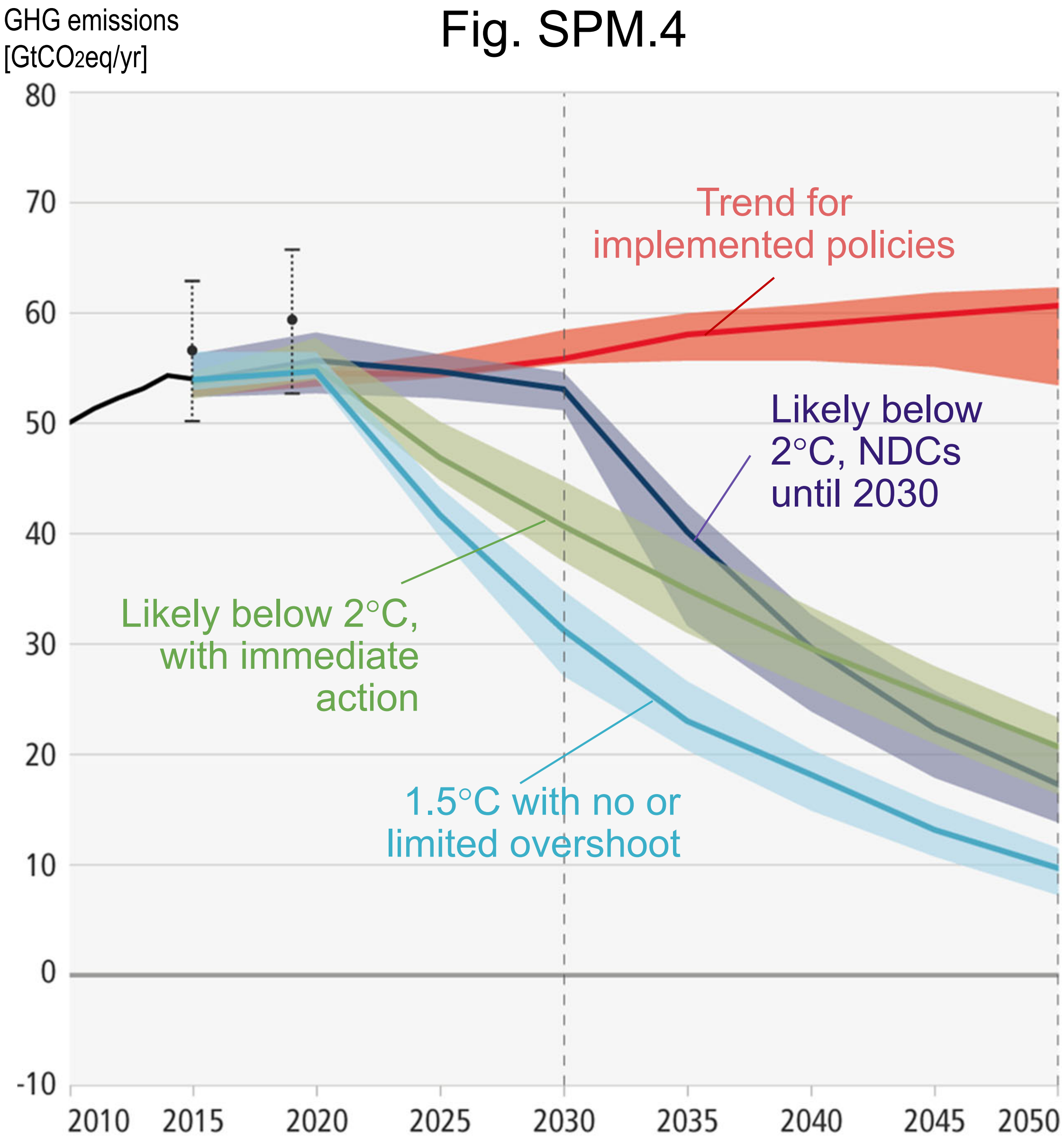
（Fig. 3.5）



IPs	**CurPol**	Current Policies	**C7**
	ModAct	Moderate Actions	**C6**
The pathways consisting with the long-term goals of Paris Agreement (IMPs)	**GS**	Gradual strengthening	**C3**
	Neg	Extensive use of net negative emissions	**C2**
	Ren	Focus on Renewables	**C1**
	LD	Focus on Low Demands	**C1**
	SP	Shifting Pathways	**C1**

NDCs and long-teem goals under Paris Agreement

Fig. SPM.4

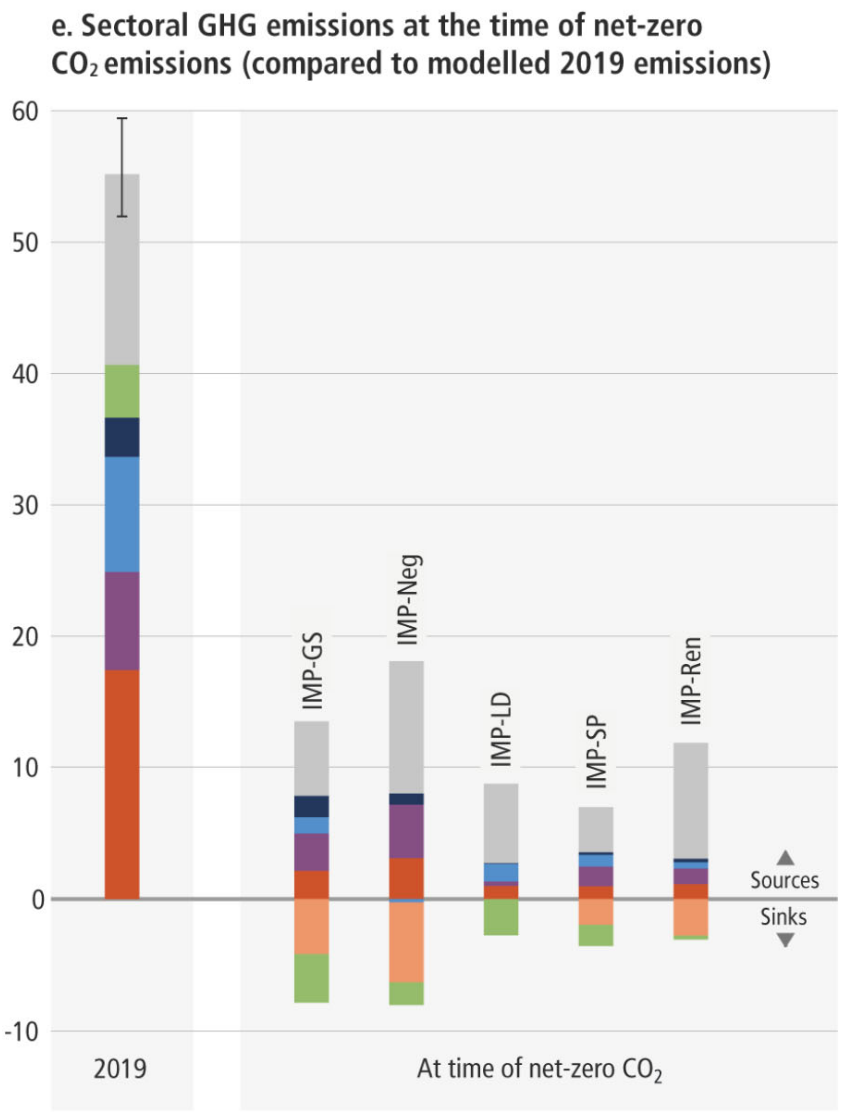


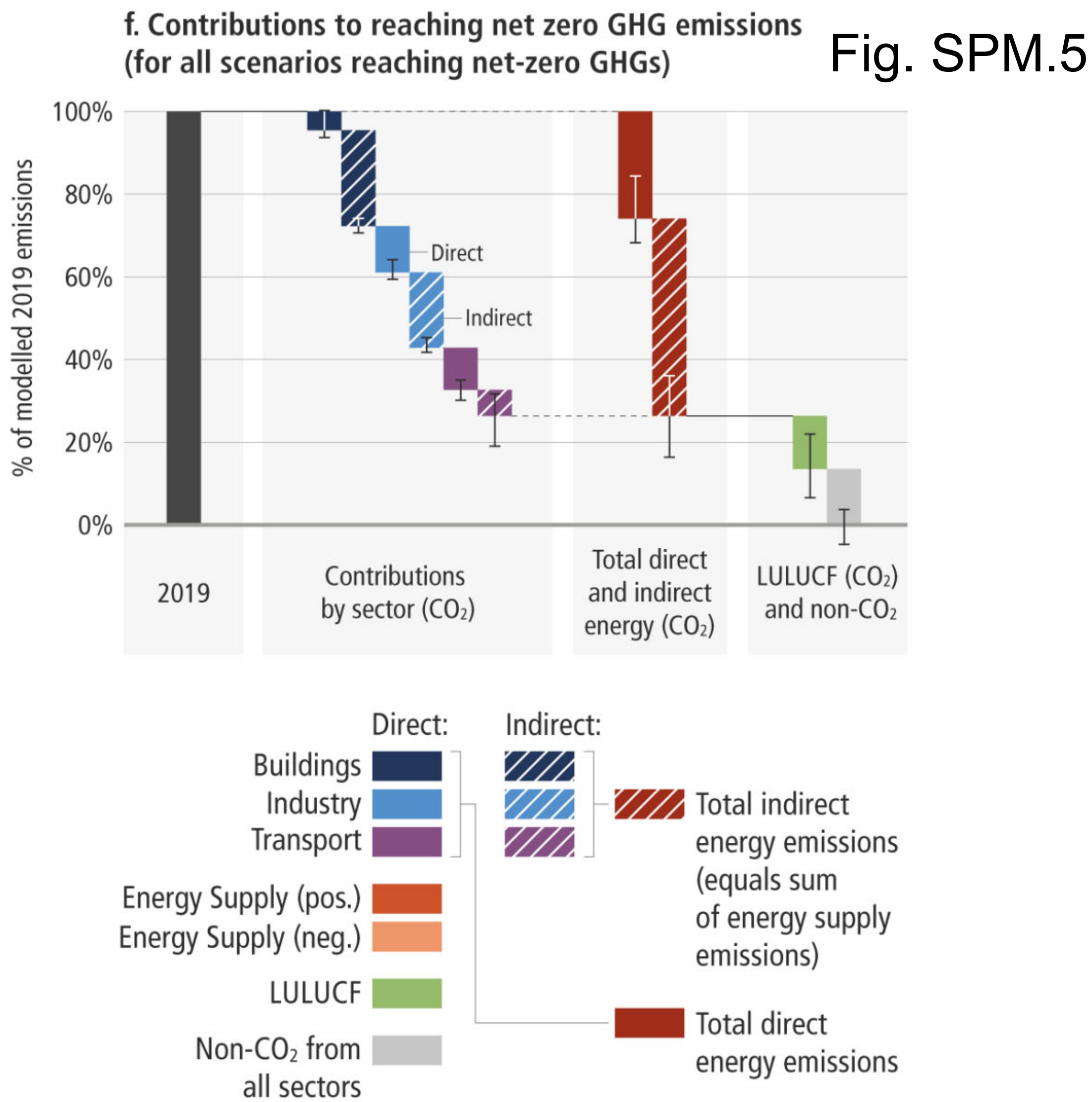
Note)
NDCs, announced prior to COP26 up to 11 October 2021. (The NDCs announced after this date are not included.)

"Unconditional elements: 53 (50–57) $GtCO_2eq/yr$, Including conditional elements: 50 (47–55) $GtCO_2eq/yr$" (SPM, Table SPM 1)

- ✓ **Sectoral scenarios are analyzed in accordance with three scenarios presented in IPCC Fig. SPM.4, consistent with meeting the long-term "well below 2°C" and 1.5°C goals of the Paris Agreement.**

Several opportunities to achieve CN: IPCC AR6



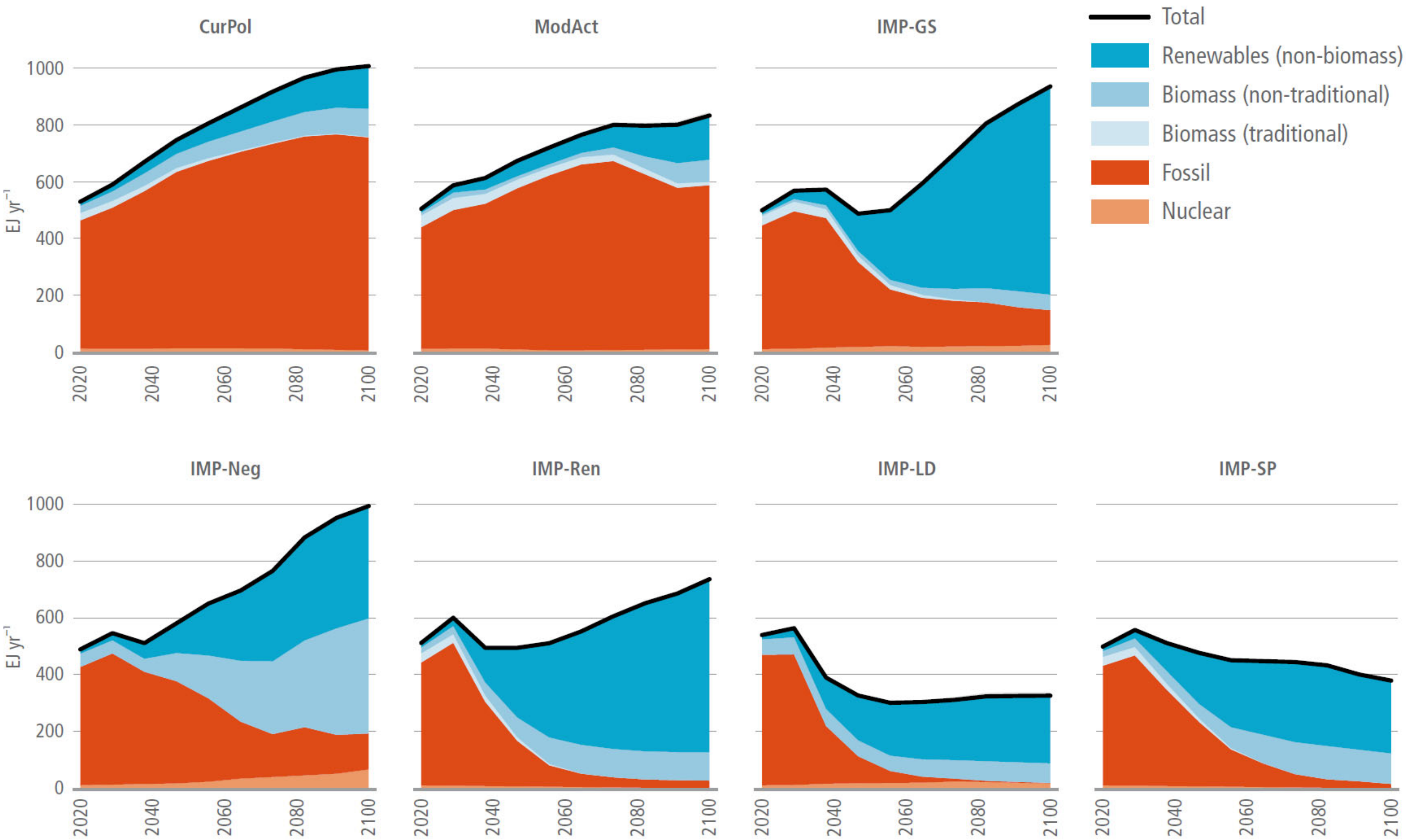


"The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO2 or GHG emissions are to be achieved." (SPM C.11)

In all scenario except Low Demand scenario, CDR options including large-scale afforestation are cost-effective to achieve net zero of CO2. Furthermore, for net zero GHG emissions, CDR is indispensable.

Global primary energy supply in each of the Illustrative Pathways (IPs)

Fig. 3.8

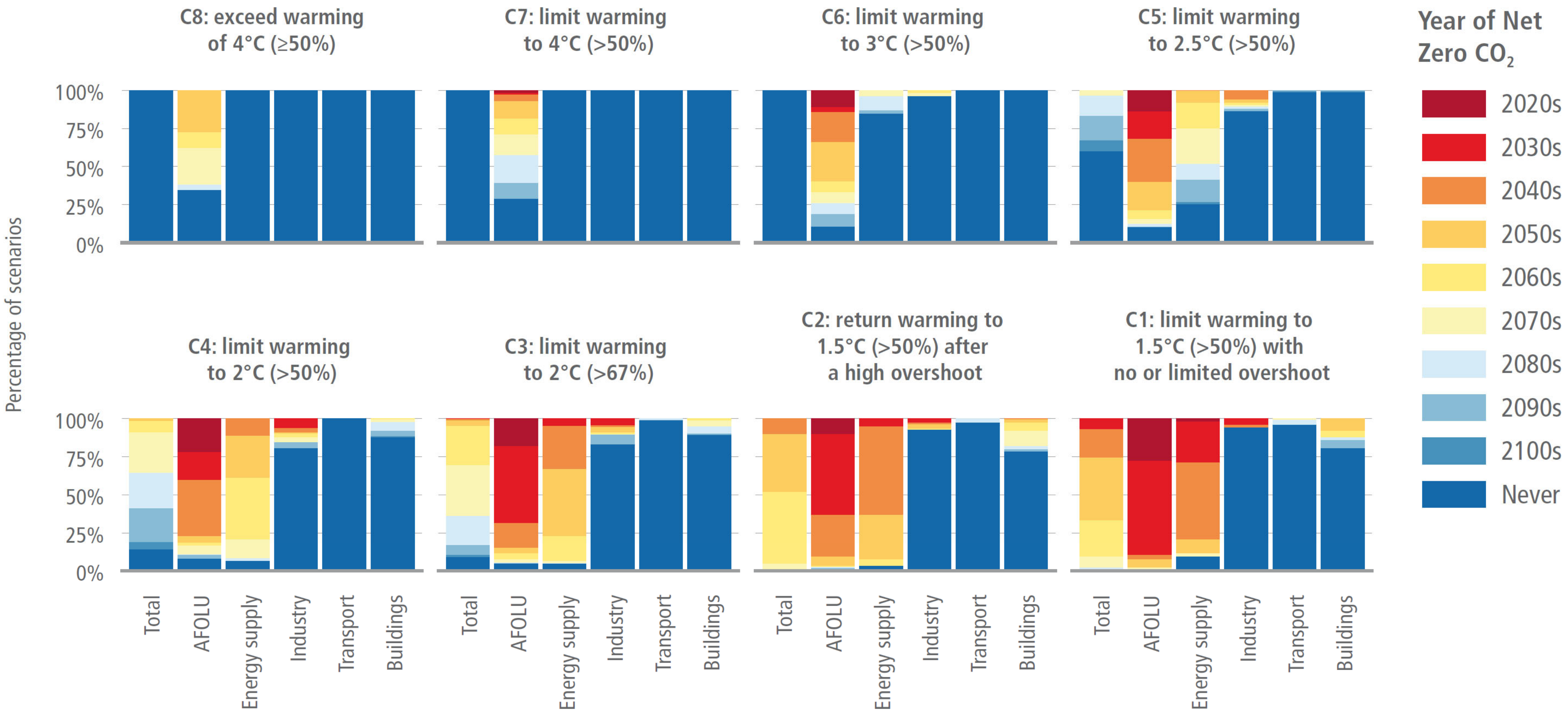


Electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging to supply the entire energy system with renewable energy. (Chapter 6 ES)

- ✓ **Fossil fuels use is likely to increase continually up to 2050 in CurPol and ModAct scenarios.**
- ✓ **Fossil fuels use would be varied even in 2050 under 2°C, 1.5°C scenarios.**

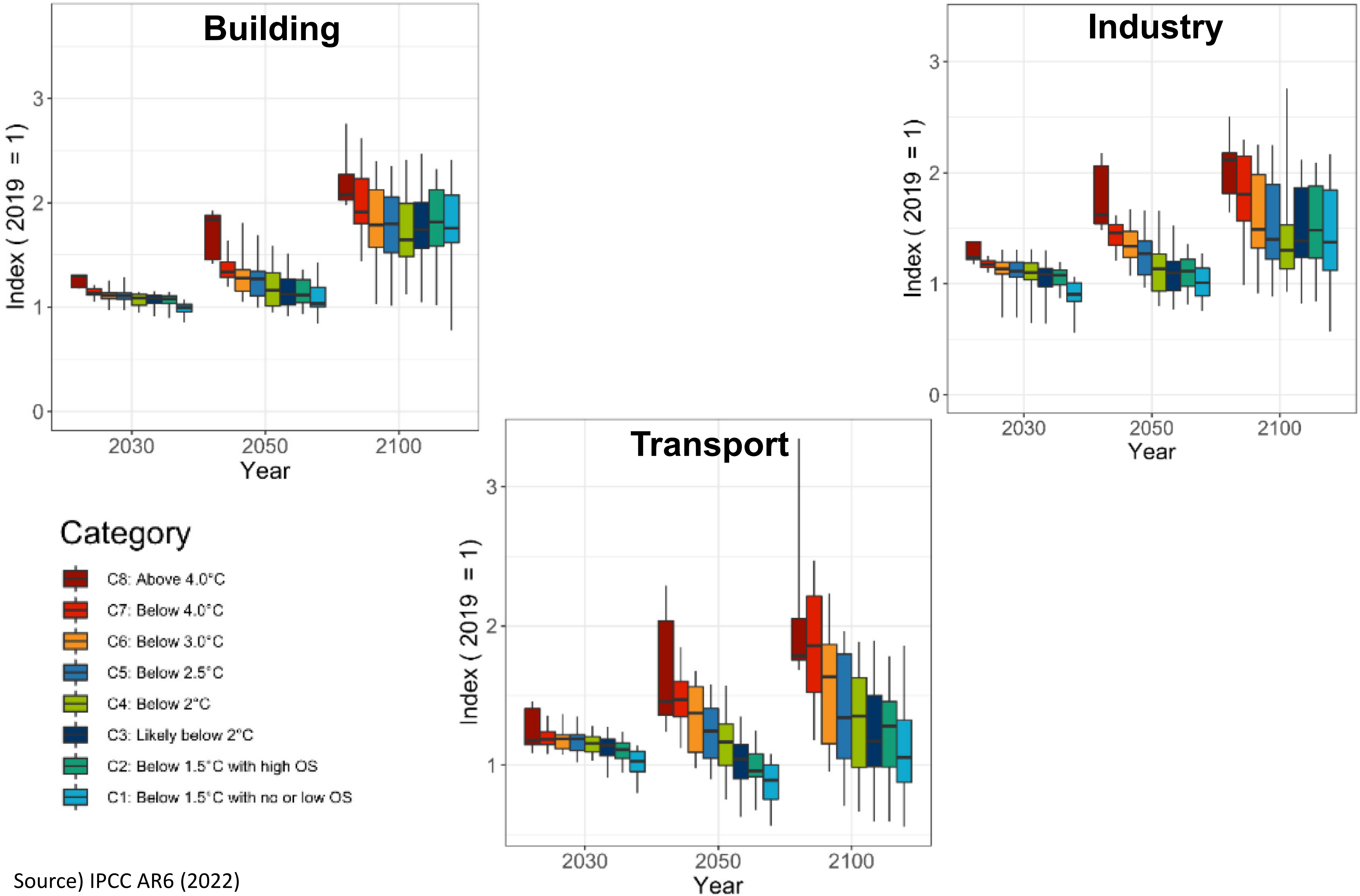
Actualizing CN: Decade in which sectoral CO_2 emissions first reach net negative values

Fig. 3.19



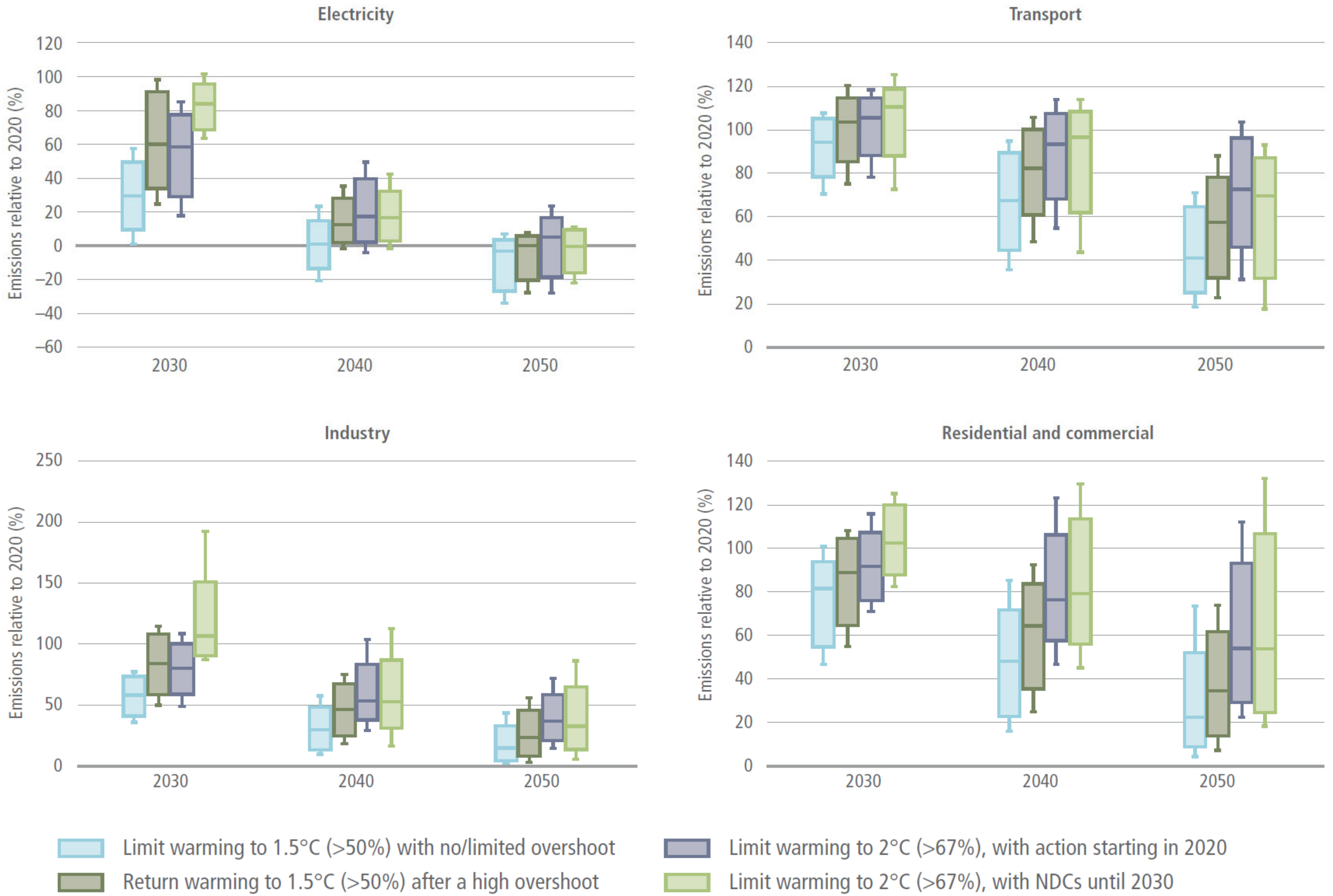
There are few assessments in IAM scenarios which indicate net zero emissions within this century in Industry, Transport, and Buildings sectors under any emission pathways including 1.5°C pathways. => Offsetting with CDR would be cost-effective.

Global final energy consumption by sector



Source) IPCC AR6 (2022)

Global CO_2 emissions by sector for the 2 °C and 1.5 °C scenarios (C1, C2, and C3 categories)



Source) IPCC AR6 (2022)

Note) Boxes indicate 25th and 75th percentiles, while whiskers indicate 5th and 95th percentiles.

NGFS Scenarios

NGFS: Network for Greening the Financial System

NGFS scenario participating research institutions and model overview

Comparison	Climate impacts	Transition pathways	Economic impacts
External research partners	Climate Analytics PIK	PIK UMD IIASA	NIESR
Models	Climate models participating in the ISIMIP project CLIMADA	REMIND-MAgPIE 3.0-4.4 GCAM 5.3+ MESSAGEix-GLOBIOM 1.1-M-R12	NiGEM v1.22 NGFS version IAMs (only GDP provided as an output in the database)
Inputs	Atmospheric concentrations of emissions and associated radiative forcing Economic exposure data for assessment of economic impacts	Constraints from an emissions budget and other climate policies at the global and regional level	Carbon tax prices and revenues, energy consumption, "useful energy", physical risk damage functions
Key assumptions and uncertainties	Physical relationships between various aspects of the climate system Changes in climate at the local scale	Technology costs. Inter-temporal optimisation (for REMIND-MAgPIE and MESSAGEix-GLOBIOM); dynamic recursive (for GCAM). Optimal government policy design and capital reallocation	Econometric relationships between variables hold. Rational expectations and perfect foresight
Outputs	**Climate indicators** (e.g. temperature, precipitation, river flow, agricultural yields, soil moisture) **Economic indicators** (e.g. direct losses from flooding and cyclones, area and population exposed to extreme weather)	Energy demand, energy capacity, investment in energy, energy prices, carbon prices, emissions trajectories, temperature trajectories, agricultural variables, water variables, GDP	GDP (and components), unemployment, inflation, productivity, personal disposable income, house prices, interest rates, exchange rates, equity prices, etc.
Time horizon	Time steps of 5 years, up to 2100 in Explorer Up to daily time steps for underlying ISIMIP data	Time steps of 5 years up to 2100 (10 years from 2060 onwards for REMIND-MAgPIE & MESSAGEix-GLOBOM)	Annual steps, up to 2050 (NiGEM)

（Source）NGFS (2022)

- **GDP and population estimates used in the IAMs are based on the projections under the SSP2 (intermediate scenario).**
- **A database of climate scenarios with technical reports is available from the NGFS portal.**

https://www.ngfs.net/ngfs-scenarios-portal/

Overview of the three models employed for the NGFS transition scenarios

Integrated Assessment Model	GCAM 5.3+	MESSAGEix_GLOBIOM 1.1	REMIND-MAgPIE 3.0-4.4
Short name	GCAM	MESSAGEix-GLOBIOM	REMIND-MAgPIE
Solution concept	Partial Equilibrium (price elastic demand)	General Equilibrium (this version has fixed demands for materials)	REMIND: General Equilibrium MAgPIE: Partial Equilibrium model of the agriculture sector
Anticipation	Recursive dynamic (myopic)	Intertemporal (perfect foresight)	REMIND: Intertemporal (perfect foresight) MAgPIE: Recursive dynamic (myopic)
Solution method	Cost minimisation	Welfare maximisation	REMIND: Welfare maximisation MAgPIE: Cost minimisation
Temporal dimension	Base year: 2015 Time steps: 5 years Horizon: 2100	Base year: 1990 Time steps: 5 (2005-2060) and 10 years (2060-2100) Horizon: 2100	Base year: 2005 Time steps: 5 (2005-2060) and 10 years (2060-2100) Horizon: 2100
Spatial dimension	32 world regions	12 world regions	12 world regions
Technological change	Exogenous	Exogenous	Endogenous for Solar, Wind and Batteries
Technology dimension	58 conversion technologies	64 conversion technologies	50 conversion technologies
Demand sectors and subsector detail	Buildings (residential and commercial buildings with heating, cooling, and other services), Industry (Cement, Chemicals,	Buildings, Industry (Cement, Chemicals, Steel, Non-ferrous metals, Other), Transport	Buildings, Industry (Cement, Chemicals, Steel, Other), Transport (various modes and technologies)

Source: NGFS (2022)

Six scenarios of NGFS (2021, 2022 versions)

		Physical risk	Transition risk			
Category	**Scenario**	**Policy ambition**	**Policy reaction**	**Technology change**	**Carbon dioxide removal** ⁻	**Regional policy variation** ⁺
Orderly	Net Zero 2050	1.4°C	Immediate and smooth	Fast change	Medium-high use	Medium variation
	Below 2°C	1.6°C	Immediate and smooth	Moderate change	Medium-high use	Low variation
Disorderly	Divergent Net Zero	1.4°C	Immediate but divergent across sectors	Fast change	Low-medium use	Medium variation
	Delayed Transition	1.6 °C	Delayed	Slow / Fast change	Low-medium use	High variation
Hot house world	Nationally Determined Contributions (NDCs)	2.6°C	NDCs	Slow change	Low-medium use	Medium variation
	Current Policies	3°C +	Non-currente policies	Slow change	Low use	Low variation

Colour coding indicates whether the characteristic makes the scenario more or less severe from a macro-financial risk perspective^

- Lower risk
- Moderate risk
- Higher risk

(Source) NGFS (2022)

Orderly

Net Zero 2050: Limiting global temperature rise to 1.5℃ and achieving net-zero global CO_2 emissions around 2050, through ambitious climate chance policies and innovation

Below 2℃: Increasing the stringency of climate change policies in stages, with a 67% probability of limiting global temperature increase to less than 2℃

Disorderly

Divergent Net Zero: Achieving Net zero around 2050, but at a high cost due to different policies introduced across sectors

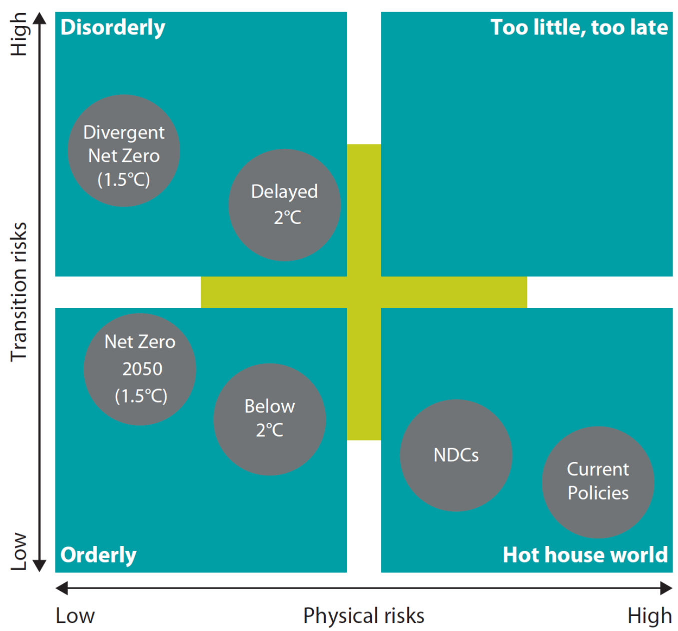
Delayed transition: Annual emissions will not decrease until 2030, and stringent policies are needed to keep emissions below 2℃. In addition, there are constraints on the removal of CO_2.

Hot House World

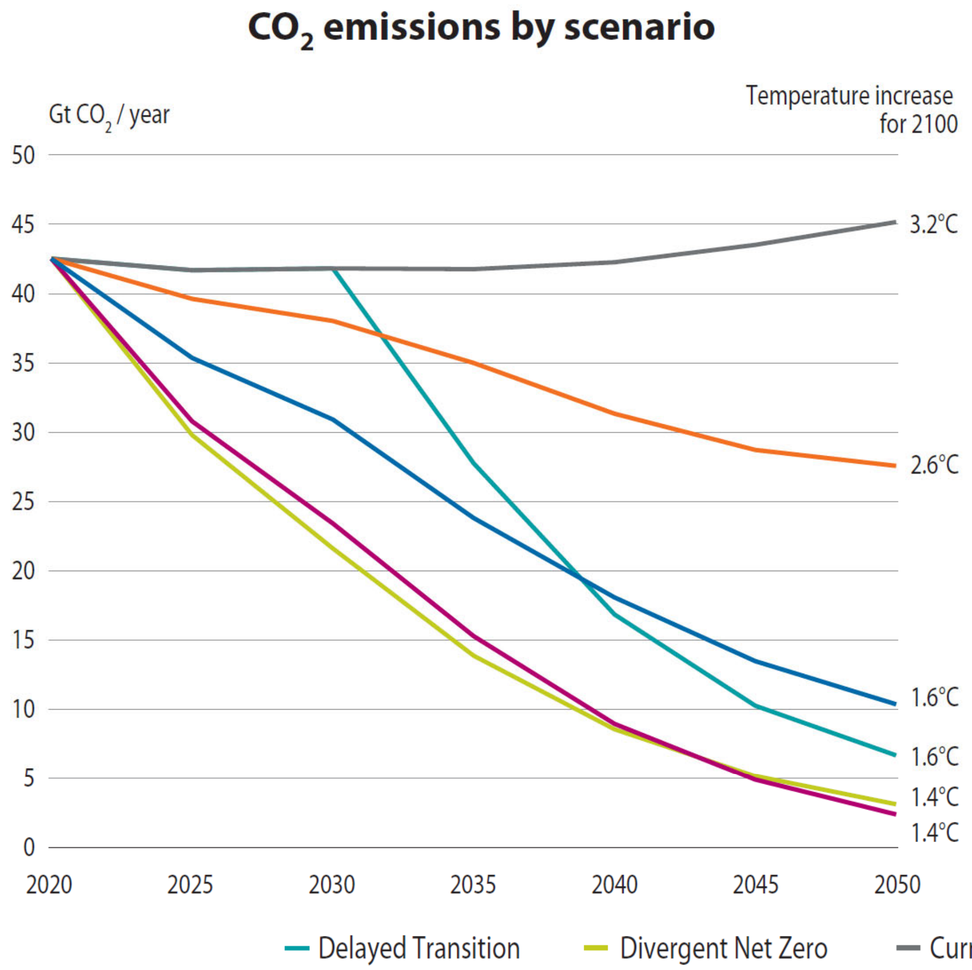
NDCs: Using NDCs as of March 2022 (2022 version)

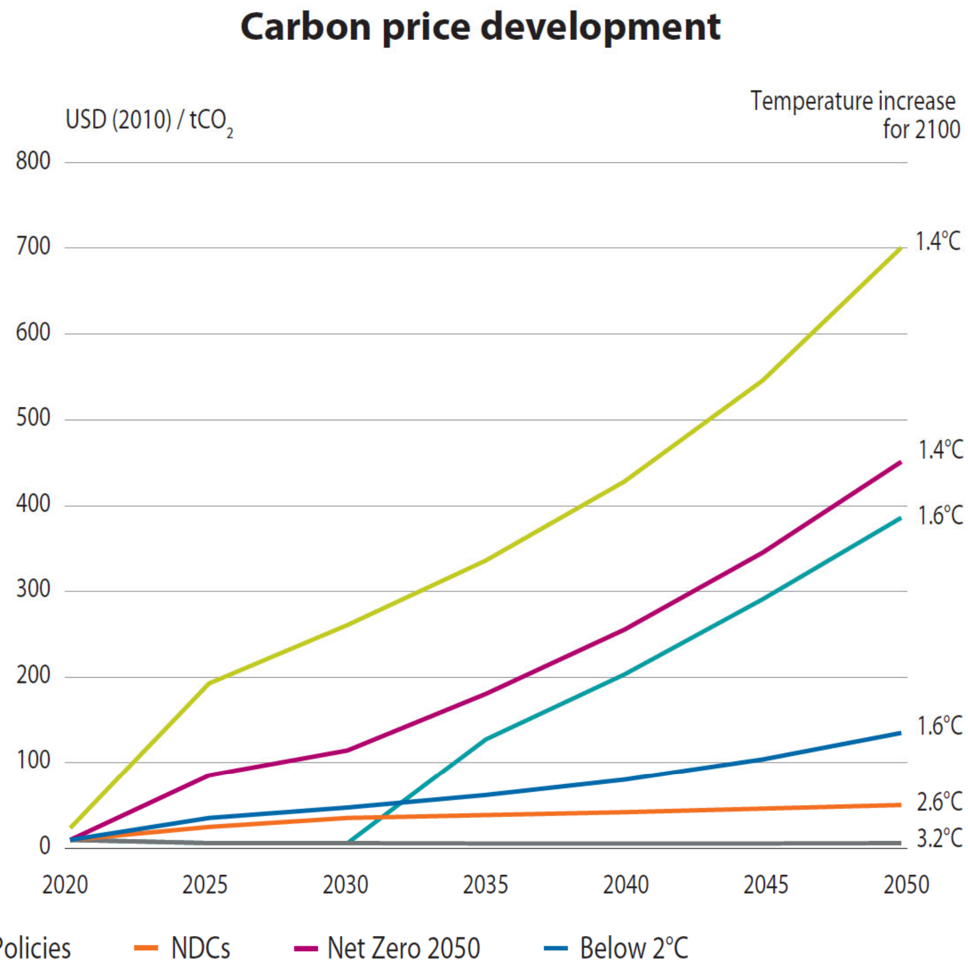
Current Policies

NGFS scenarios framework



CO_2 emissions and carbon prices for each NGFS scenario





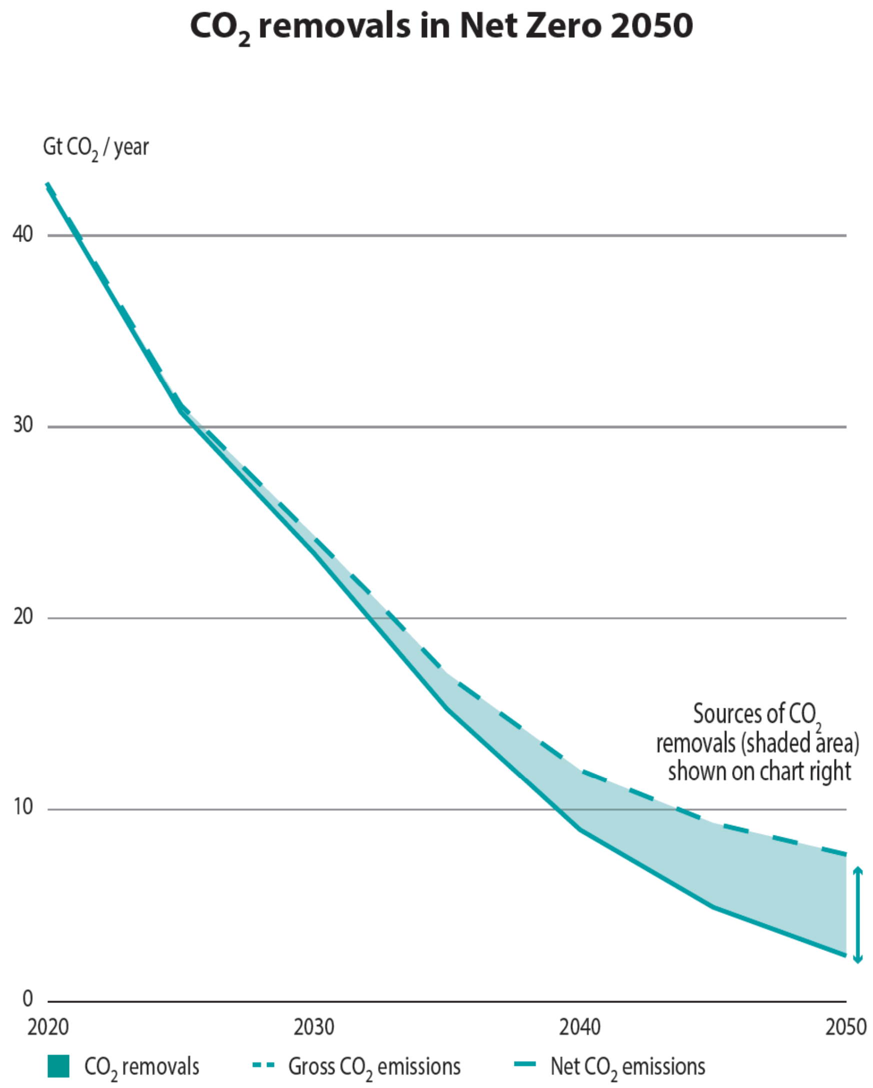
World aggregates mask strong differences across sectors and jurisdictions. Regionally and sectorally granular information is available on the IIASA database. End of century warming outcomes shown. 5-year time step data.
Source: IIASA NGFS Climate Scenarios Database, REMIND model.

The chart represents shadow carbon prices, which is a measure of policy intensity. Carbon prices are weighted global. Regionally and sectorally granular information is available on the IIASA database.
Source: IIASA NGFS Climate Scenarios Database, REMIND model.

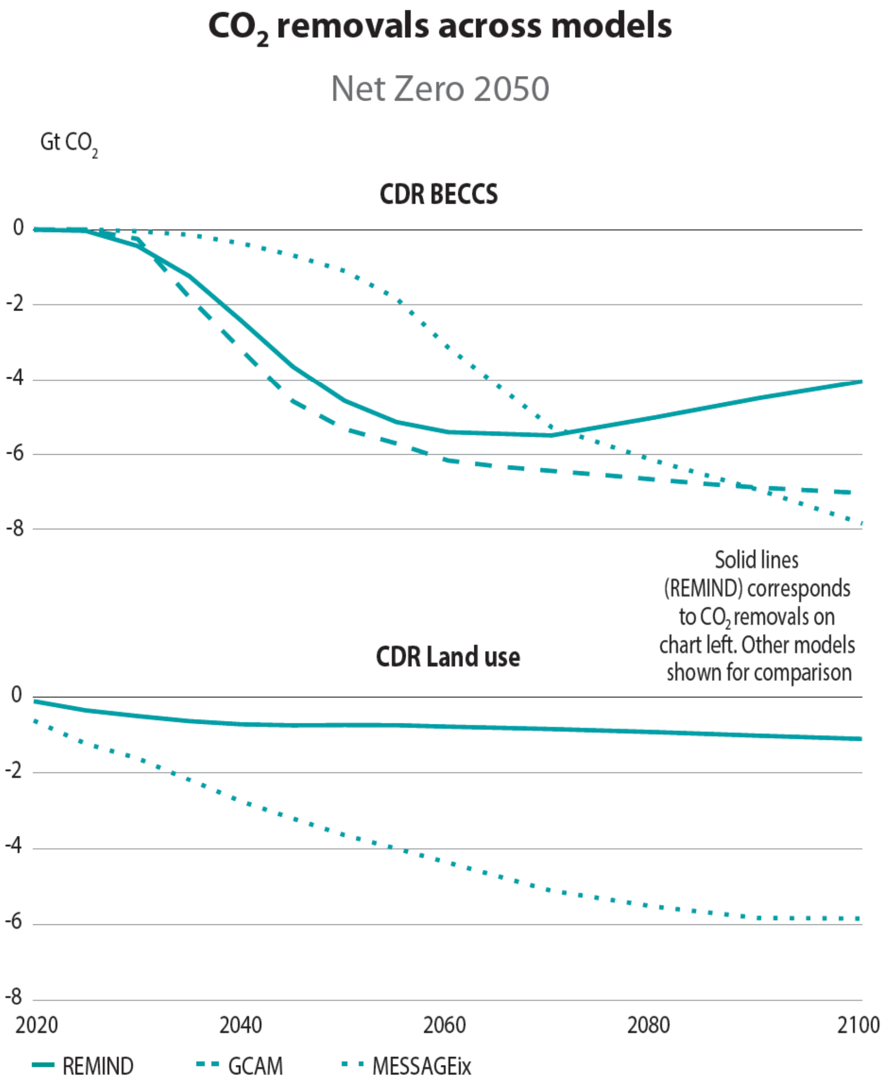
(Source) NGFS (2022)

- **The NGFS scenarios are also very similar to IPCC Fig. SPM.4 for the 2℃ and 1.5℃ equivalent scenarios.**

Outlook for CO_2 removal technology CDR in the NGFS scenario



Source: IIASA NGFS Climate Scenarios Database , REMIND model.

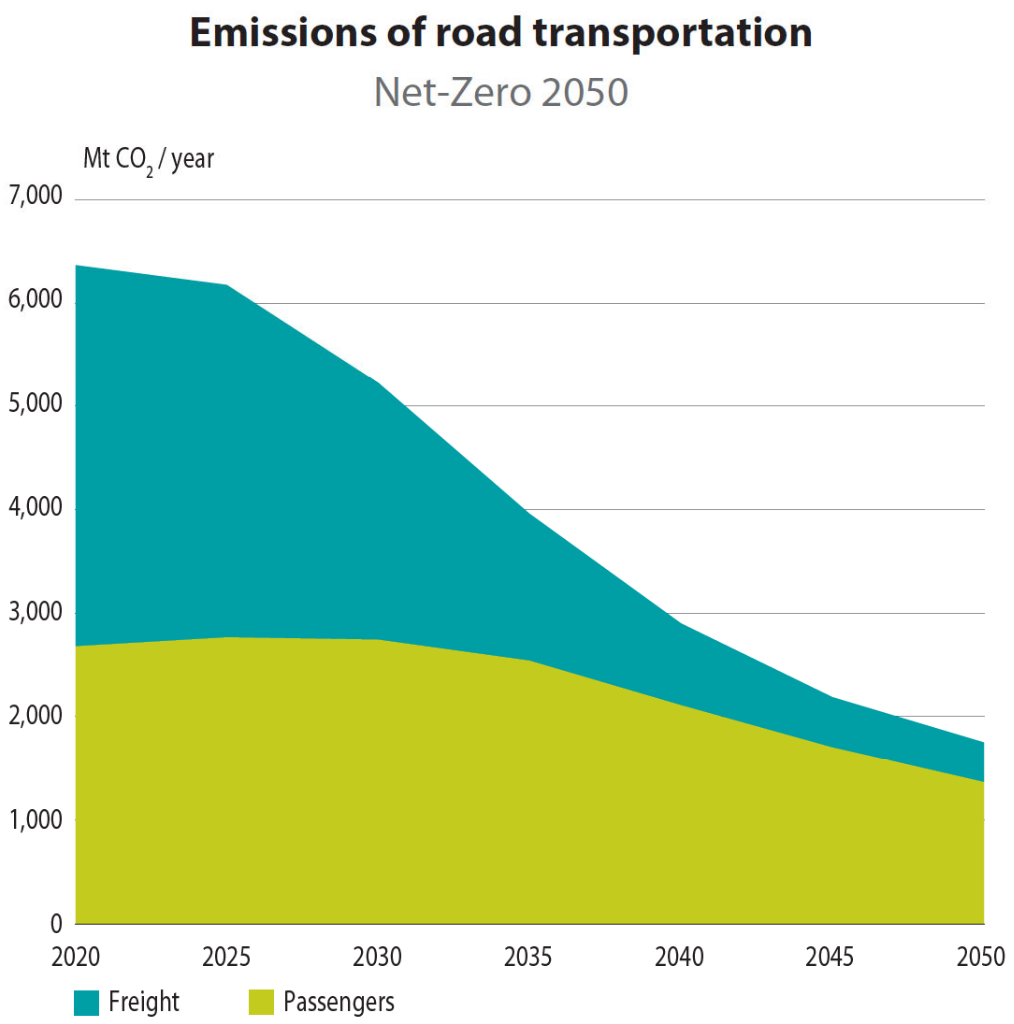


Source: IIASA NGFS Climate Scenarios Database.

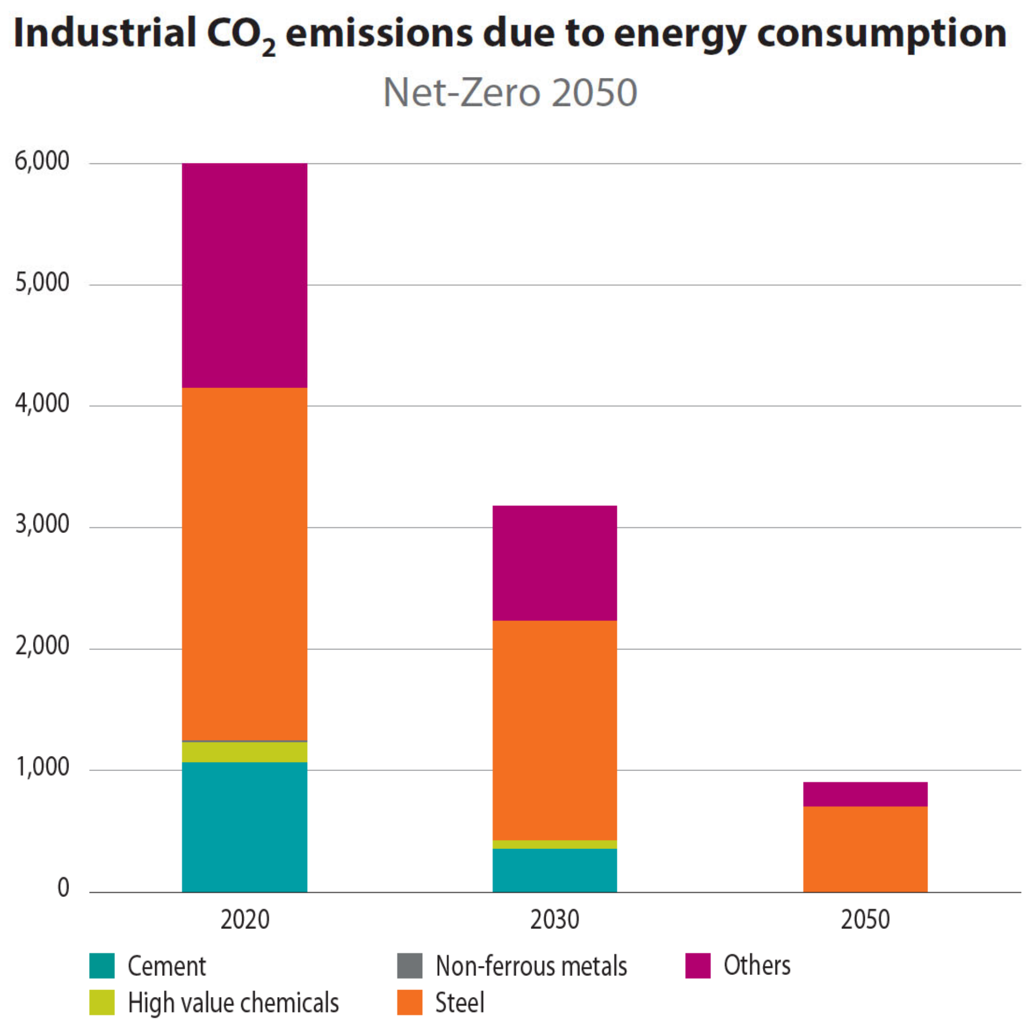
（Source）NGFS (2022)

- In the NGFS scenario, land use change (afforestation) and BECCS are considered, but DACCS is not.
- Nevertheless, a CDR of about 7 $GtCO_2$/yr is projected under the Net Zero 2050 scenario.

Emissions by sector in the NGFS Net-Zero 2050 (example)



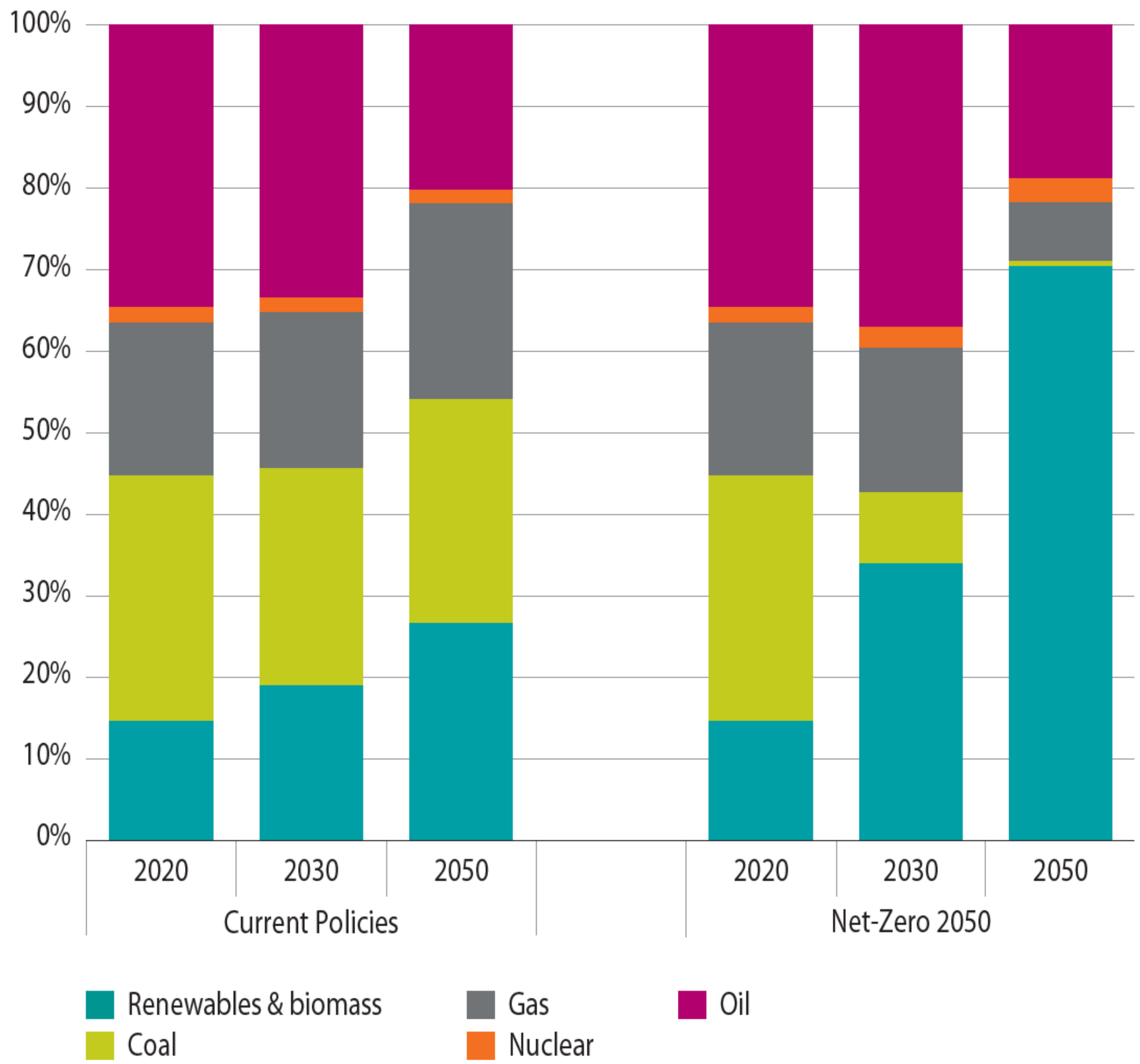
Source: IIASA NGFS Scenario Database, REMIND model.



Source: IIASA NGFS Scenario Database, MESSAGE model.

（Source）NGFS (2022)

Composition of total primary energy supply in the NGFS Net-Zero 2050 (example)



Direct equivalent accounting method used, which is predominant in publications on long-term transition pathways.
See Technical Documentation for further details.
Source : IIASA NGFS Climate Scenarios Database, REMIND model.

（Source）NGFS (2022)

Major updates in the 2023 version of the NGFS scenarios

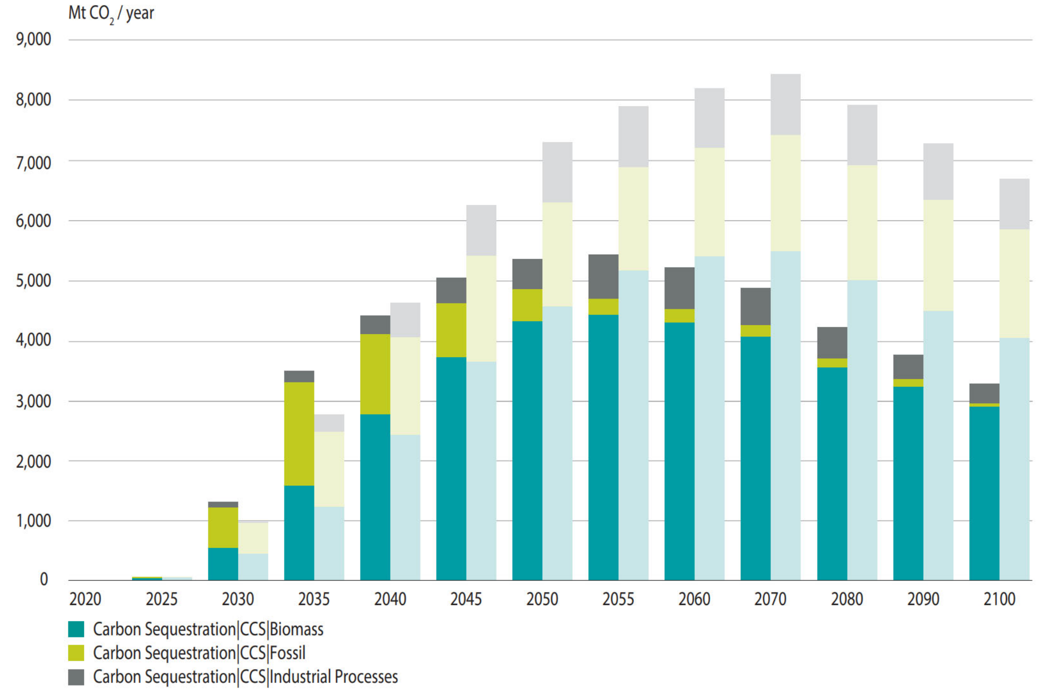
- **Scenarios data** have been updated to reflect:
  - the **new country-level policies** to reach net-zero emissions (e.g. as part of the EU Fit-for-55, the US Inflation Reduction Act, etc.) with a cut-off date of March 2023, contributing to slightly decreasing physical risks;
  - the **latest GDP and population data** using the latest snapshot from the IMF World Economic Outlook 2022;
  - the **current geopolitical context**, including consequences of the war in Ukraine on energy prices, contributing to an overall increase in disorderliness;
  - the **latest trends** in renewable energy technologies (e.g., solar and wind), and key mitigation technologies; for example, capital costs for solar PV will decrease faster according to the new projections.

- **Limits on the availability of Carbon Capture and Storage (CCS) technologies** have been introduced, making the scenarios more adverse due to lower overall availability of these technologies. This is modelled via explicit constraints on the process level such as setting a time-dependent maximum area available for afforestation or maximum yearly bioenergy with CCS potentials. Direct Air Carbon Capture and Storage (DACCS) technologies were switched off in all scenarios, in particular because of the uncertainty with regards to their development.

（Source）NGFS (2023)

Carbon Sequestration Phase IV vs Phase III

REMIND, Phase III in transparent coloring



- **In addition to reflecting the latest trends, the 2023 version of the NGFS transition scenario assumed exogenous constraints on CCS availability.**

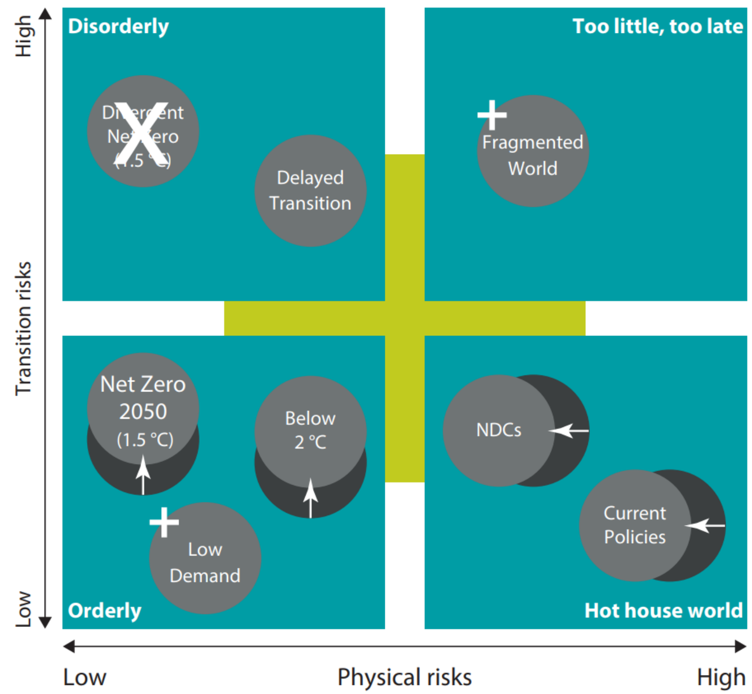
NGFS scenarios of 2023 version

Quadrant	Scenario	Physical risk: End of century warming *(model averages)*	Transition risk: Policy reaction	Transition risk: Technology change	Transition risk: Carbon dioxide removal $^{-}$	Transition risk: Regional policy variation $^{+}$
Orderly	Low Demand (NEW)	1.4 °C (1.6 °C)	Immediate	Fast change	Medium use	Medium variation
	Net Zero 2050	1.4 °C (1.6 °C)	Immediate	Fast change	Medium-high use	Medium variation
	Below 2 °C	1.7 °C (1.8 °C)	Immediate and smooth	Moderate change	Medium use	Low variation
Disorderly	Delayed Transition	1.7 °C (1.8 °C)	Delayed	Slow/Fast change	Medium use	High variation
Hot house world	Nationally Determined Contributions (NDCs)	2.4 °C (2.4 °C)	NDCs	Slow change	Low use	Medium variation
	Current Policies	2.9 °C (2.9 °C)	None – current policies	Slow change	Low use	Low variation
Too-little-too-late	Fragmented World (NEW)	2.3 °C (2.3 °C)	Delayed and Fragmented	Slow/Fragmented change	Low-medium use	High variation

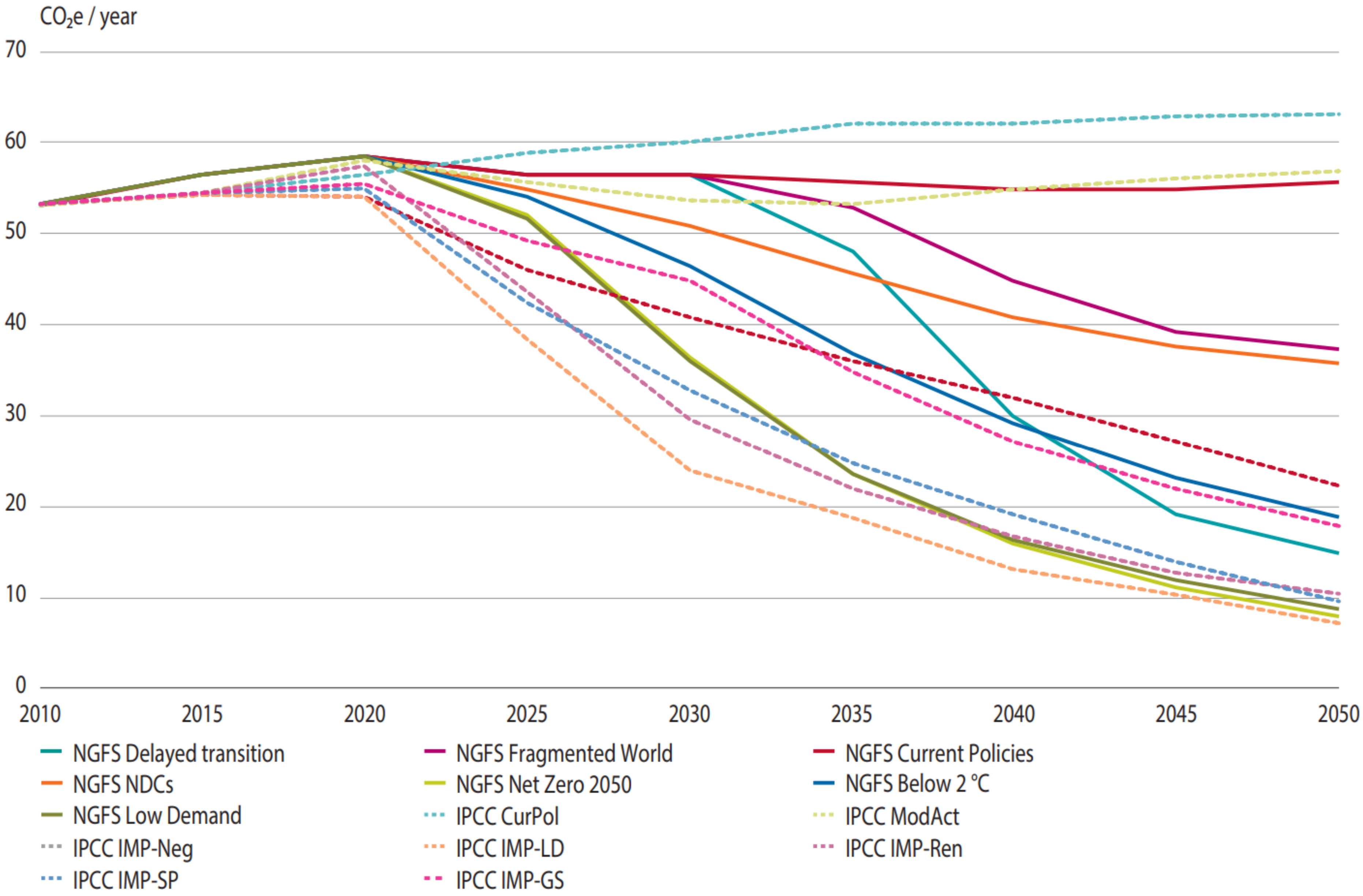
Colour coding indicates whether the characteristic makes the scenario more or less severe from a macro-financial risk perspective $^{\wedge}$

- Lower risk
- Moderate risk
- Higher risk

NGFS scenarios framework: from Phase III to Phase IV

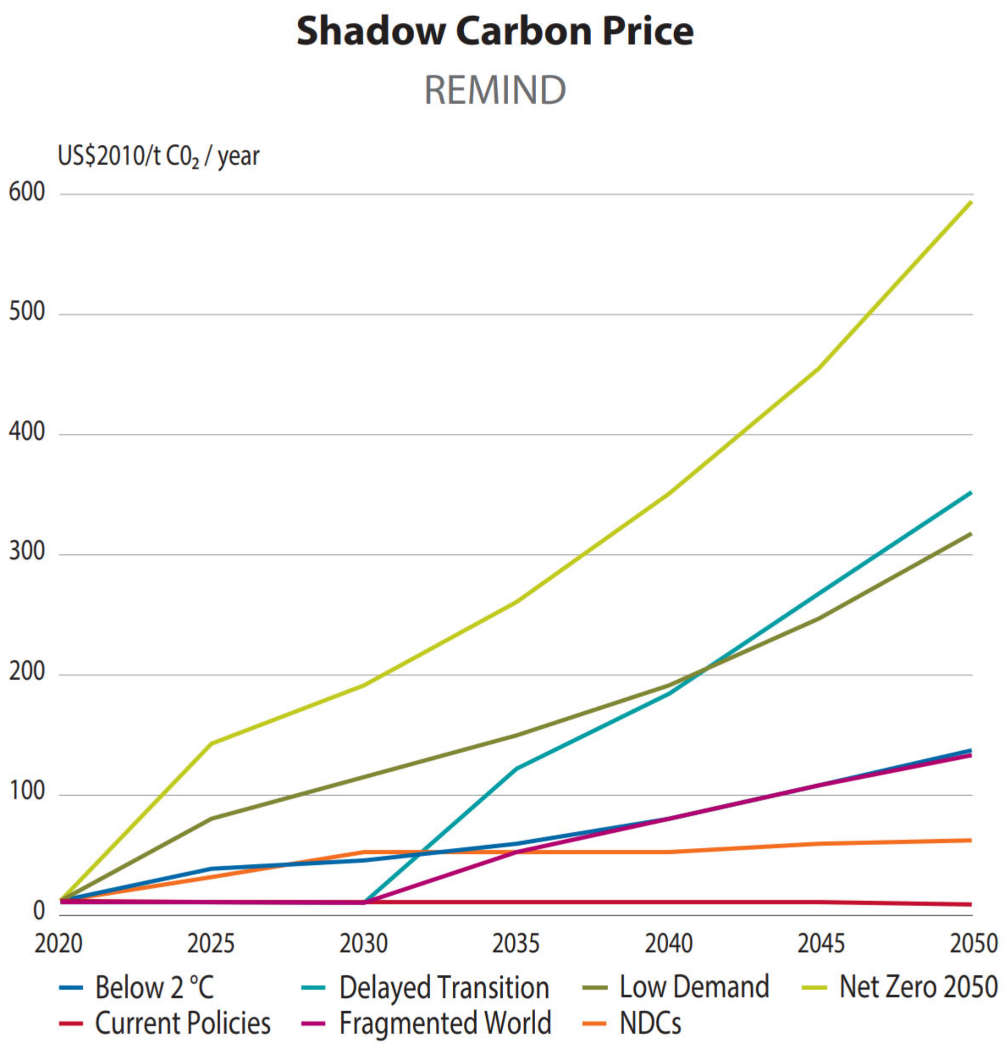


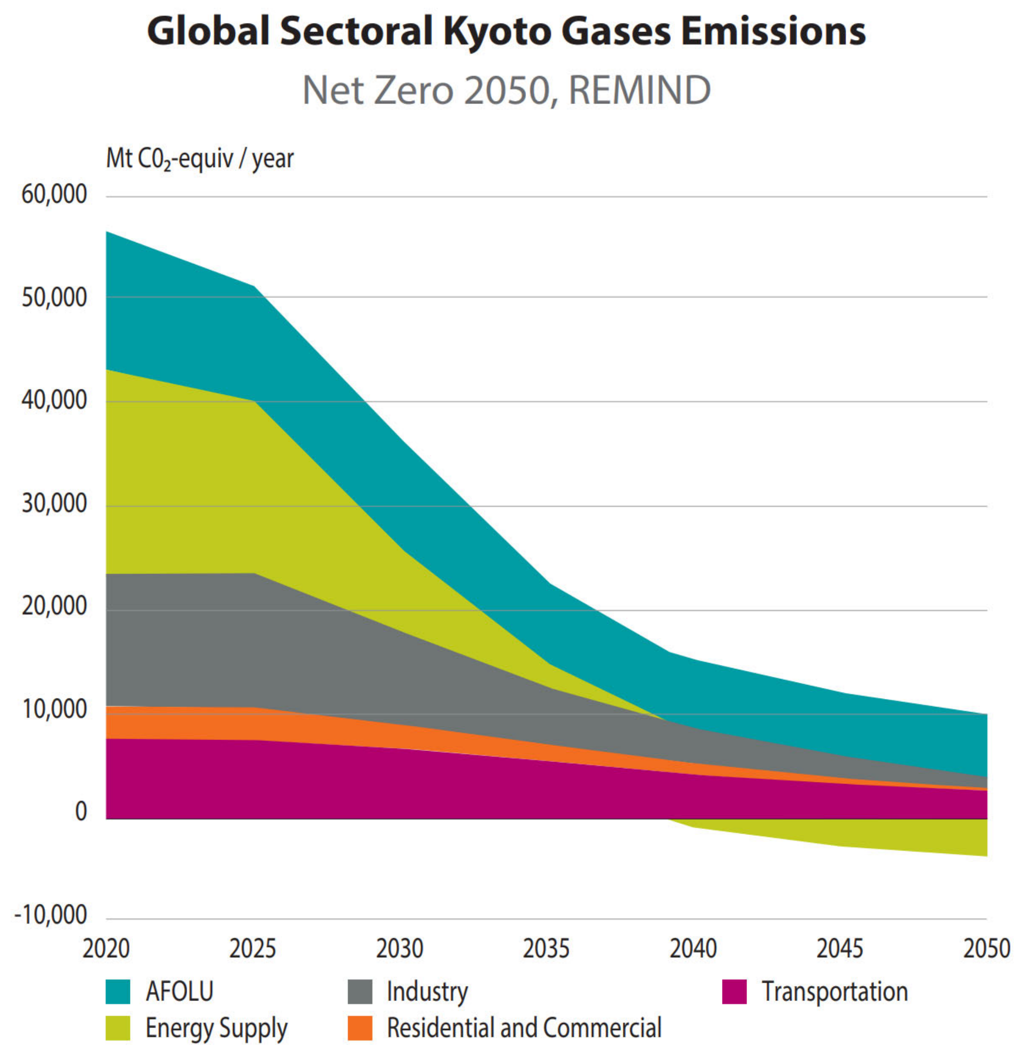
GHG emissions in the NGFS 2023 version (compared to IPCC estimates)



（Source）NGFS (2023)

Example of carbon prices and CO_2 emissions under the NGFS scenarios (REMIND model)



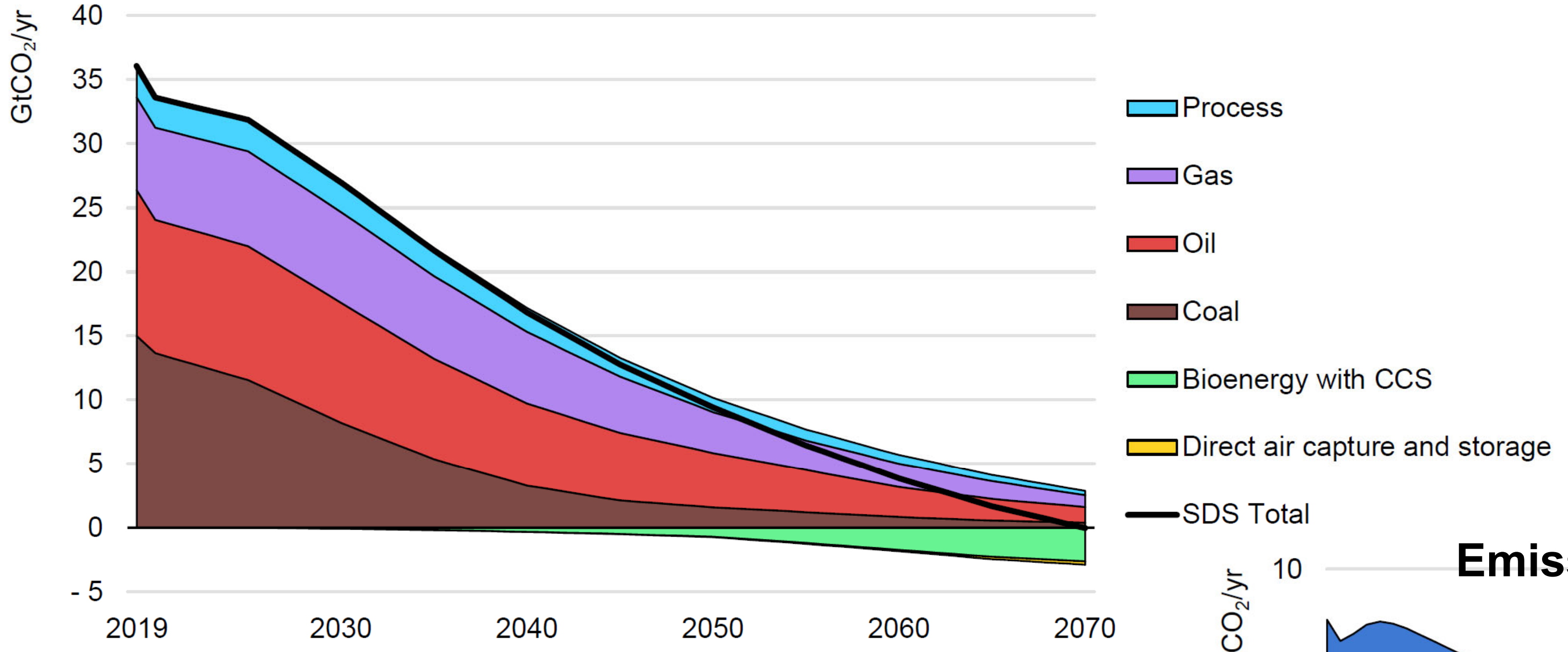


(Source) NGFS (2023)

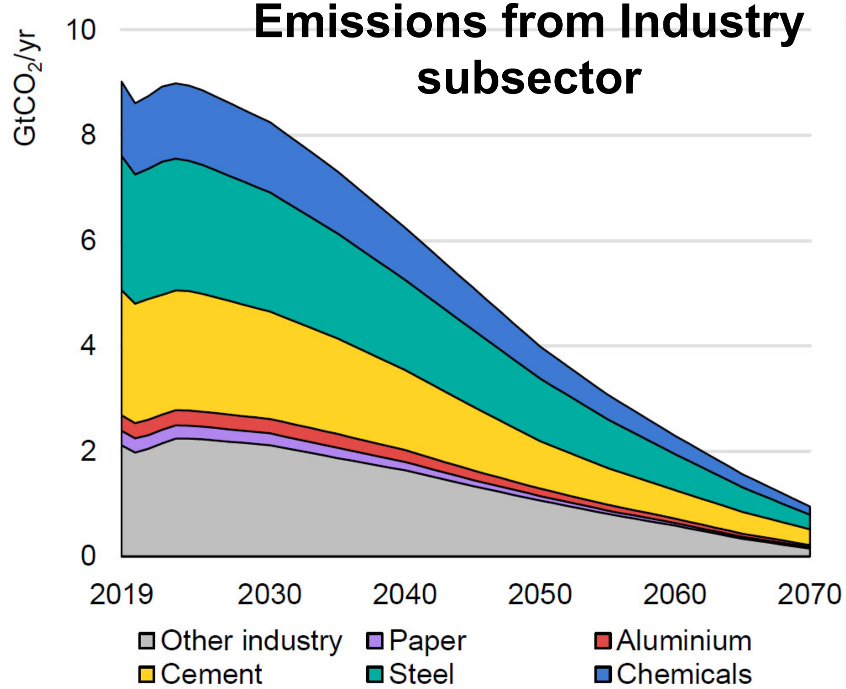
IEA Scenarios

Emissions reduction scenario in SDS in ETP2020

Figure 2.1 Global energy sector CO_2 emissions by fuel and technology in the Sustainable Development Scenario, 2019-70



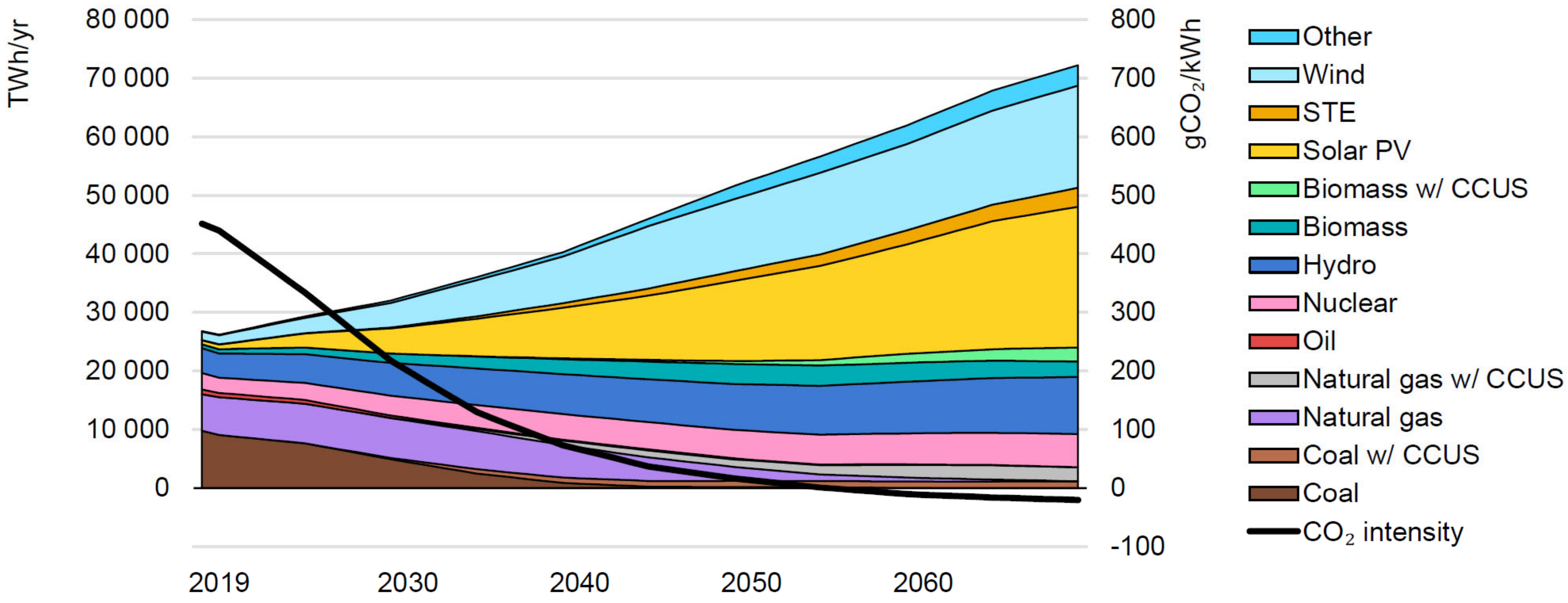
Notes: CCS = carbon capture and storage. SDS= Sustainable Development Scenario.



SDS: Sustainable Development Scenario
A scenario with less than 1.8 °C, equivalent to “well below 2 °C” target under the Paris agreement

Electricity generation scenario in SDS in ETP2020

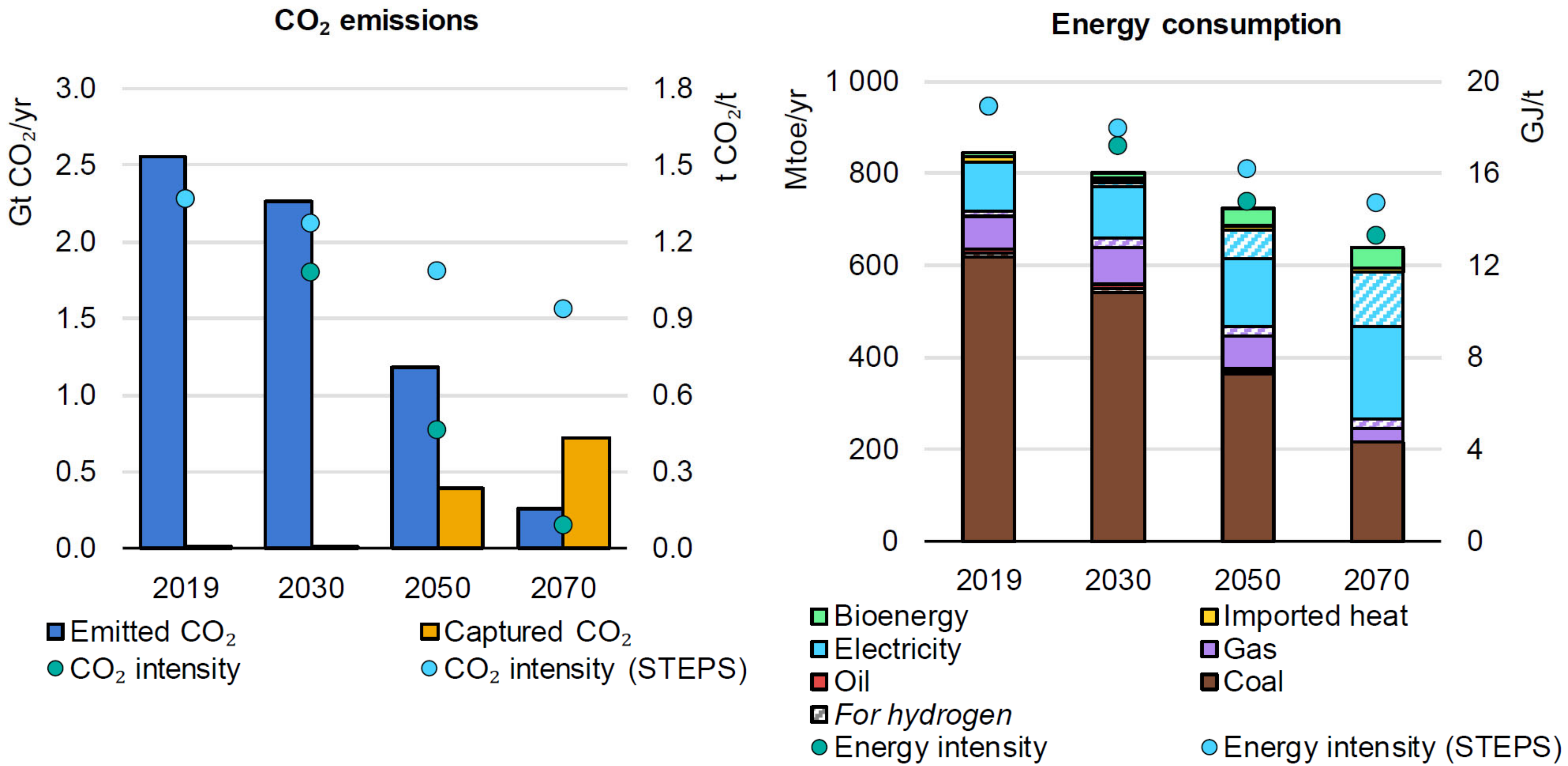
Figure 3.2 Global power generation by fuel/technology in the Sustainable Development Scenario, 2019-70



Notes: TWh = terawatt-hours; gCO_2/kWh = grammes of CO_2 per kilowatt-hour; STE = solar thermal electricity; PV = photovoltaic; CCUS = carbon capture, utilisation storage. Other includes geothermal power, ocean energy and hydrogen.

Iron and steel sector emissions and energy consumption in SDS in ETP2020

Figure 4.10 Global iron and steel sector direct CO_2 emissions and energy consumption in the Sustainable Development Scenario, 2019-70

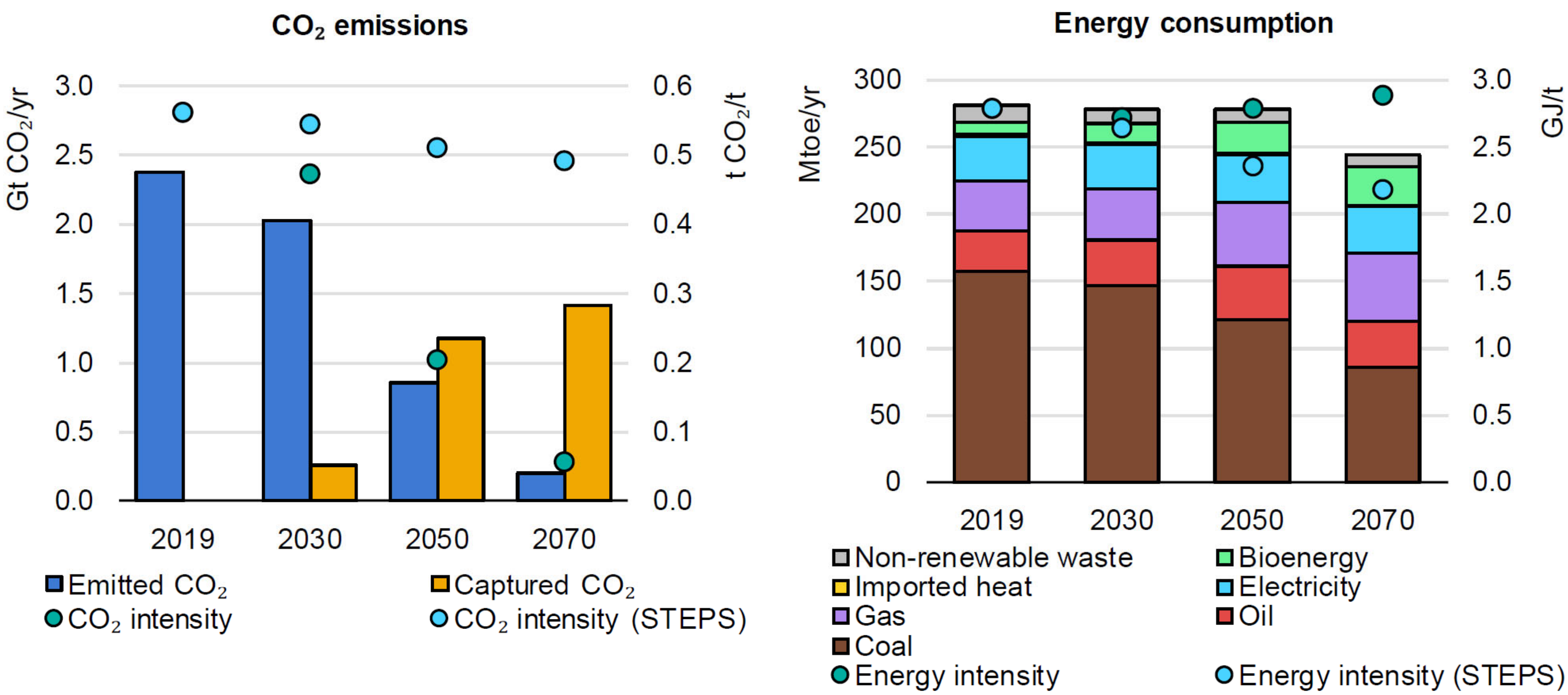


Note: STEPS = Stated Policies Scenario.

Cement sector emissions and energy consumption in SDS in ETP2020

RIT Research Institute of Innovative Technology for the Earth

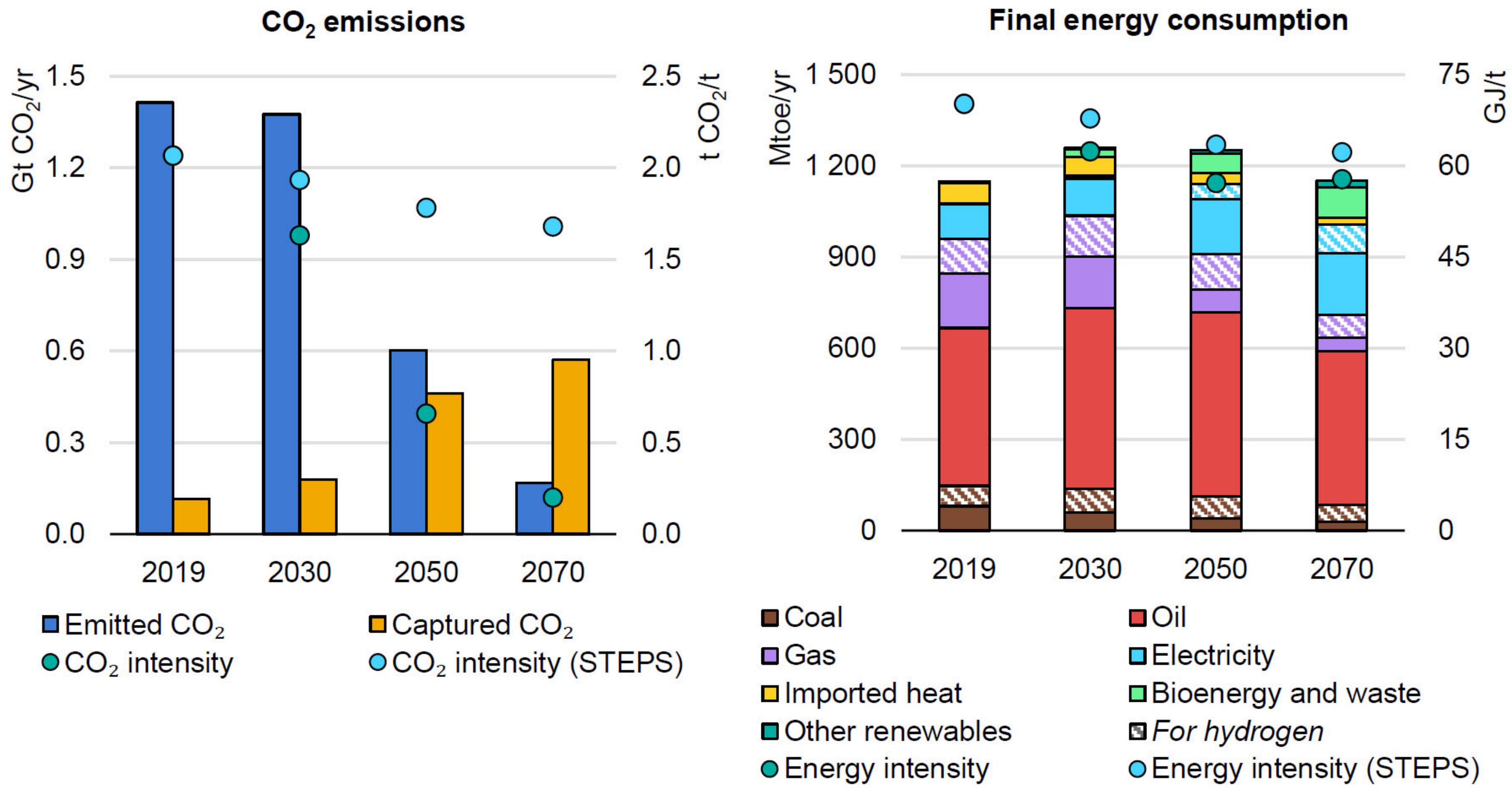
Figure 4.16 Global cement sector direct CO_2 emissions and energy consumption in the Sustainable Development Scenario, 2019-70



Notes: STEPS = Stated Policies Scenario. Energy intensity here includes all energy used per tonne of cement, including additional energy needs for some strategies deployed in the Sustainable Development Scenario – chemical absorption carbon capture and storage, calcined clay use and alternative fuel use. This explains the increasing overall energy intensity by 2070.

Chemical sector emissions and energy consumption in SDS in ETP2020

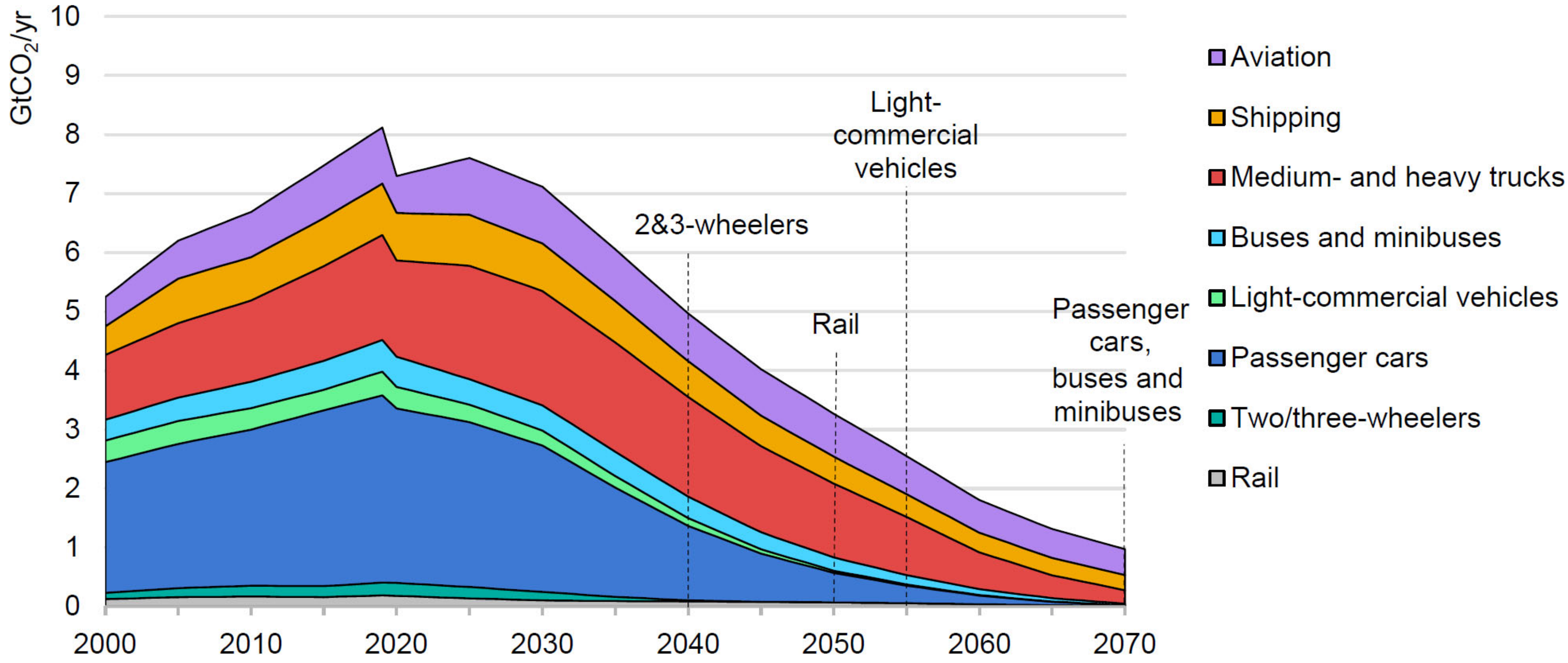
Figure 4.5 Global chemical sector direct CO_2 emissions and energy consumption in the Sustainable Development Scenario, 2019-70



Notes: STEPS = Stated Policies Scenario. Captured CO_2 includes that which is captured then used as feedstock for urea production, as well as that which is captured and stored. Energy consumption includes that used as feedstock. Sectoral energy and CO_2 intensities are calculated based on total primary chemical production and total chemical sector energy consumption.

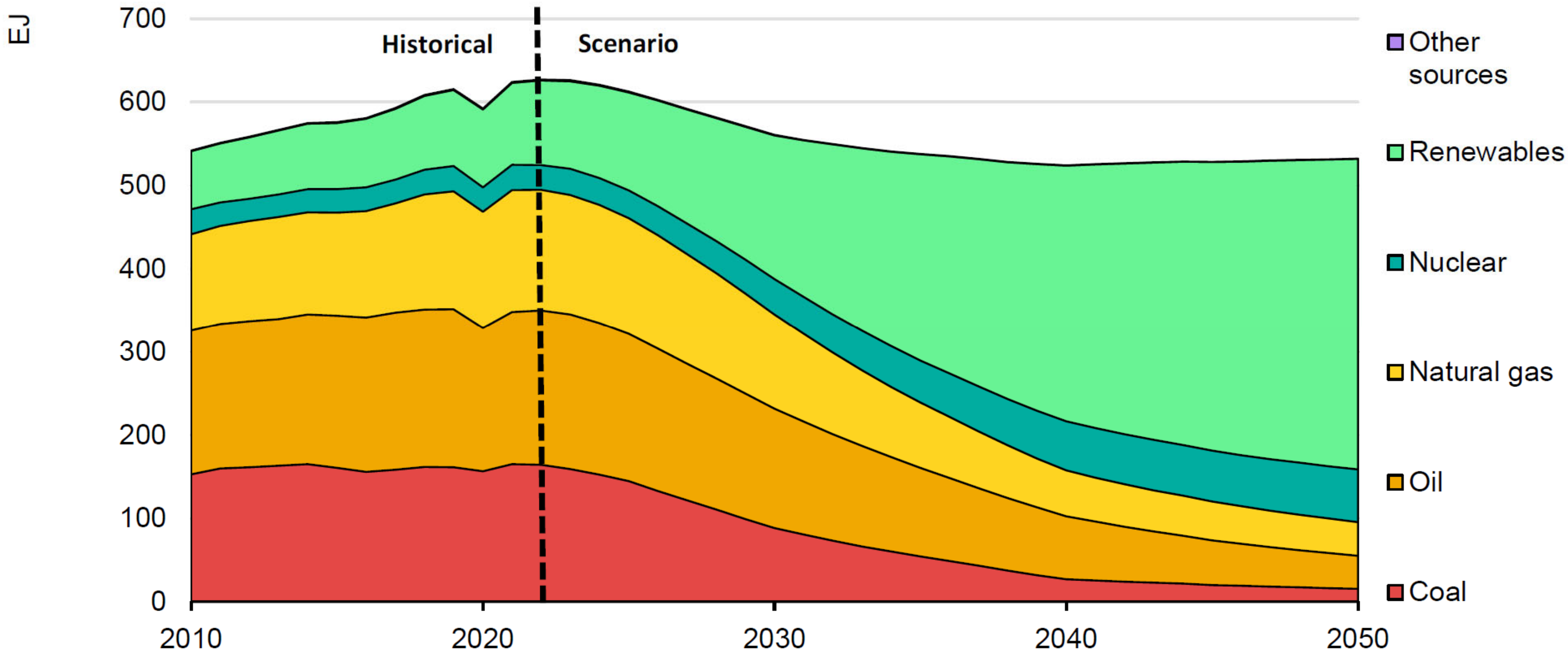
Transport emissions scenario in SDS in ETP2020

Figure 3.16 Global CO_2 emissions in transport by mode in the Sustainable Development Scenario, 2000-70

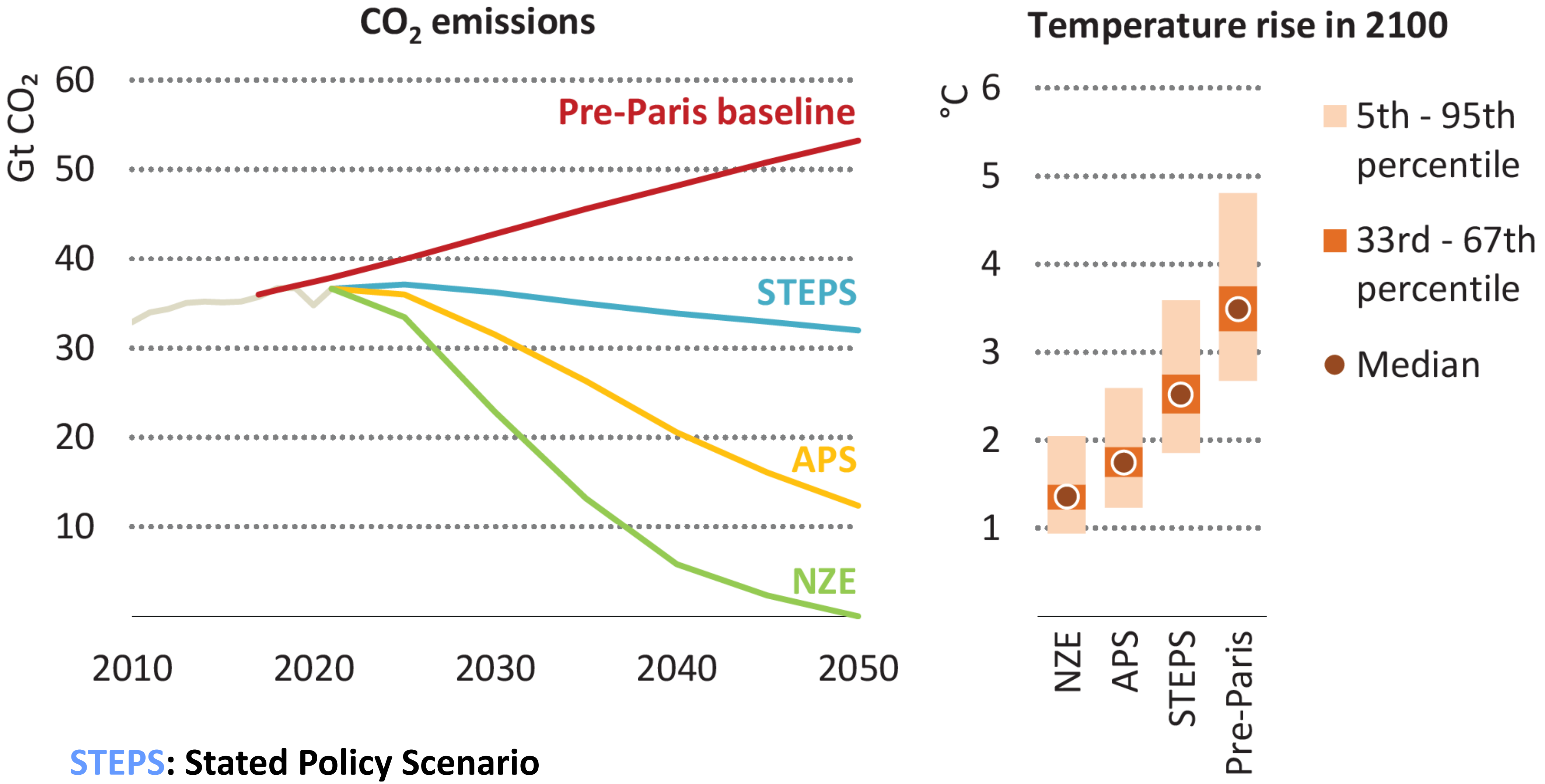


Notes: Dotted lines indicate the year in which various transport modes have largely stopped consuming fossil fuels and hence no longer contribute to direct emissions of CO_2 from fossil fuel combustion. Residual emissions in transport are compensated by negative emissions technologies, such as BECCS and DAC, in the power and other energy transformation sectors.

Global primary energy supply in the NZE scenario in ETP2023



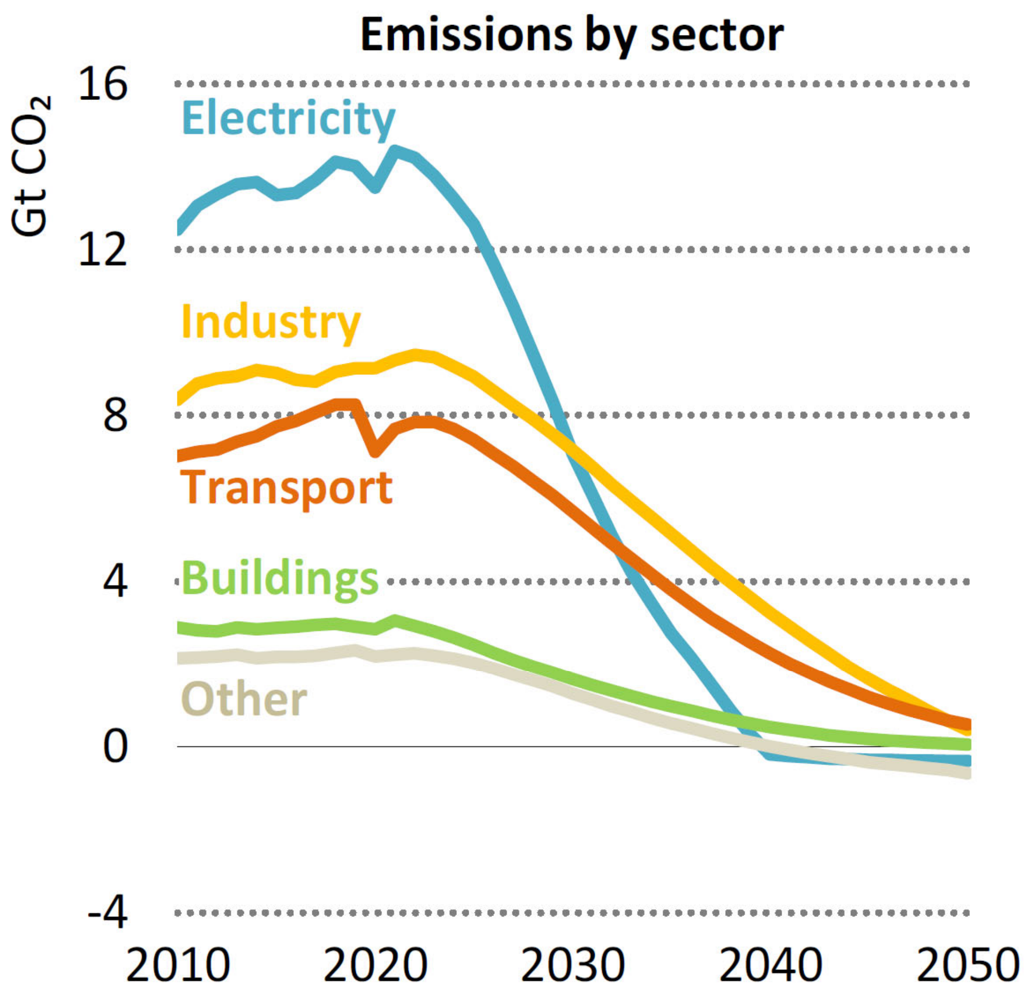
Energy-related and process CO2 emissions and temperature rise by scenario in WEO2022

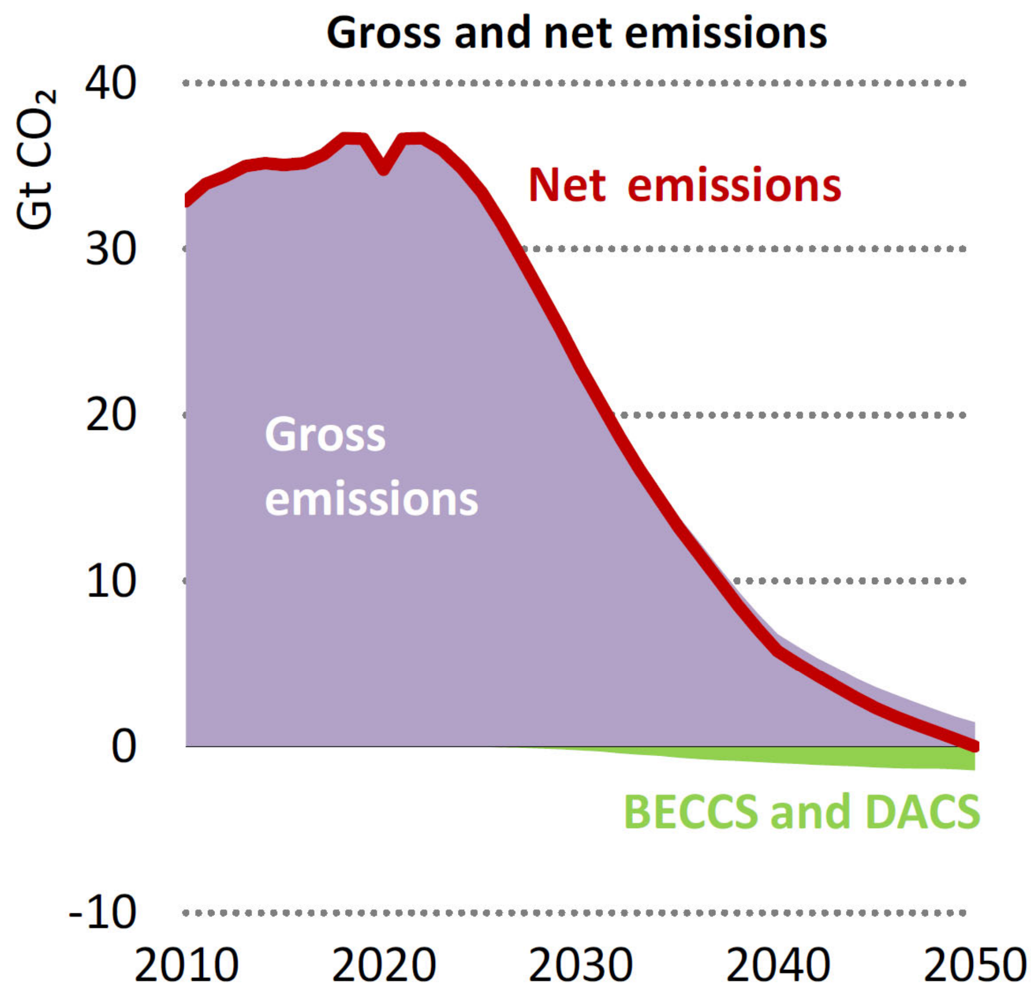


STEPS: Stated Policy Scenario
APS: Announced Pledges Scenario
NZE: Net Zero Emissions by 2050 scenario

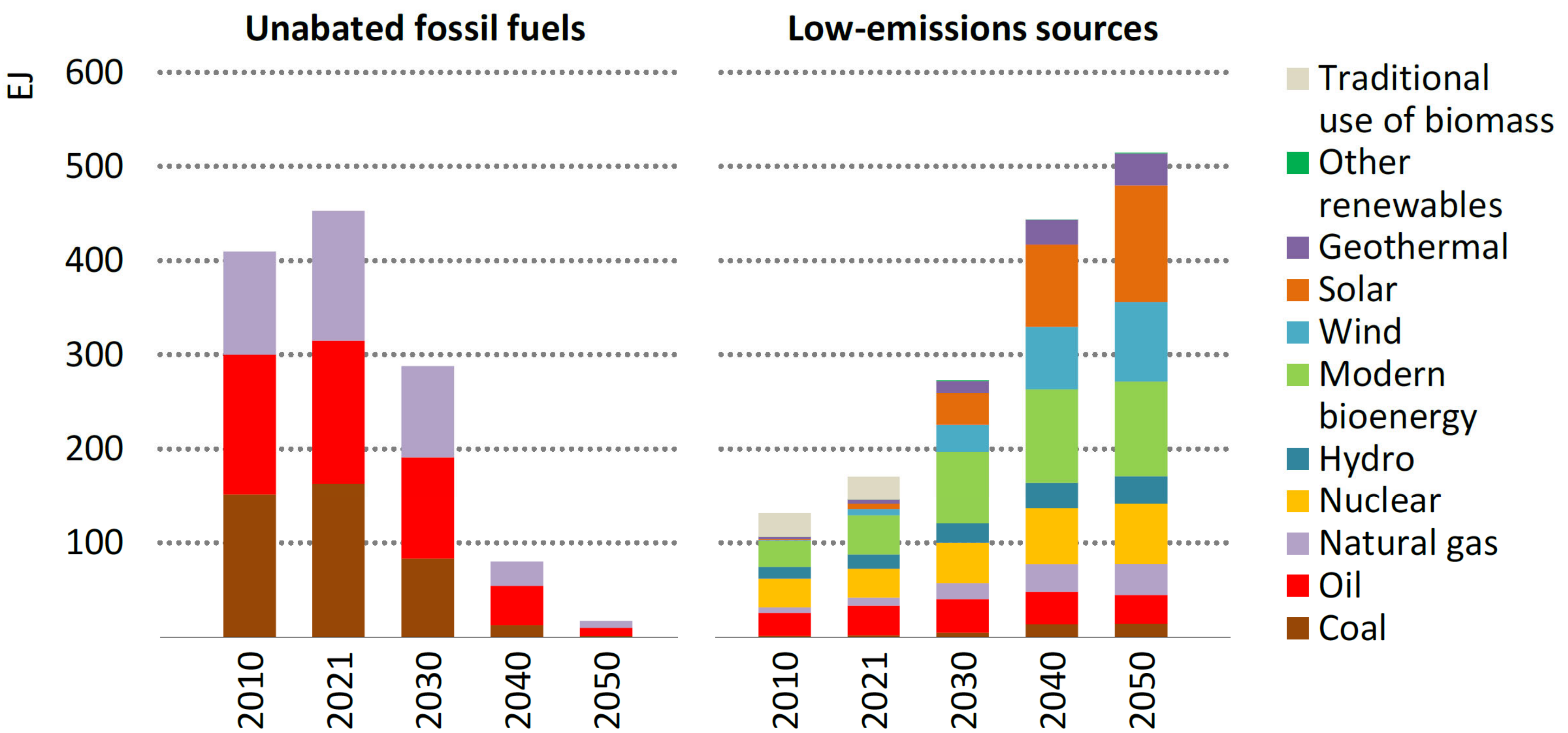
Note) CO2 emissions from energy and industrial process

CO_2 emissions by sector and gross and net emissions in the NZE scenario in WEO2022

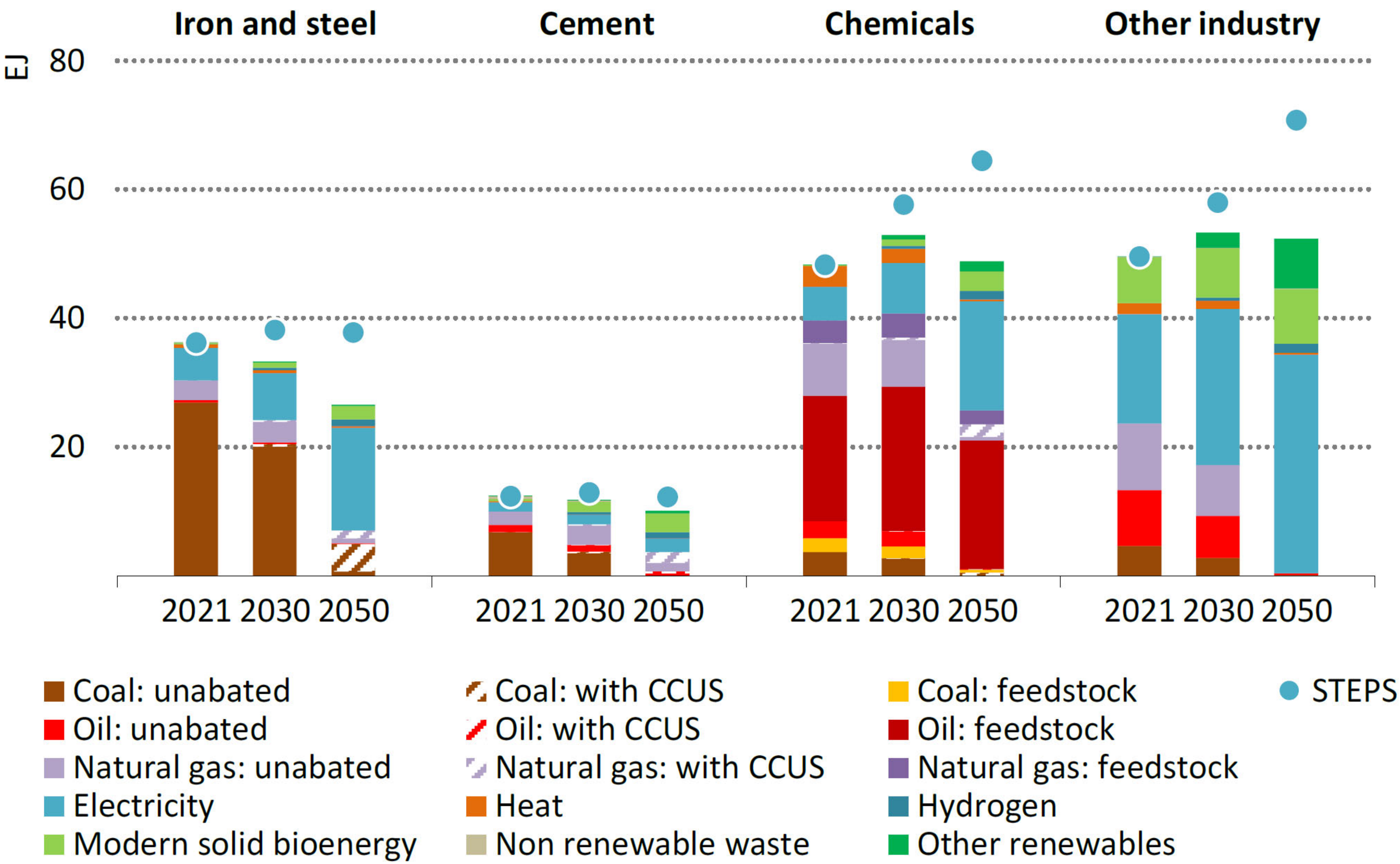




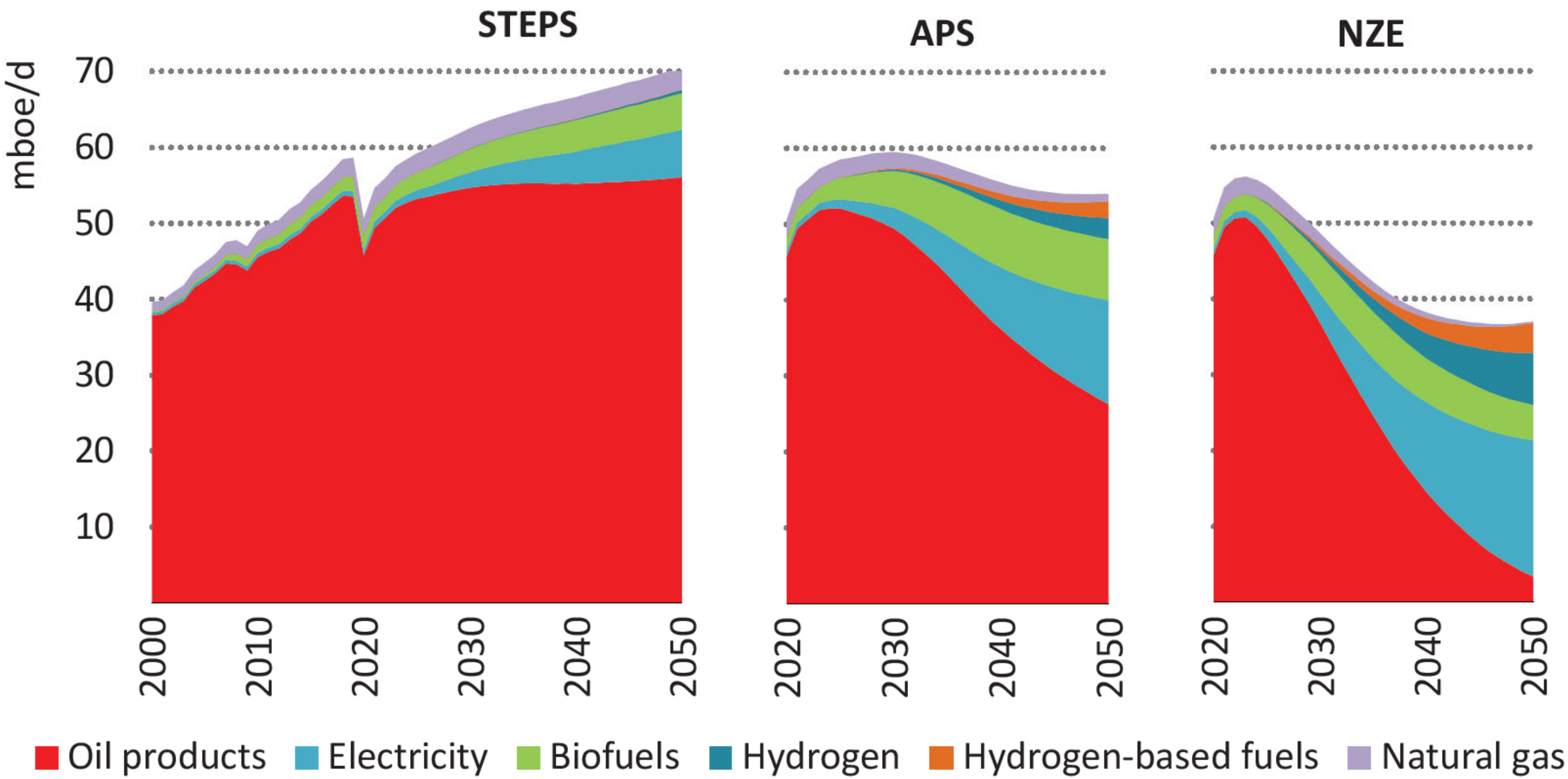
Total primary energy supply in the NZE scenario in WEO2022



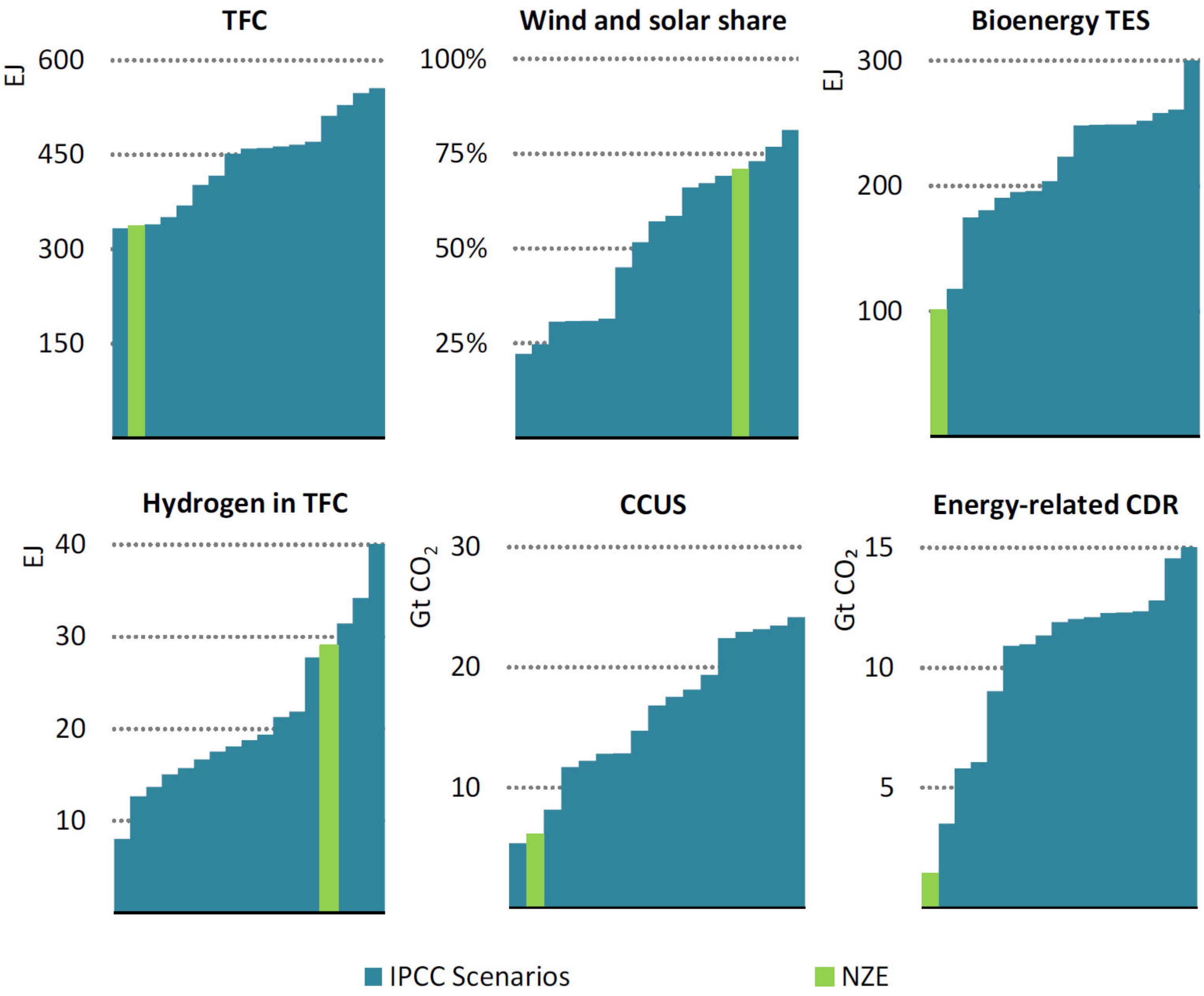
Final energy consumption in industry sub-sectors in the NZE scenario in WEO2022



Energy use in transport by scenario in WEO2022



Comparison with selected IPCC scenarios and the NZE scenario in WEO2022



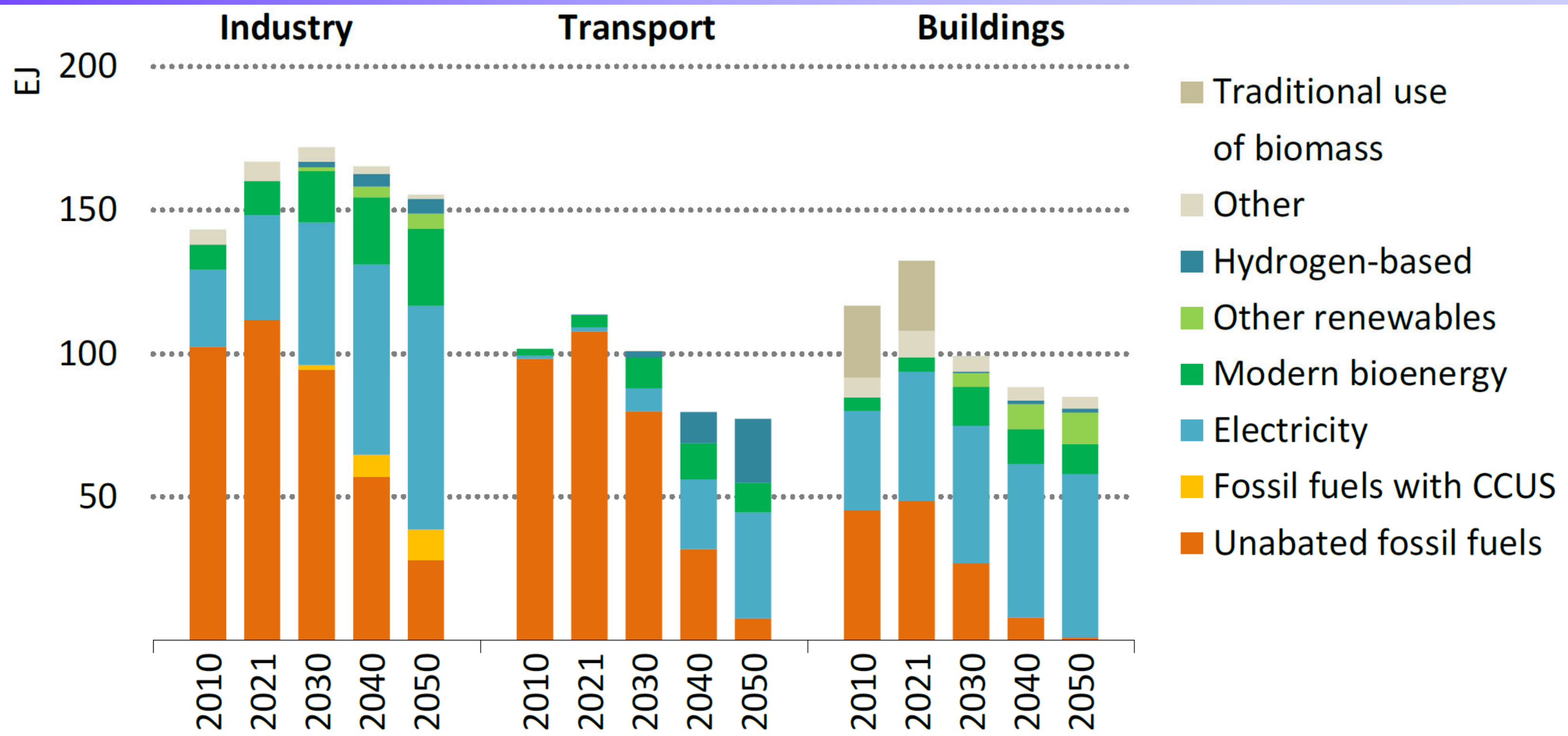
Note) The IPCC scenarios for comparison are only those that reach zero CO2 emissions from energy by 2050 (16 scenarios). The IPCC 1.5 °C scenarios (C1, C2) have 230 scenarios registered.

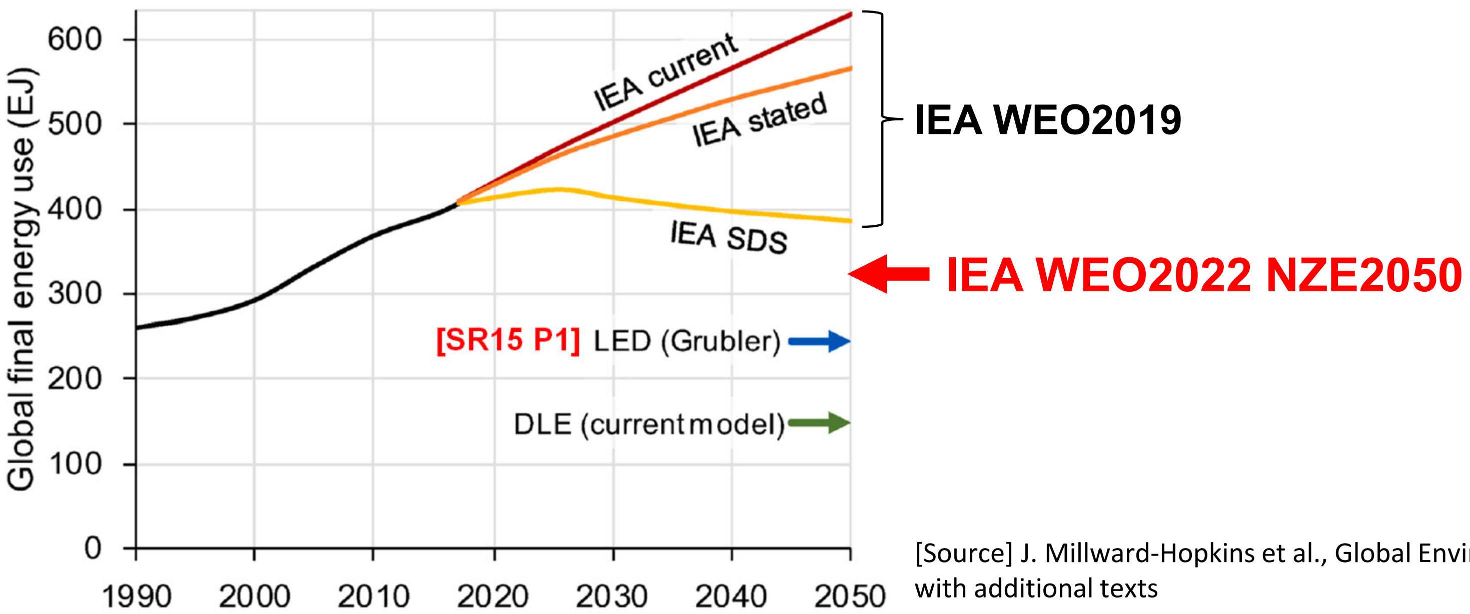
The NZE scenario by IEA can be argued, when compared with scenario analyses by international IAM, as a scenario with

- ✓ **considerably less energy consumption**
- ✓ **higher wind and solar**
- ✓ **considerably small biomass**
- ✓ **considerably less CCS/CDR,**

thus rather a "deviated" scenario than an average one

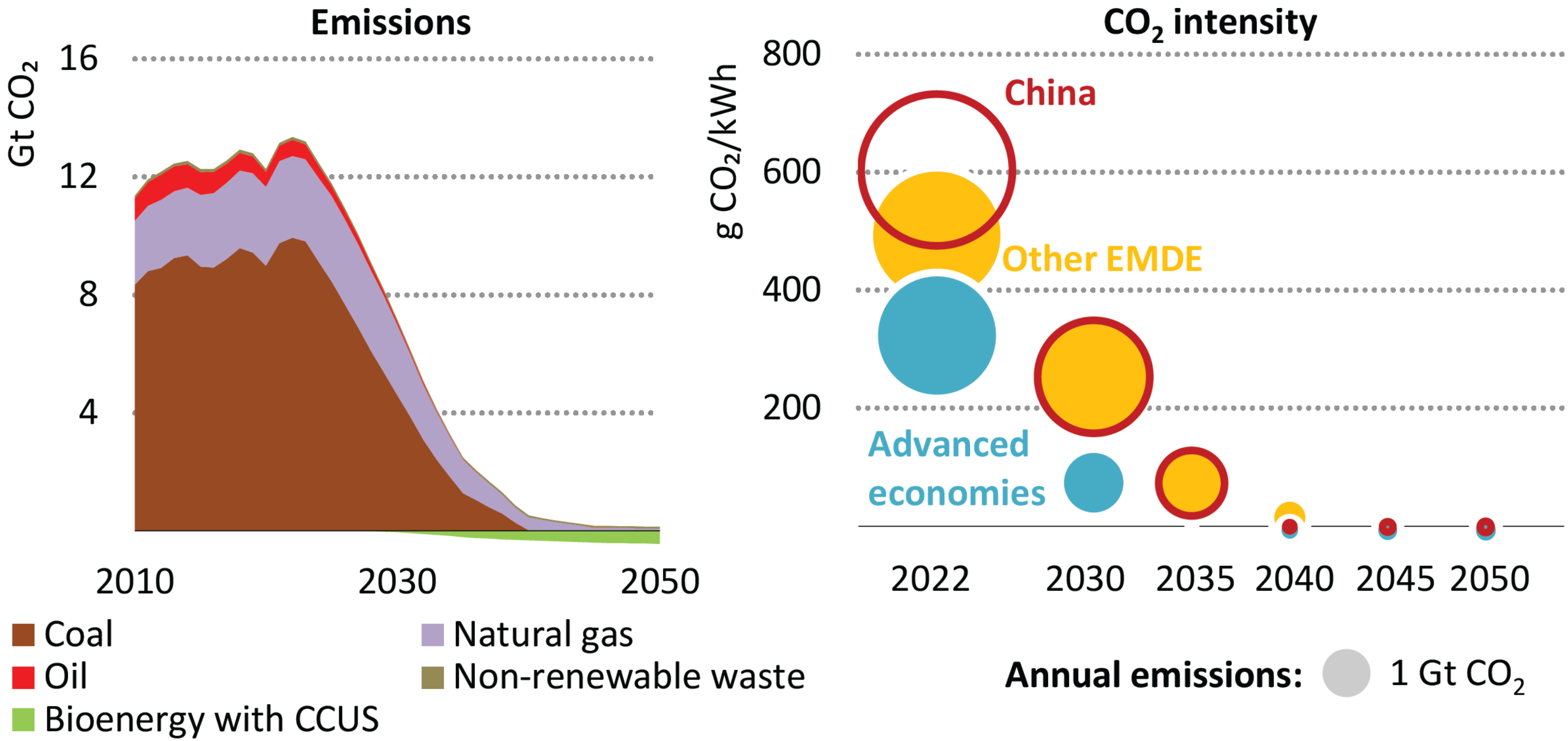
Total final energy consumption by sector in the NZE scenario in WEO2022





[Source] J. Millward-Hopkins et al., Global Environmental Change (2020) with additional texts

Global electricity sector emissions and CO_2 intensity of electricity generation in the NZE Scenario (2023)



- **A rapid decline in fossil fuel generation without CCUS is expected.**
- **Nearly-zero CO2 intensity of electricity generation is expected in 2040.**

2. Development of Quantitative Scenarios and Transition Roadmaps by Using DNE21+ Model

Note) The developed scenarios and roadmaps using the model present average transition pathways for countries and sectors. Decisions about technology choices or investments by individual entities and projects should be made under various circumstances. Individual entities and projects should not treat these roadmaps uniformly as a basis for investment decisions and such, as these could be changed depending on various assumptions.

Energy Assessment Model: DNE21+
(Dynamic New Earth 21+)

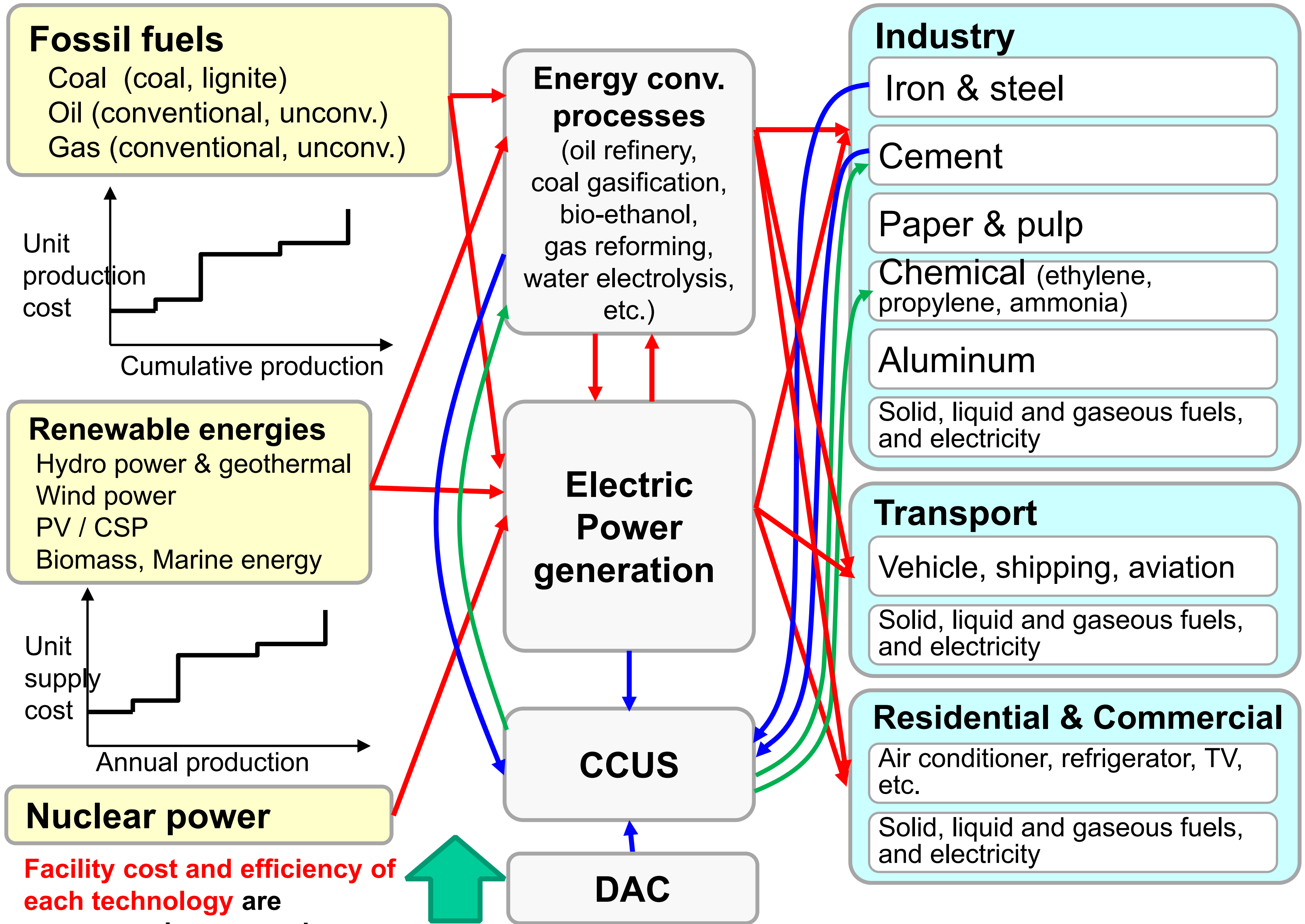
- Systemic cost evaluation on energy and CO_2 reduction technologies is possible.
- Linear programming model (minimizing world energy system cost; with appox. 10mil. variables and approx. 10mil. constrained conditions)
- Evaluation time period: 2000-2100
  Representative time points: 2005, 2010, 2015, 2020, 2025, 2030, 2040, 2050, 2070 and 2100
- World divided into 54 regions
  Large area countries, e.g., US and China, are further disaggregated, totaling 77 world regions.
- Interregional trade: coal, crude oil/oil products, natural gas/syn. methane, electricity, ethanol, hydrogen, CO_2 (provided that external transfer of CO_2 is not assumed in the baseline)
- Bottom-up modeling for technologies on energy supply side (e.g., power sector) and CCUS
- For energy demand side, bottom-up modeling conducted for the industry sector including steel, cement, paper, chemicals and aluminum, the transport sector, and a part of the residential & commercial sector, considering CGS for other industry and residential & commercial sectors.
- Bottom-up modeling for international marine bunker and aviation.
- Around 500 specific technologies are modeled, with lifetime of equipment considered.
- Top-down modeling for others (energy saving effect is estimated using long-term price elasticity.)

- **Regional and sectoral technological information provided in detail enough to analyze consistently.**
- **Analyses on non-CO_2 GHG possible with another model RITE has developed based on US EPA's assumptions.**

- **Model based analyses and evaluation provide recommendation for discussions on some energy and climate change policy making processes, e.g., cap-and-trade system, Environmental Energy Technology Innovation Plan, 6th Energy Strategic Plan for the Government of Japan, and also contribute to IPCC scenario analyses.**

The structure of DNE21+ model

Oil prices in baseline assuming no climate measures are exogenously assumed, and other price factors, e.g., unit production costs, concession fees, are adjusted. In emission reduction case, prices are endogenously decided accordingly.



Facility cost and efficiency of each technology are exogenously assumed.

For main sectors modeled in a bottom-up way, economic activities and service demands (e.g., production of crude steel and cement, passenger service demand) are exogenously assumed.

The caveats of the model analyses

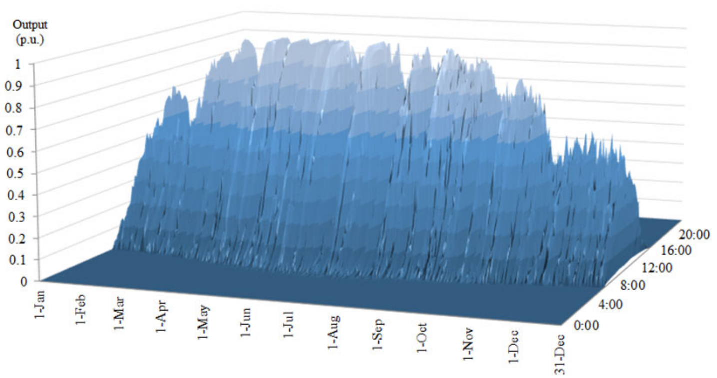
- The DNE21+ model features a capability of global energy system assessment while maintaining consistencies in prices and volumes of energy trade. The model emphasizes worldwide consistency for assumptions. For example, the potentials of solar, wind, or CO2 storage for each country are estimated with the same estimation methodology, based on worldwide GIS data.
- This feature allows it to easily conduct comparative assessments of technology and economic potentials among countries. On the other hand, each country's situation (e.g. social and physical constraints towards nuclear, renewable energies, or CCS in Japan) is not fully considered.
- Therefore, a more detailed analysis of Japan requires separate and further consideration of country-specific constraints. For example, power grid configuration in Japan is not considered in the model which makes it difficult to assess differences in grid integration costs of VRE among areas. => The results of the study with the power generation mix model by the University of Tokyo and the IEEJ are employed (see next page).
- This scenario analysis does not consider energy security issues, although actual policies should take GHG reduction measures while considering energy security.
- Being a dynamic optimization model, a midpoint (e.g. 2050) assessment can be done while capturing the future outlook towards 2100. It assesses based on cost minimization, and therefore arbitrary scenario settings are excluded to the utmost; however, this may cause extreme changes such as sudden and complete technology replacement once economic rationality is established. Especially, analysis results of transition should be interpreted with caution. (There exist various decision-makers in the real world and technology choices often follow a diffusion curve instead of abrupt change. Compared to econometric models that can represent them well, this optimization model may show abrupt changes.)

Integration cost of VRES: integration with a power generation mix model by Univ. of Tokyo and IEEJ

- As DNE21+ is a global model and not suitable for the analysis regarding internal power grid and regional conditions of renewable energy, it applies the results of the study on the assumption of integration cost under high VRE penetration based on an optimal power generation mix model, by Fujii-Komiyama Laboratory, the University of Tokyo and the Institute of Energy Economics, Japan.
- Time fluctuation of VRE output is modeled based on nationwide meteorological data, e.g., AMeDAS, to estimate the optimal configuration (power generation and storage system) and the annual operation by linear programming.
- Calculated with hourly modeling by 5 divided regions (Hokkaido, Tohoku, Tokyo, Kyushu and others). Prerequisites for power generation cost, resource constraint, etc, are defined in line with DNE21+.

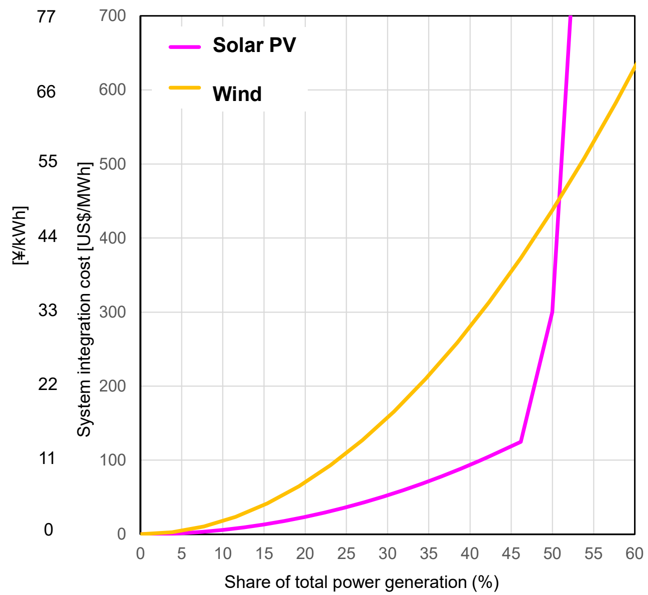
Considered in modeling･･･ Output control, power storage system (pumped hydro, lithium-ion battery and hydrogen storage), reduction of power generation facility utilization, inter-regional power transmission lines, electricity loss in storage and transmission

Not considered in modeling･･･ Intra-regional power transmission lines, power grid, influence of decrease of rotational inertia, grid power storage by EV, prediction error of VRE output, supply disruption risk during dark doldrums



Output example of PV

Grid integration costs approximated from the analysis of the Univ. of Tokyo – IEEJ power generation mix model＝Assumption on grid integration costs in DNE21+ (Marginal cost when each implementation share is realized)



As the VRE ratio increases, marginal integration costs tend to rise relatively rapidly. This is because under the circumstance where a large amount of VRE has already been installed, if it is further installed, it will be required to maintain an infrequently used power storage system or transmission line to deal with the risk that cloudy weather and windless conditions will continue for several days or more.

Assumed scenarios for the 2 °C and 1.5 °C goals

Scenarios	Global average temp. increase	Policy speed#	CDR contribution	Renewables and BEV	Differences in policy intensity among regions	Relation to other scenarios: IPCC AR6 (IPCC 2022)	NGFS (2022)	IEA
Disorderly Below 2 °C	1.7 °C in 2100 (peak:1.8 °C)	Gradual (NDCs in 2030)	medium	Medium cost reductions	Large (major developed countries: CN by 2050)	Likely below 2 C, NDC [C3b]	Disorderly: Delayed Transition	APS (WEO 2022)
Orderly Below 2 °C	1.7 °C	Rapid	Small	High cost reductions	Small (equal MAC among countries)	Likely below 2 C with immediate action [C3a]	Orderly: Below 2C	SDS (WEO 2021)
Disorderly 1.5 °C	1.4 °C in 2100 (peak:1.7 °C)	Gradual (NDCs in 2030)	Large	Medium cost reductions	Large (major developed countries: CN by 2050)	1.5 C with high overshoot (IMP-Neg) [C2]	(Disorderly: Divergent Net Zero)*	
Orderly 1.5 °C	1.4 °C in 2100 (peak:1.6 °C)	Rapid	Medium	High cost reductions	Medium (major developed countries: CN by 2050)	1.5 C with no or limited overshoot [C1]	Orderly: Net Zero2050	
1.5C-CO2_CN	Approx. below 1.5 °C	Rapid	Small (Near-zero of CO_2 by sector)	High cost reductions	Large (major developed countries: CN by 2050)	1.5 C with no or limited overshoot [C1]		NZE

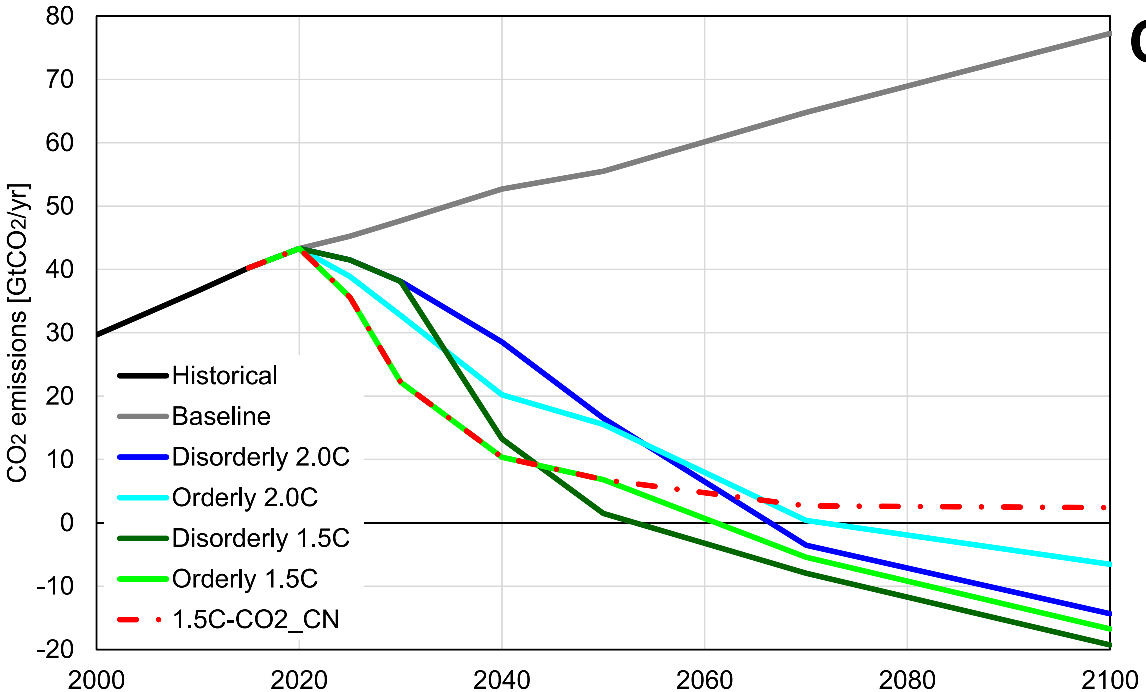
The emission reduction targets in 2030 of NDCs submitted in the end of December 2021 are considered.

* The emissions pathway is rather similar to the Orderly 1.5 °C

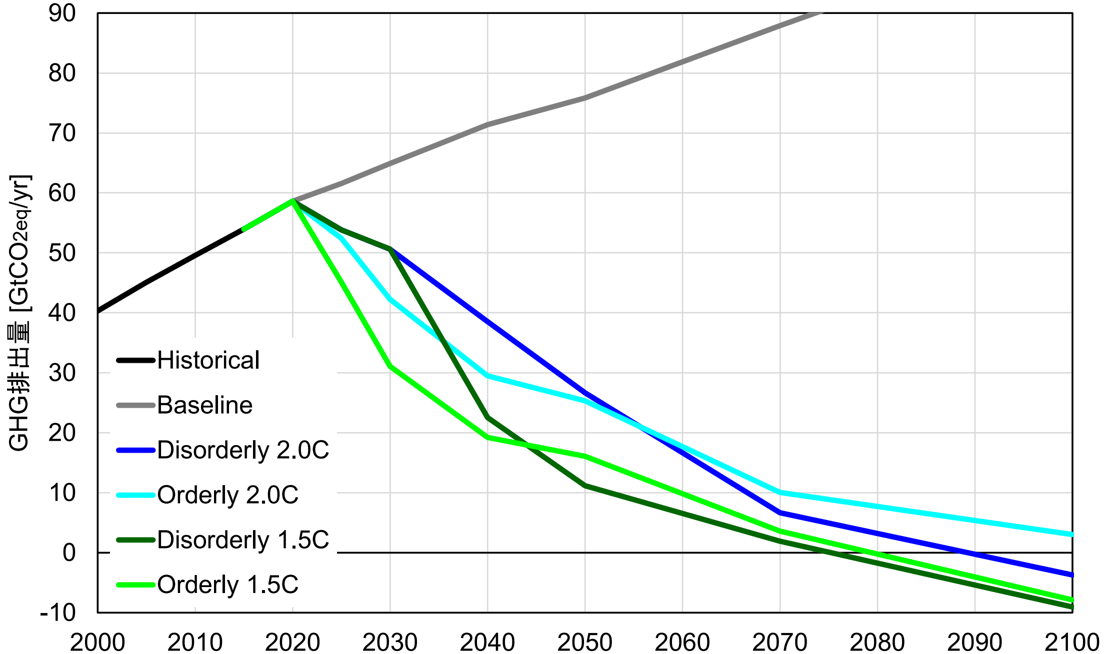
- ✓ **The assumed scenarios are consistent with the long-term goals of Paris Agreement, and cover the existing scenarios which are widely referred globally.**
- ✓ **The scenarios also cover a certain range of uncertainties in technologies and policies.**

Global emissions pathways

CO2

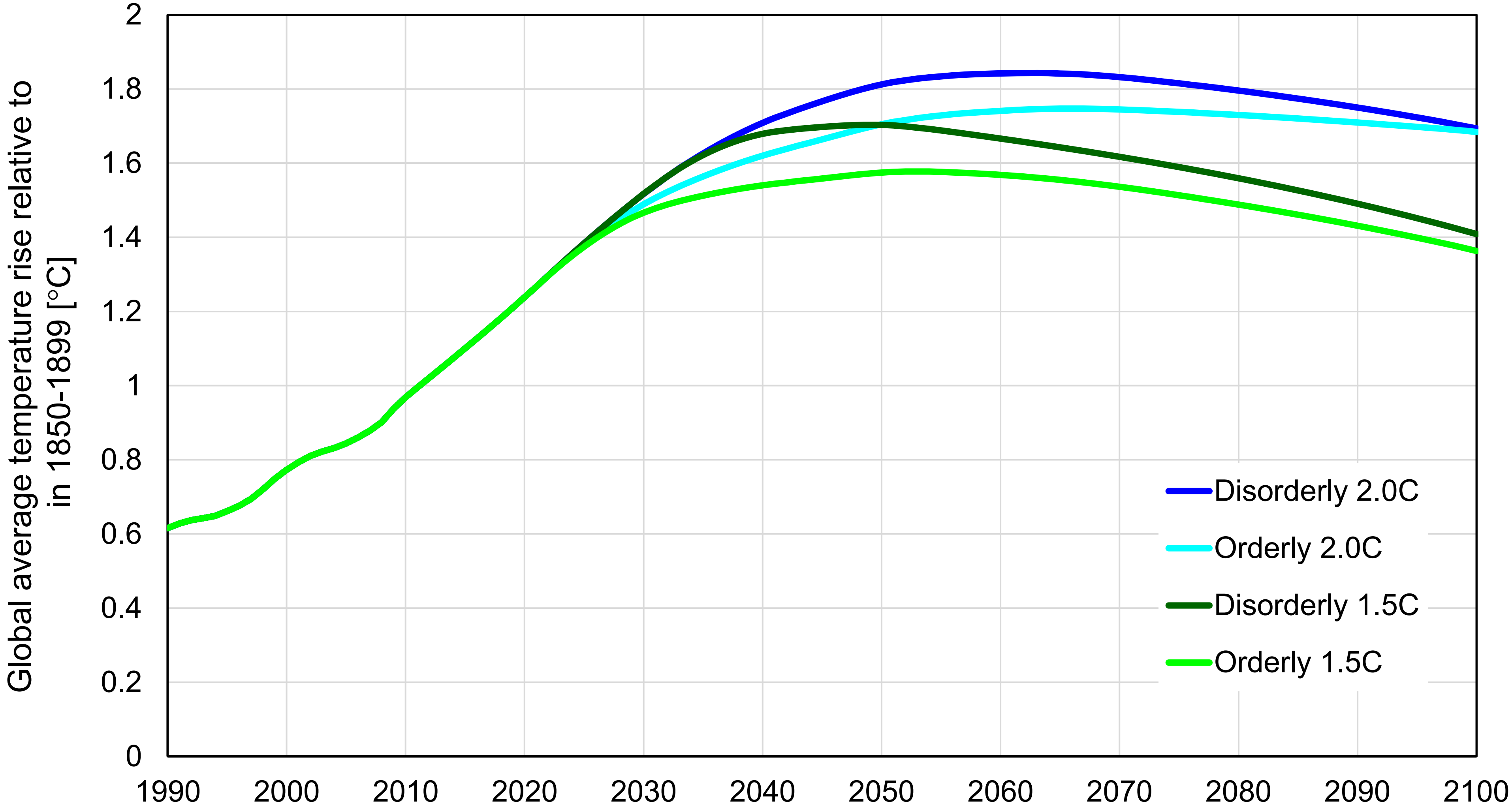


GHG



- ✓ **Global CO_2 emissions reach net zero by around 2050-60 under 1.5°C scenarios, and the GHG emissions reach net zero by around 2075-80.**
- ✓ **For the 2.0°C scenarios, the CO_2 and GHG emissions reach net zero by around 2065-80 and 2090-2100, respectively.**
- ✓ **GHG emissions in 2030 are estimated to be 51 $GtCO_2eq$./y due to NDCs.**

Global average temperature rise for the assumed scenarios



(0) World

CO_2 marginal abatement costs for the 2 °C scenarios

Disorderly 2.0C

Unit: \$/tCO_2

	2030	2040	2050
Japan	470	298	500
US	199	241	229
EU27	282	208	284
Korea	147	80	118
China	35		
Others	Different among countries due to different NDCs		

Orderly 2.0C

	2030	2040	2050
Japan	81	251	158
US			
EU27			
Korea			
China			
Others			

CO_2 marginal abatement costs for the 1.5 °C scenarios

Disorderly 1.5C

unit: $/t$CO_2$

<table>
<tr><th></th><th>2030</th><th>2040</th><th>2050</th></tr>
<tr><td>Japan</td><td>423</td><td>456</td><td>686</td></tr>
<tr><td>US</td><td>211</td><td>291</td><td>276</td></tr>
<tr><td>EU27</td><td>283</td><td>291</td><td>324</td></tr>
<tr><td>Korea</td><td>141</td><td rowspan="3">291</td><td rowspan="3">269</td></tr>
<tr><td>China</td><td>39</td></tr>
<tr><td>Others</td><td>Different among countries due to different NDCs</td></tr>
</table>

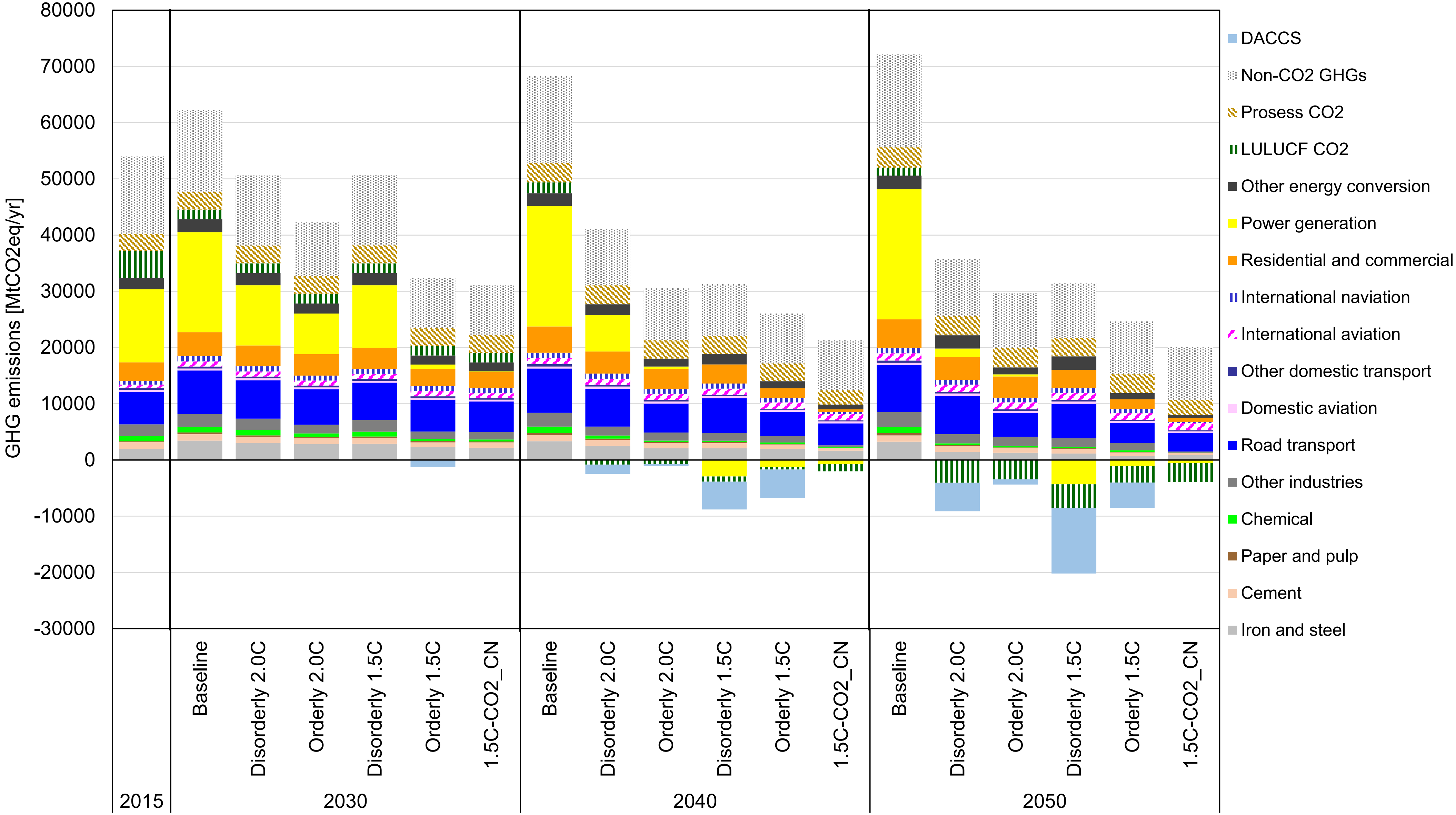
Orderly 1.5C

<table>
<tr><th></th><th>2030</th><th>2040</th><th>2050</th></tr>
<tr><td>Japan</td><td rowspan="4">234</td><td>518</td><td>466</td></tr>
<tr><td>US</td><td rowspan="3">492</td><td>301</td></tr>
<tr><td>EU27</td><td>323</td></tr>
<tr><td>Korea, China and others</td><td>267</td></tr>
</table>

1.5C-CO2_CN

<table>
<tr><th></th><th>2030</th><th>2040</th><th>2050</th></tr>
<tr><td>Japan</td><td rowspan="4">281</td><td rowspan="4">706</td><td>345</td></tr>
<tr><td>US</td><td>310</td></tr>
<tr><td>EU27</td><td>350</td></tr>
<tr><td>Korea, China and others</td><td>293</td></tr>
</table>

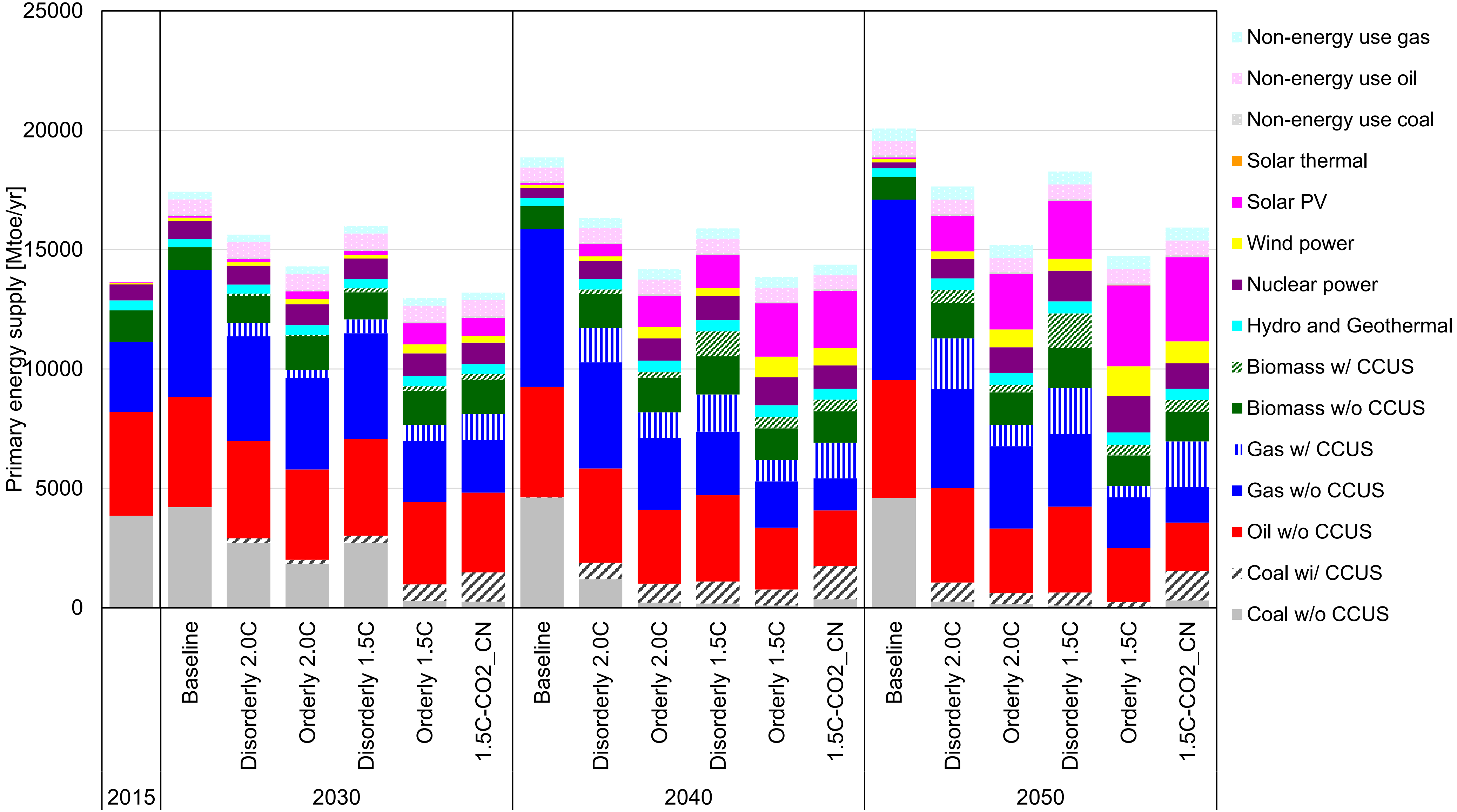
GHG emissions (World)



Note) The 1.5C-CO2_CN scenario analyzes only on CO2, but the figure includes non-CO2 GHG emissions of Orderly 1.5C.

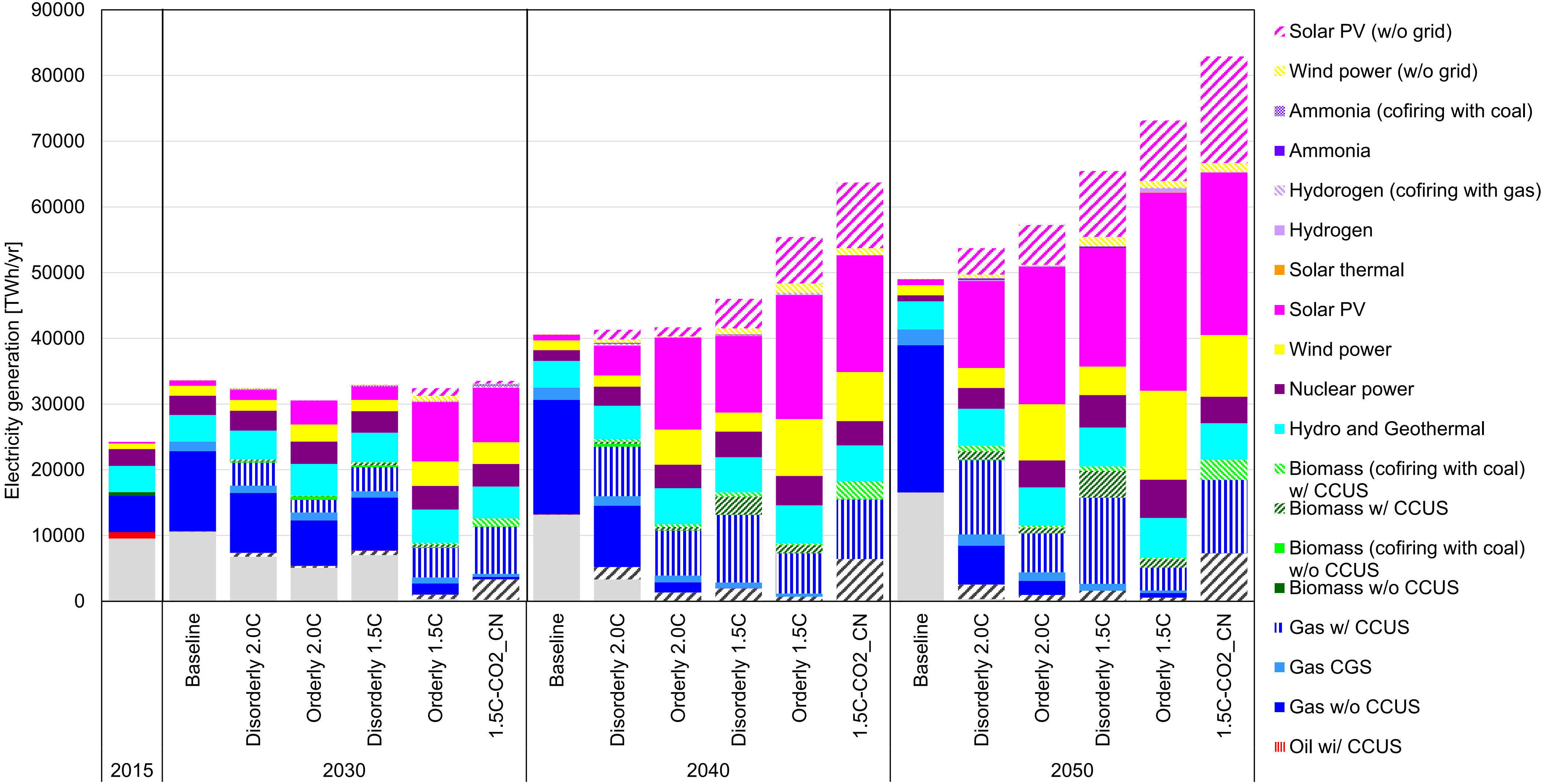
- ✓ **The amounts of CO_2 fixations due to CDR is approximately 20GtCO$_2$eq/yr in 2050 for the Disorderly 1.5°C, and those for other scenarios are below 10 GtCO$_2$eq/yr.**
- ✓ **Non-CO_2 GHG emissions of approx. 10 GtCO$_2$eq/yr remain in 2050 even in both 2°C and 1.5°C scenarios.**

Primary energy supply (World)



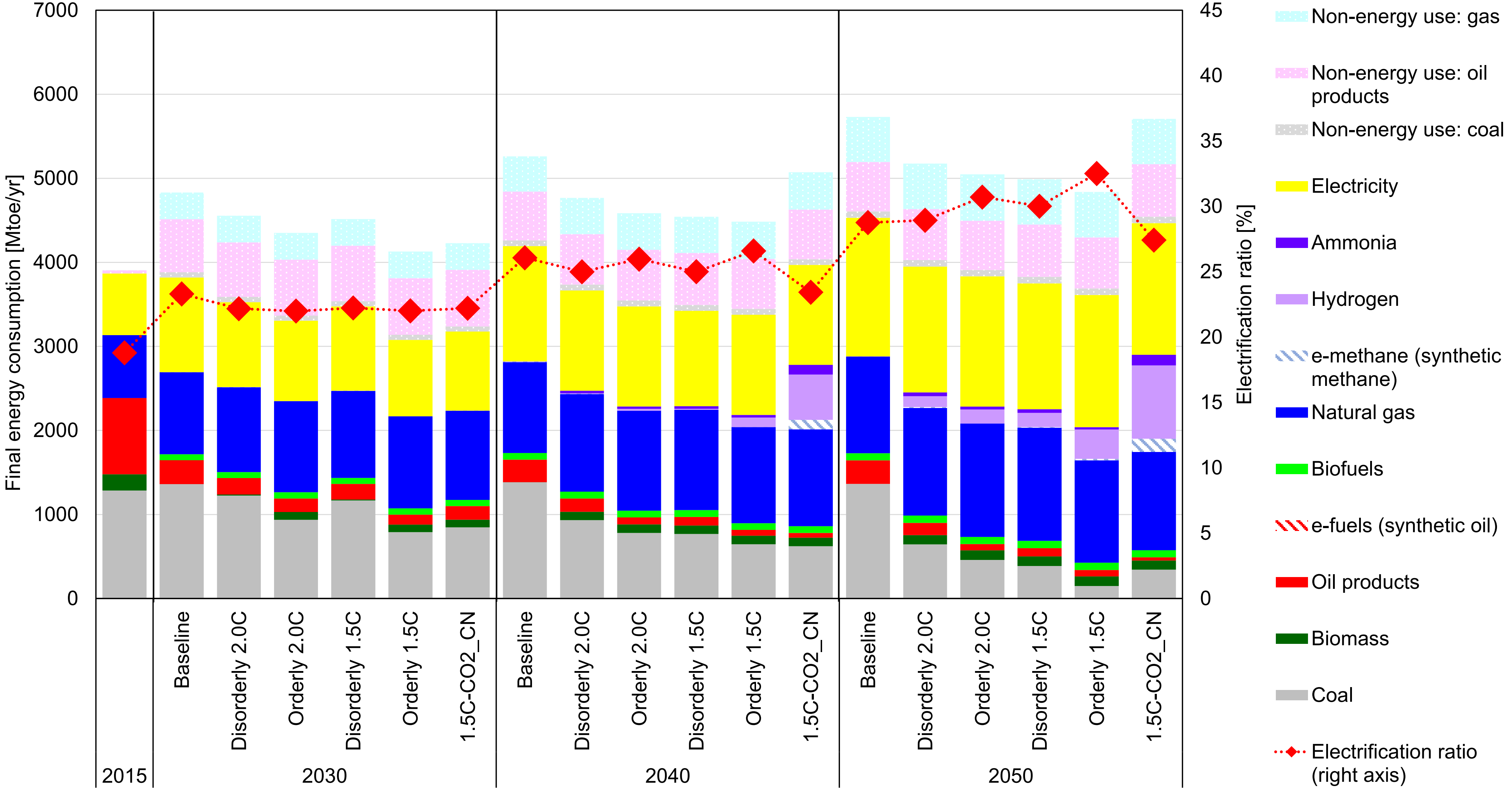
✓ **Thanks to CDR contributions, fossil fuel uses without CCS still remain in 2050 even for the 1.5°C scenarios.**

Electricity supply (World)



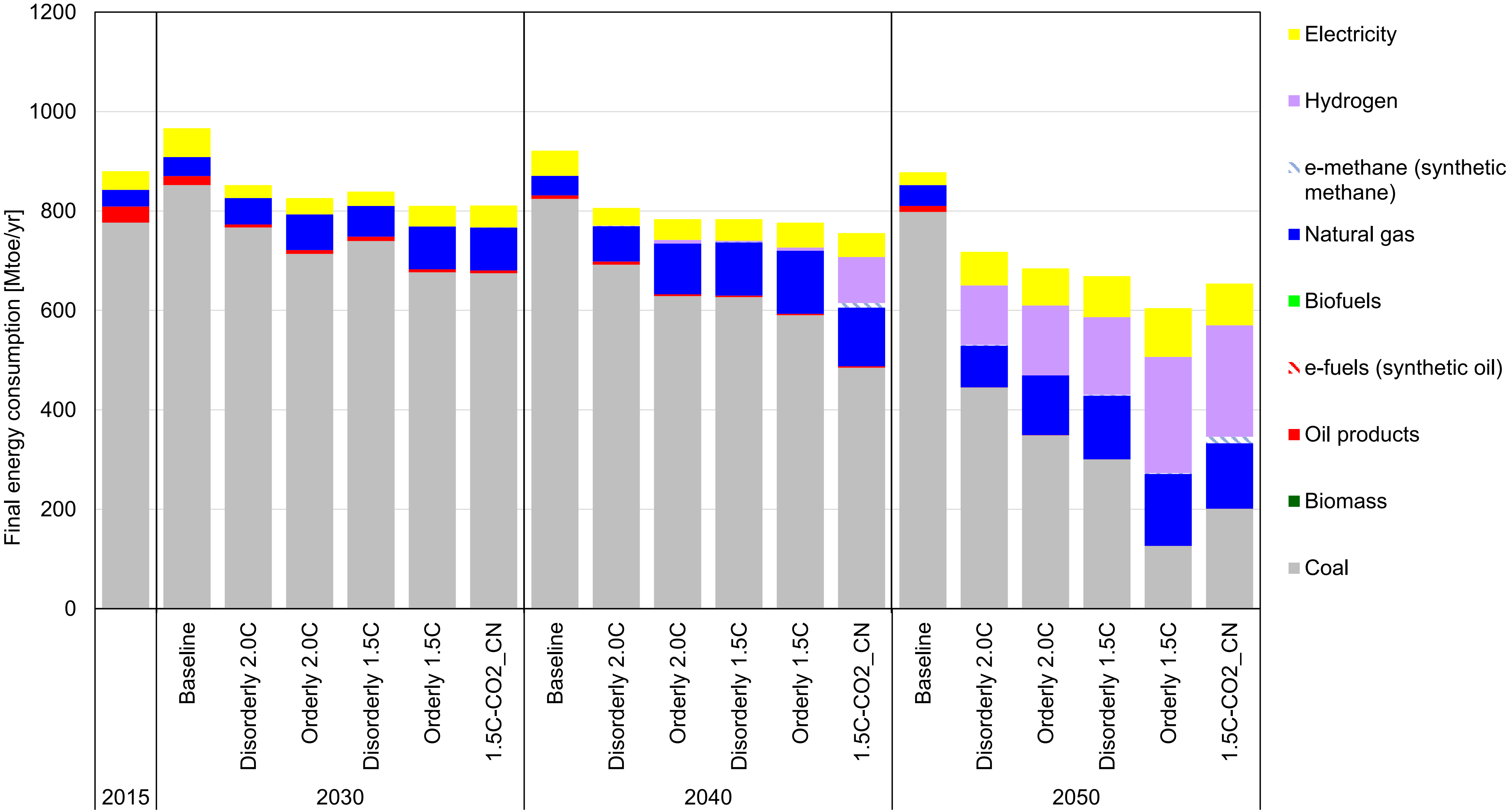
- ✓ **Potentials of CO2 geological storage is large in the world, the shares of gas power with CCS are relatively high compared with those in Japan.**
- ✓ **In the Orderly 1.5°C/2.0°C scenarios which assume larger constraints of the access of CO2 geological storage, larger deployments of solar PV and wind power are estimated.**

Final energy consumption in industry (World)



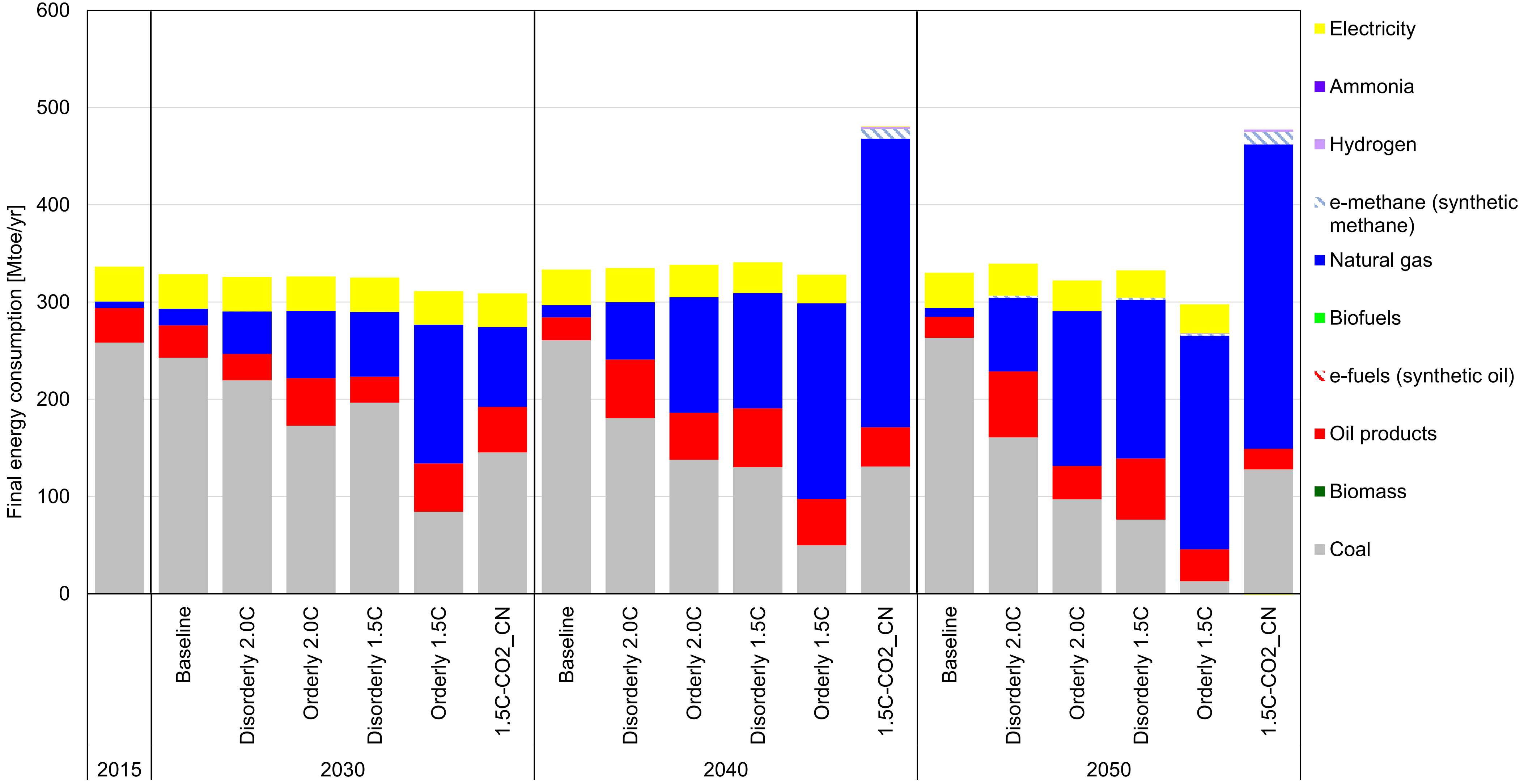
- ✓ **Coal uses reduce, and gas and electricity uses increase for the 2°C/1.5°C scenarios in the world.**
- ✓ **The shares of hydrogen, ammonia, and synthetic methane (e-methane) uses are relatively small compared with those of Japan due to cheaper renewables and CCS, and larger power grid connections.**

Final energy consumption in iron & steel (World)



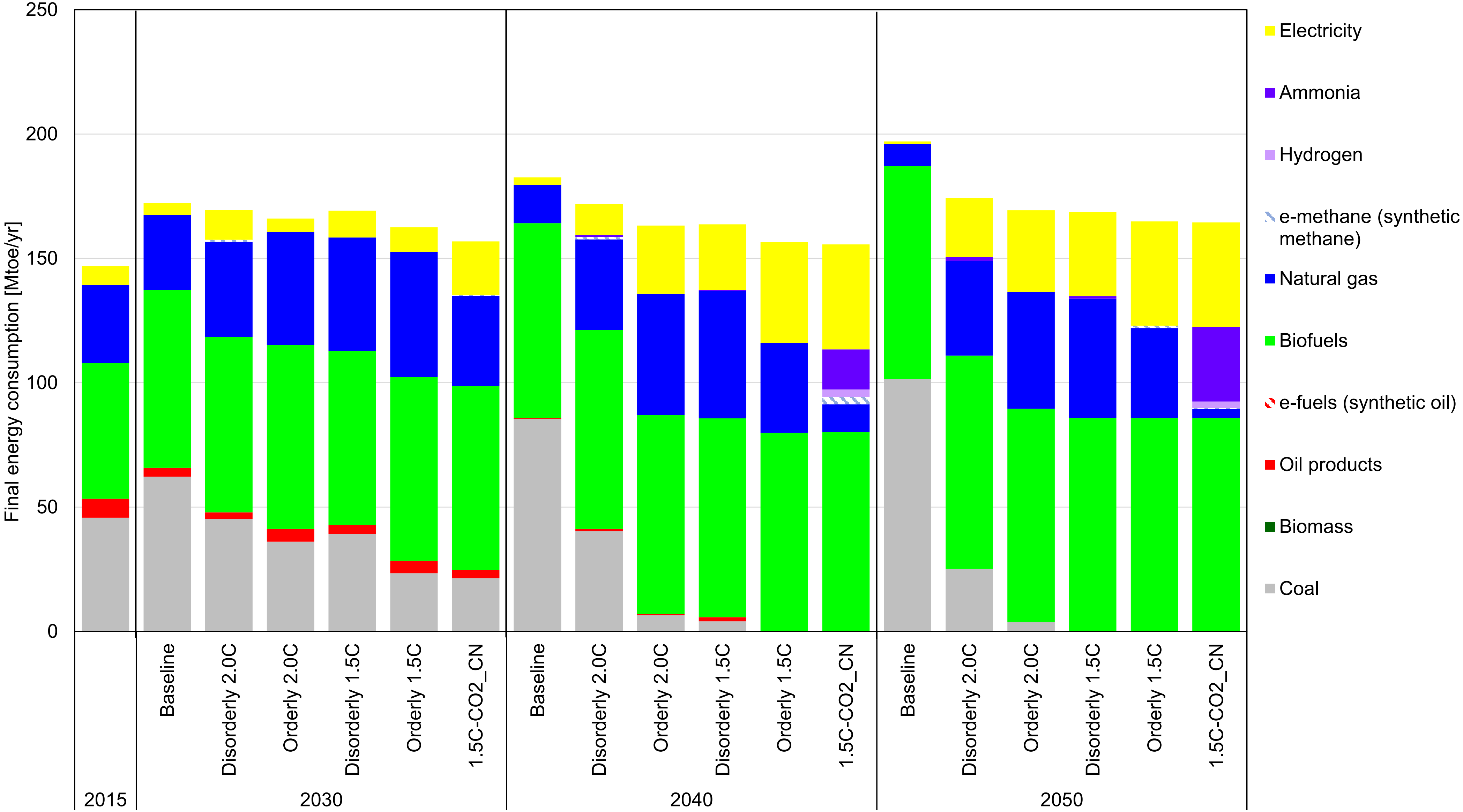
- ✓ **Total final energy consumption will decrease due to energy savings and shifts to electric furnace. Meanwhile coal is still major energy sources by around 2040.**
- ✓ **After 2040, hydrogen from outside of steel making processes (e.g., Super COURSE50) are used, and hydrogen-use DRI are cost-effective options in 2050, and large hydrogen uses are observed**

Final energy consumption in cement (World)



- ✓ **A shift from coal to gas is cost-effective under 2°C/1.5°C scenarios.**
- ✓ **While efficiency continues to improve, there are some cases in which slightly more energy is consumed compared with the Baseline, due to energy use for CO_2 capture, especially in 1.5C-CO2_CN which assumes a small contribution of CDR.**

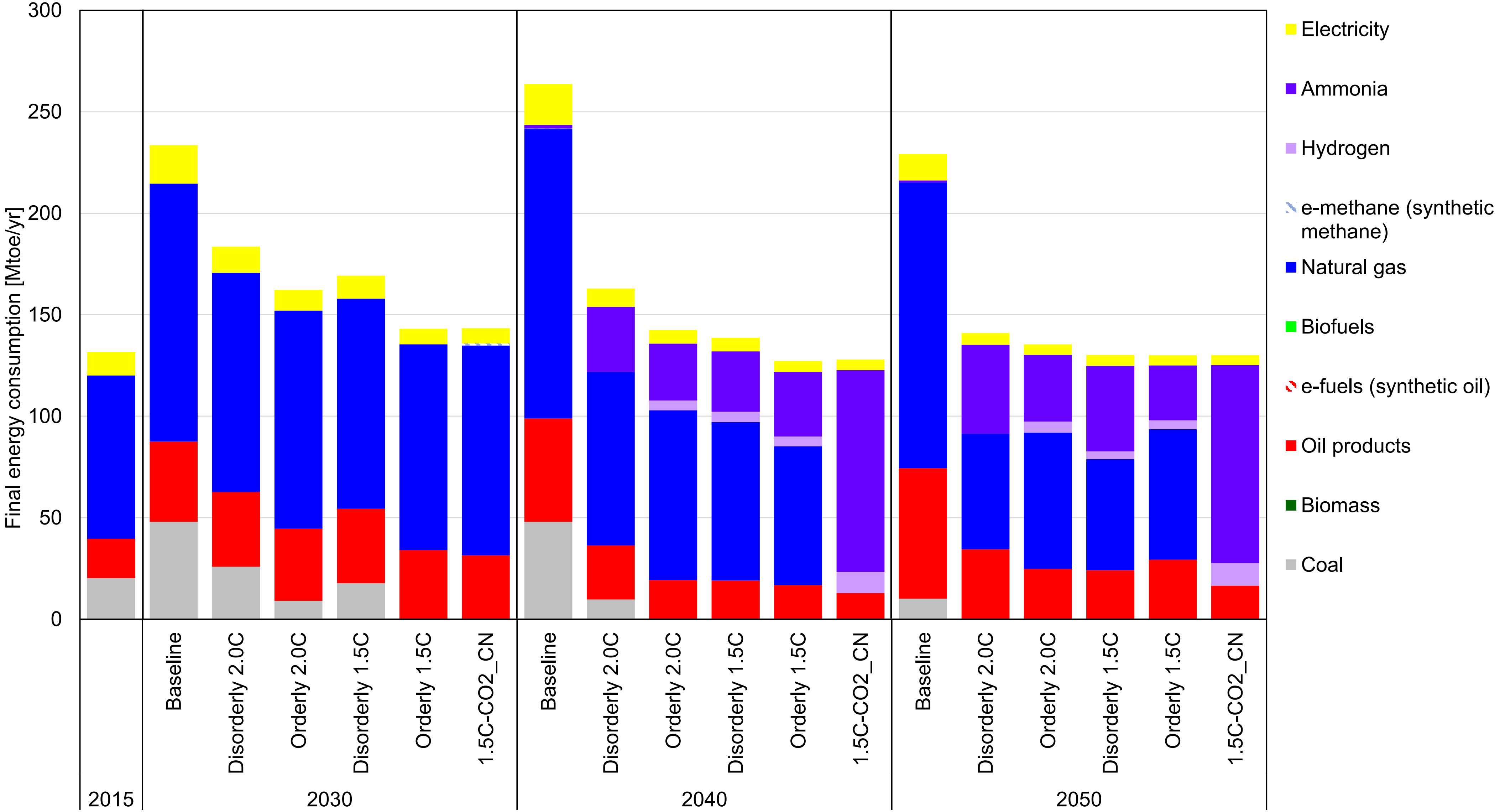
Final energy consumption in paper & pulp (World)



Note) The use of black liquor is included in biofuels consumption.

- ✓ **A shift from coal to gas is cost-effective.**
- ✓ **The uses of ammonia and synthetic methane are observed in the world, even though the amount is small. (There are certain amounts of those uses in 1.5C-CO2_CN, which assumes a small contribution of CDR.)**

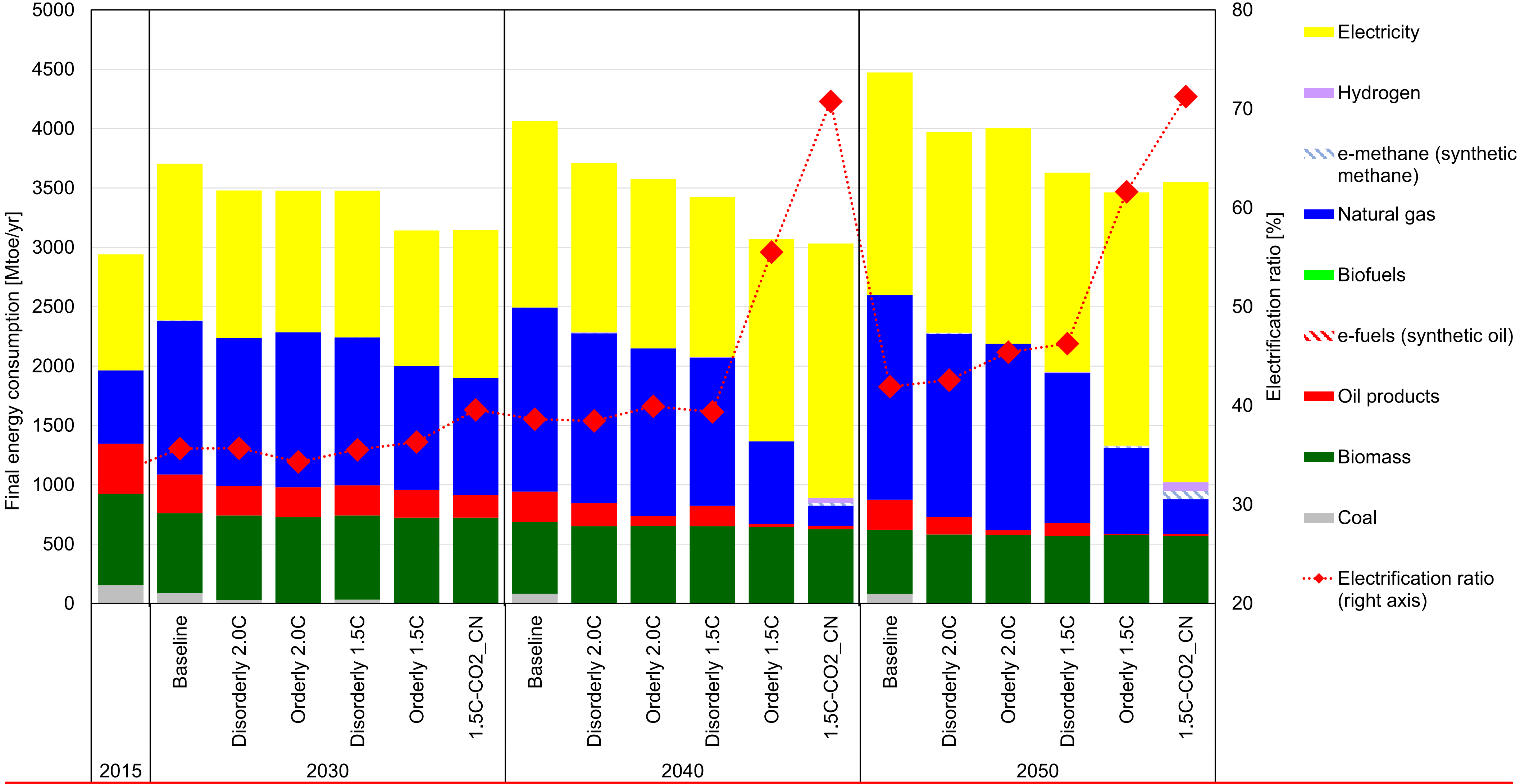
Final energy consumption in petrochemical (ethylene, propylene, and BTX productions) (World)



Note) The graph shows only energy usage consumption, and energy for raw material is not included.

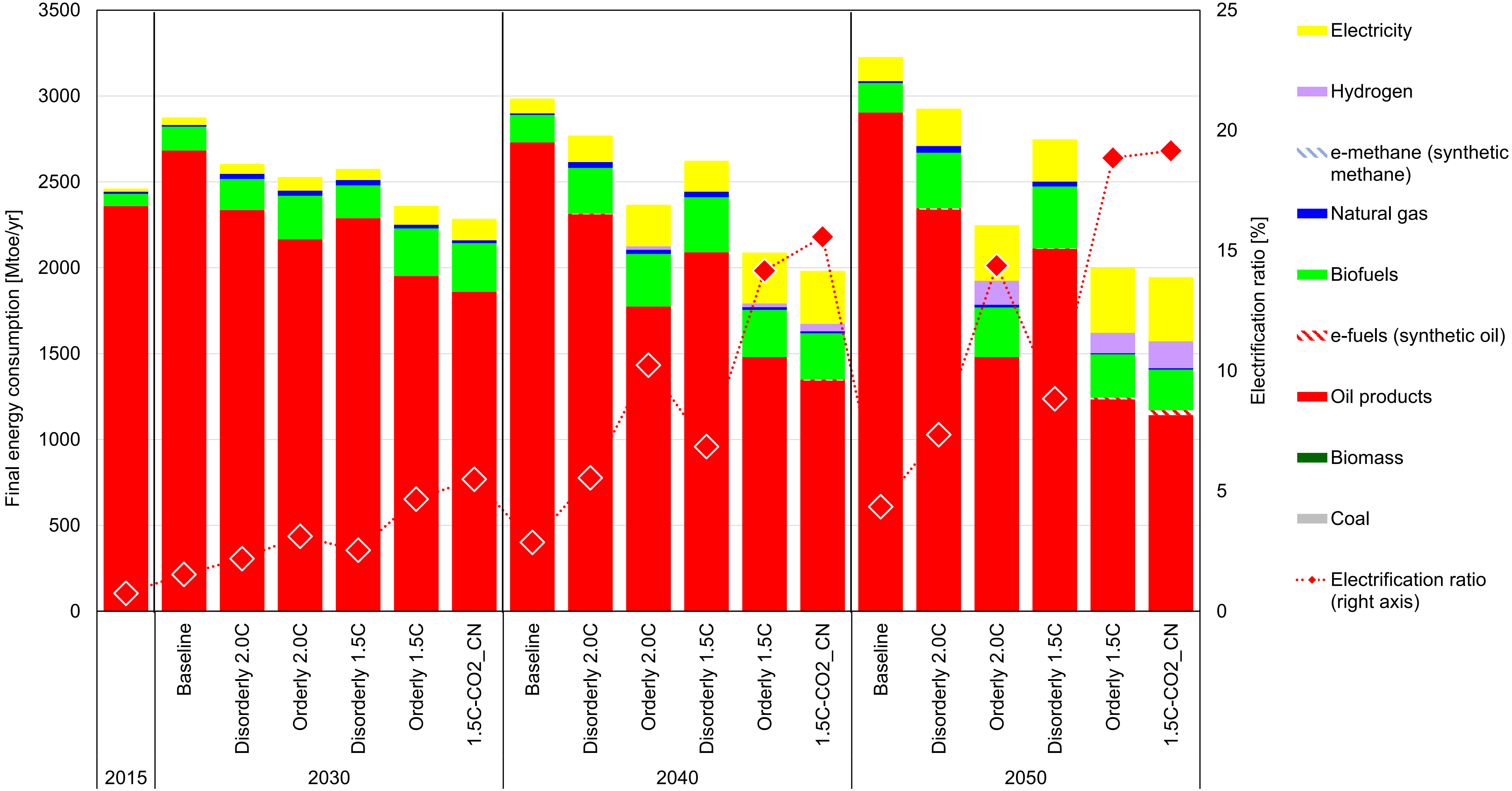
✓ **CN fuels, such as ammonia and hydrogen, are used under emissions reduction scenarios, especially in 1.5C-CO2_CN where a small contribution of CDR is assumed.**

Final energy consumption in building (World)



- ✓ **In building sector, electricity consumptions will increase greatly even for the baseline scenario. Under the 2°C/1.5°C scenarios, larger shares of electricity consumptions will be economical measures.**
- ✓ **On the other hand, for the 2°C scenarios and Disorderly 1.5°C, a certain amounts of natural gas uses are still economical measures.**

Final energy consumption in transport (World)



- ✓ The uses of electricity, bioenergy, hydrogen, and e-fuels will increase, and oil consumptions will decrease.
- ✓ However, a certain amount of oil consumptions will remain by 2050 even under the 2°C /1.5°C scenarios.

(1) Japan

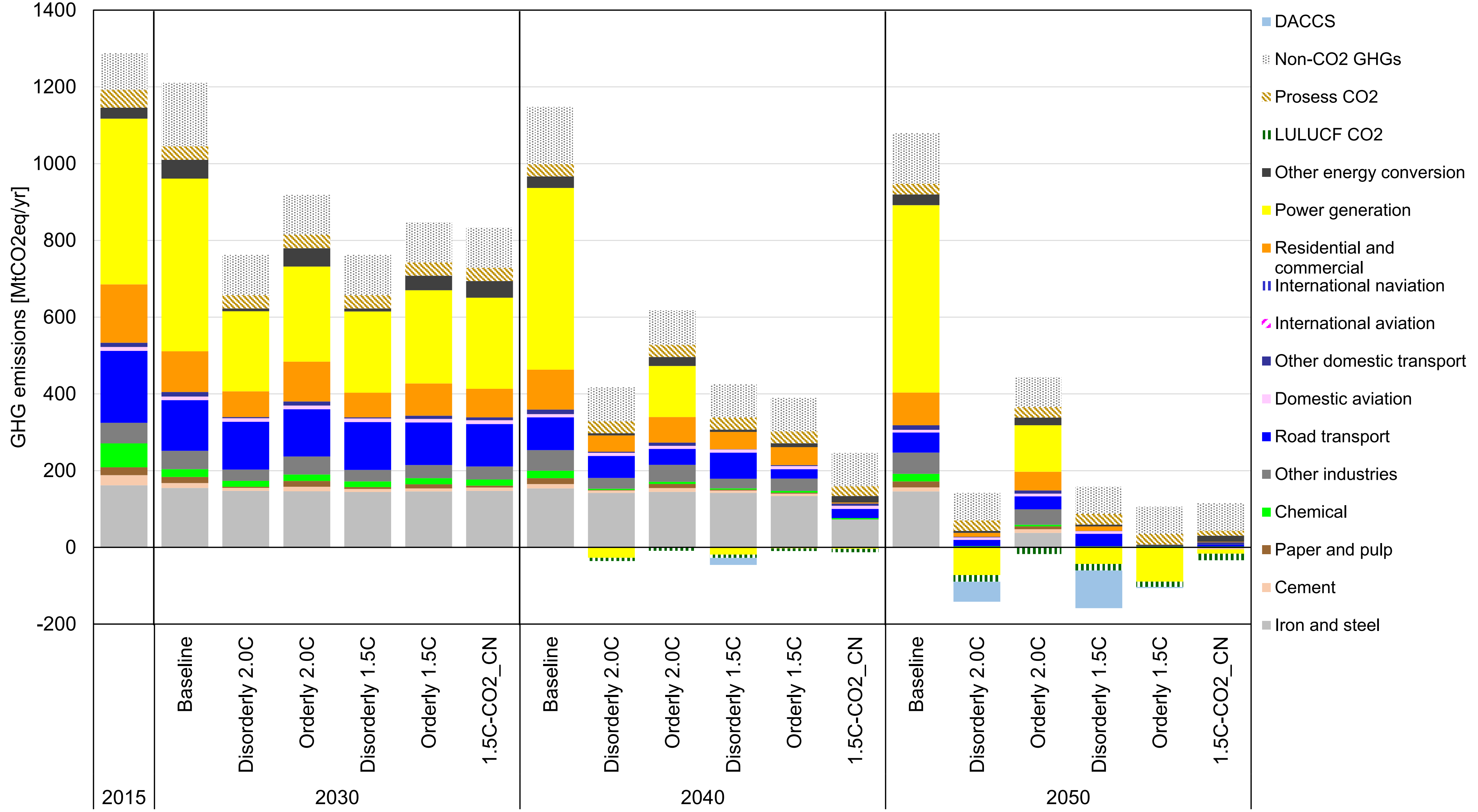
CO_2 emissions reduction cost (Japan)

Unit: billion US$/yr

	2030	2040	2050
Disorderly 2.0C	48	92	161
Orderly 2.0C	0	8	20
Disorderly 1.5C	44	116	202
Orderly 1.5C	12	80	145
1.5C-CO2_CN	22	158	95

Note) Annual cost increases in energy systems from those of the baseline scenario

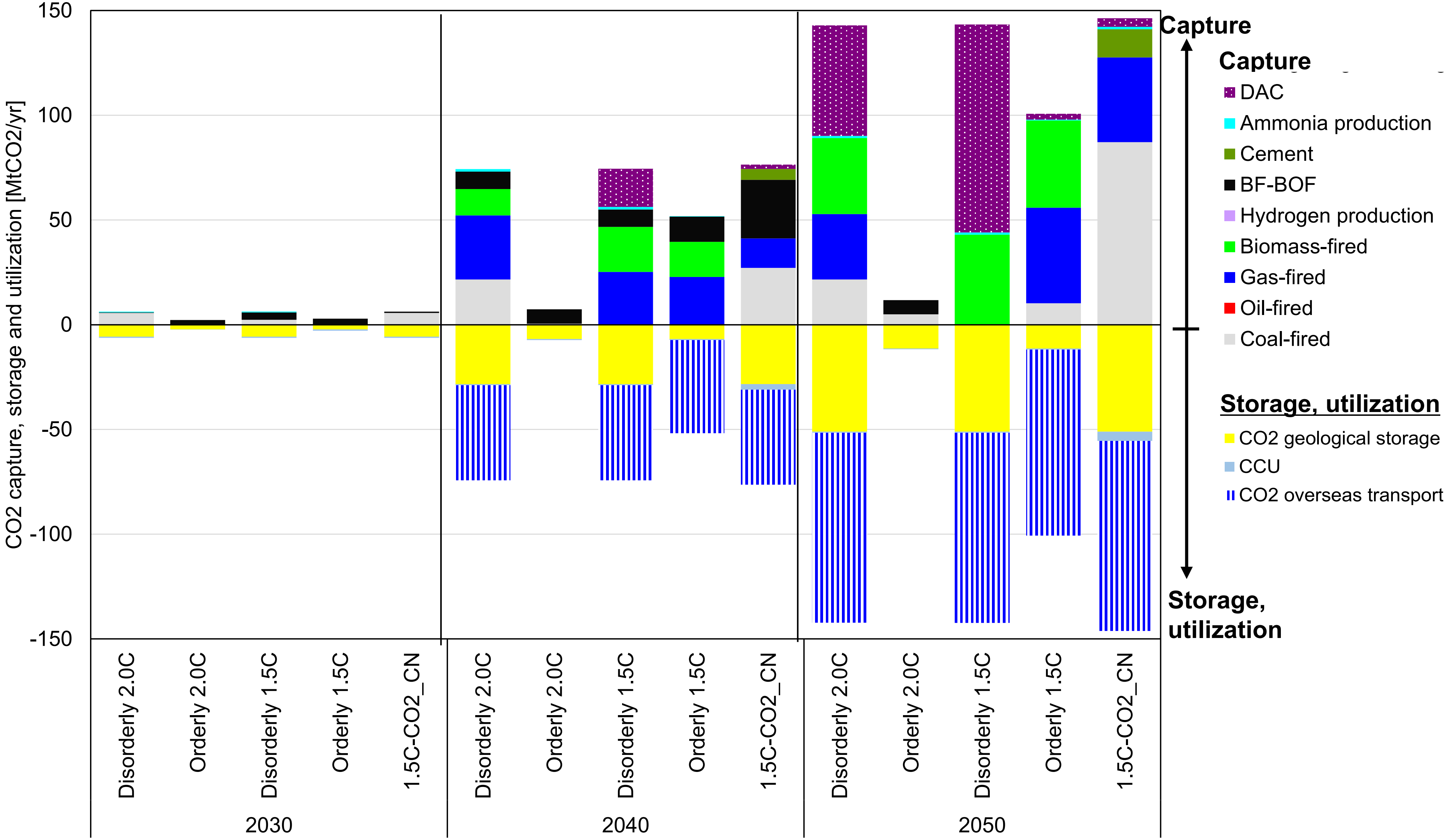
GHG emissions (Japan)



Note) For the GHG emissions other than CO2 in 1.5C-CO2_CN, the values in Orderly 1.5°C are shown here.

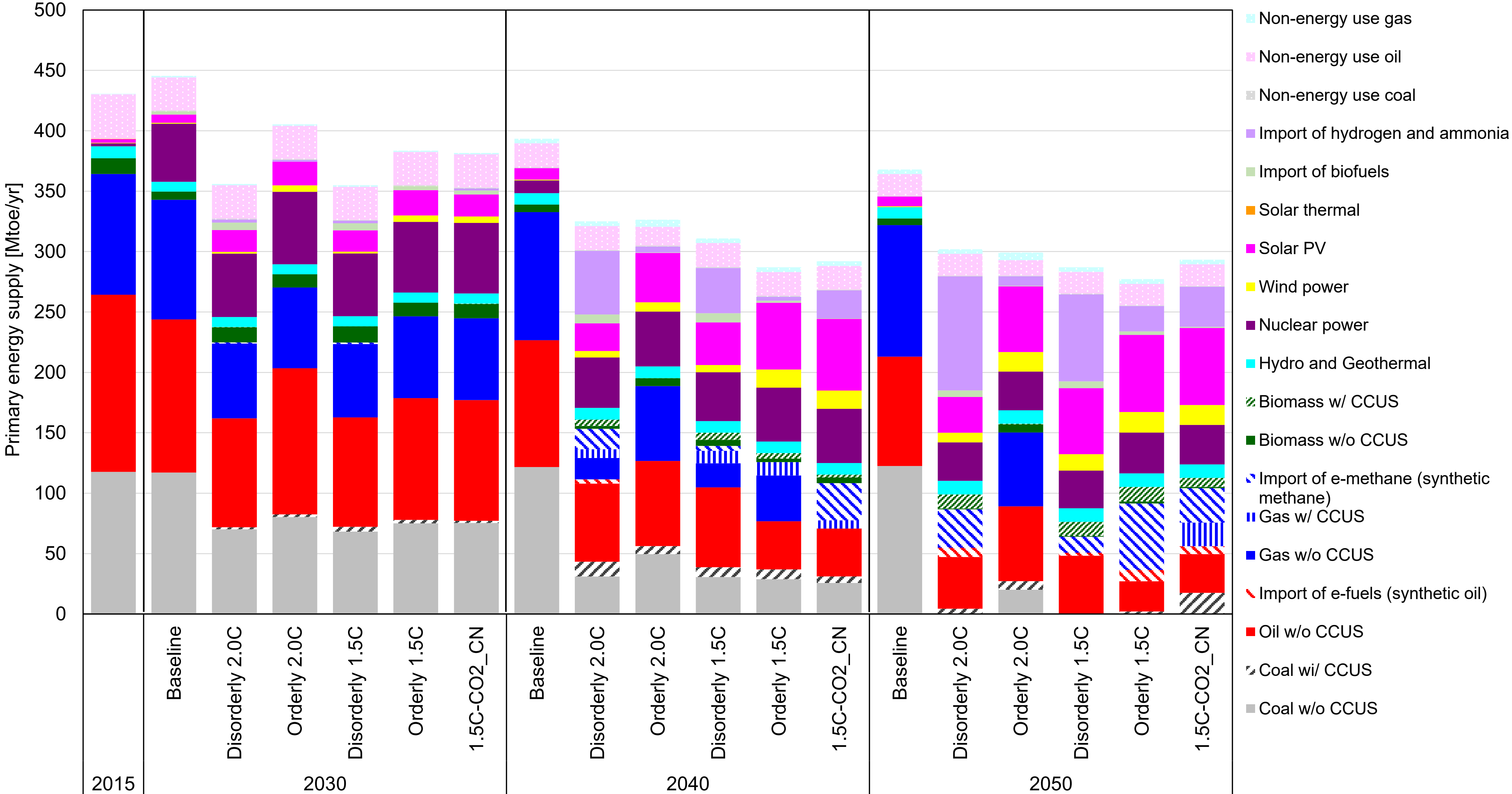
- ✓ **To achieve CN in GHG emissions in 2050, DACCS, the use of LULUCF CO_2 (fixation by forestation), and the measures for net negative CO_2 emissions in the Power sector, such as BECCS and e-methane+CCS, will be applied.**
- ✓ **In Orderly 2.0°C where CN in GHG emissions in 2050 is not assumed, the total GHG emissions will be approximately ▲69% relative to 2013, with positive CO_2 emissions from the Power sector and the Iron and steel sector.**

CO_2 balance (Japan)



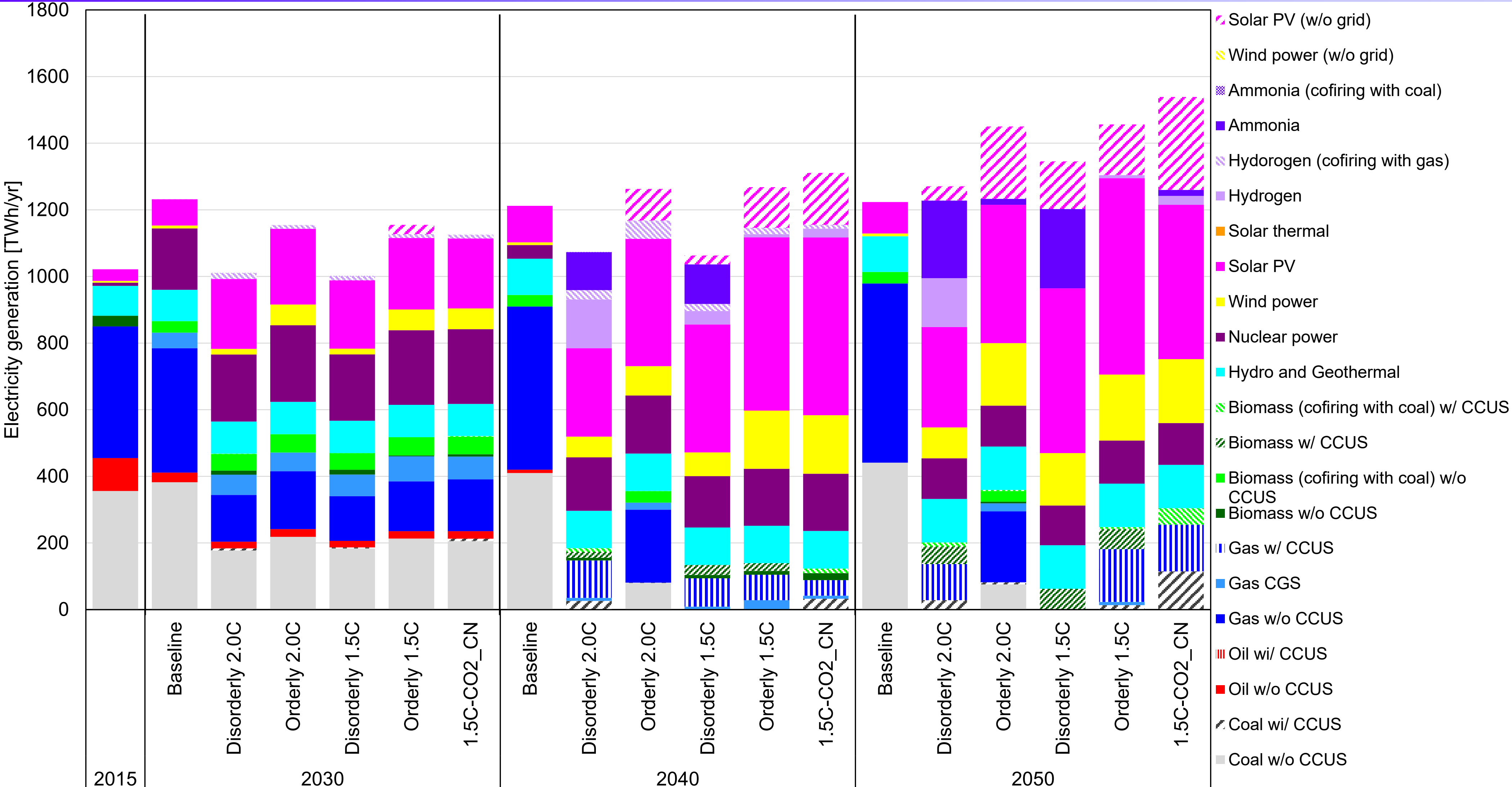
- ✓ CO_2 capture through fossil-fired power generation and BF process (Super COURSE50) are observed in 2040.
- ✓ CO_2 capture through DAC and Biomass processes will be large in 2050.
- ✓ Under 1.5C-CO_2_CN, with limited CDR uses including BECCS and e-methane+CCS in the Power sector, CO_2 is captured from coal-fired (incl. Biomass co-firing) and gas-fired, and in the Cement sector in 2050. Captured CO_2 via DAC is used for CCU.

Primary energy supply (Japan)



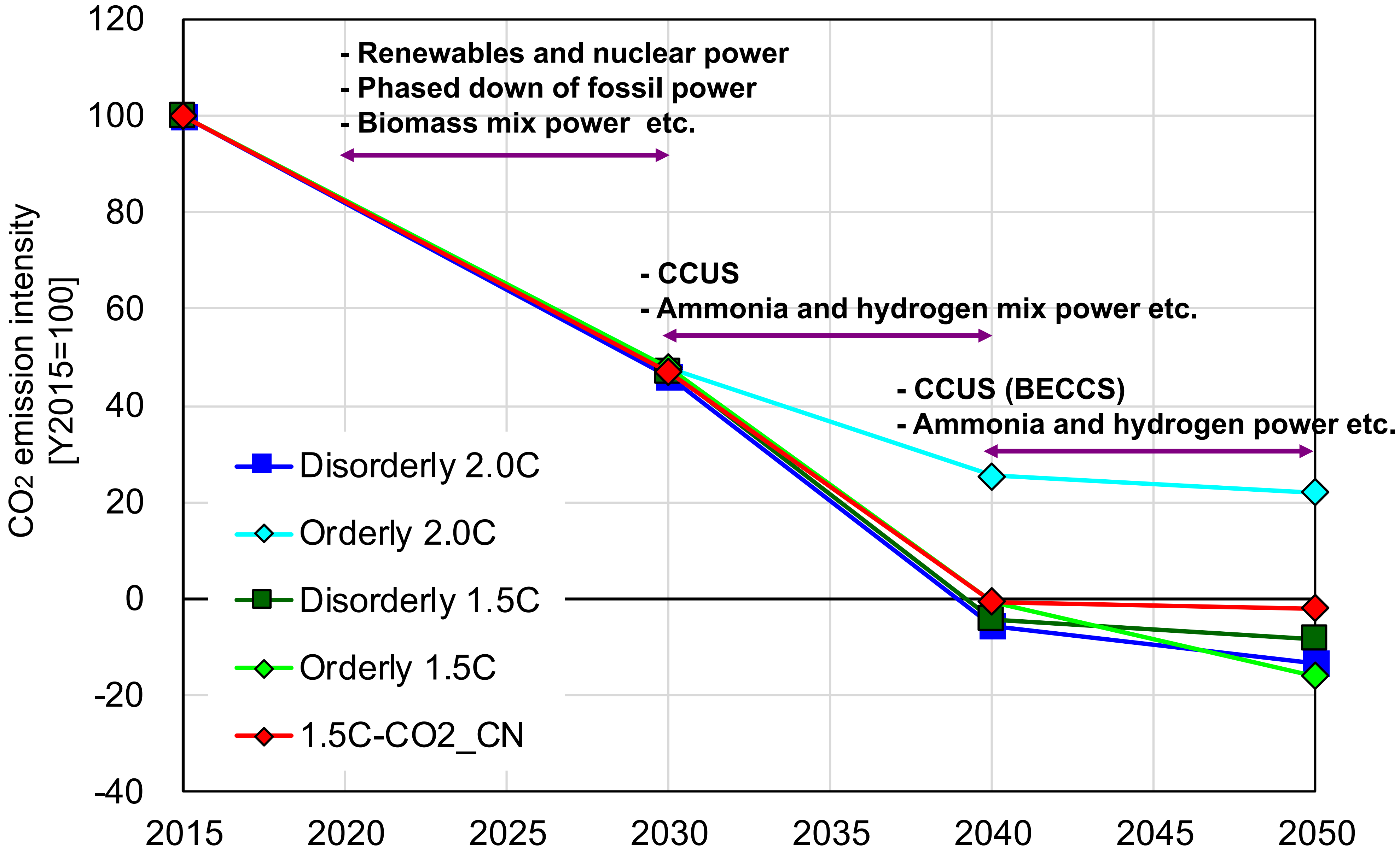
- ✓ **Import of hydrogen and ammonia, e-methane, and biofuels would be cost-effective as the MAC of Japan is higher than other countries. However, those amounts in Orderly 2.0°C are relatively small (approx. ▲69% relative to 2013 in 2050).**
- ✓ **Coal use incl. with CCUS is scarcely observed in the scenarios of GHG CN in 2050. However, in Orderly 2.0°C, some coal w/o CCUS and a reasonable amount of gas w/o CCUS are likely to remain.**
- ✓ **Import of hydrogen and ammonia, e-methane, and biofuels would be cost-effective as well in 1.5C -CO_2_CN.**

Electricity supply (Japan)



- ✓ Electricity supply is in an upward trend, especially in the strict emissions reduction scenarios.
- ✓ The deployment of renewable energy, such as solar PV, the use of CCS, and power generation with imported hydrogen and ammonia are observed. Also, e-methane is used for gas power generation in 2050 in the scenarios other than Orderly 2.0°C.
- ✓ Solar PV and wind power are likely to diffuse further due to high cost reduction in Orderly 1.5°C.
- ✓ In 1.5C-CO_2_CN, a portion of coal with CCUS increases due to the constraint of BECCS and e-methane+CCS.

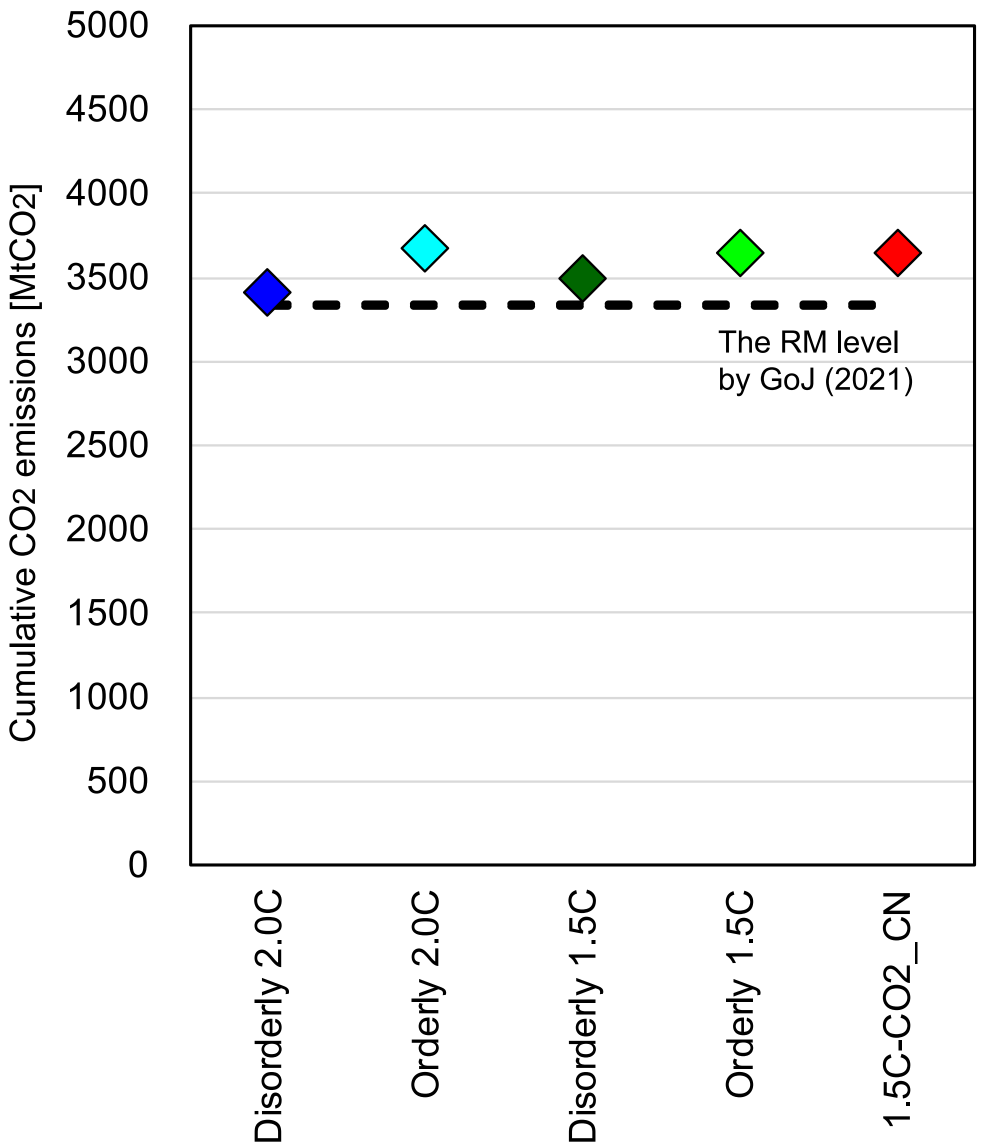
CO_2 intensity of electricity (Japan)



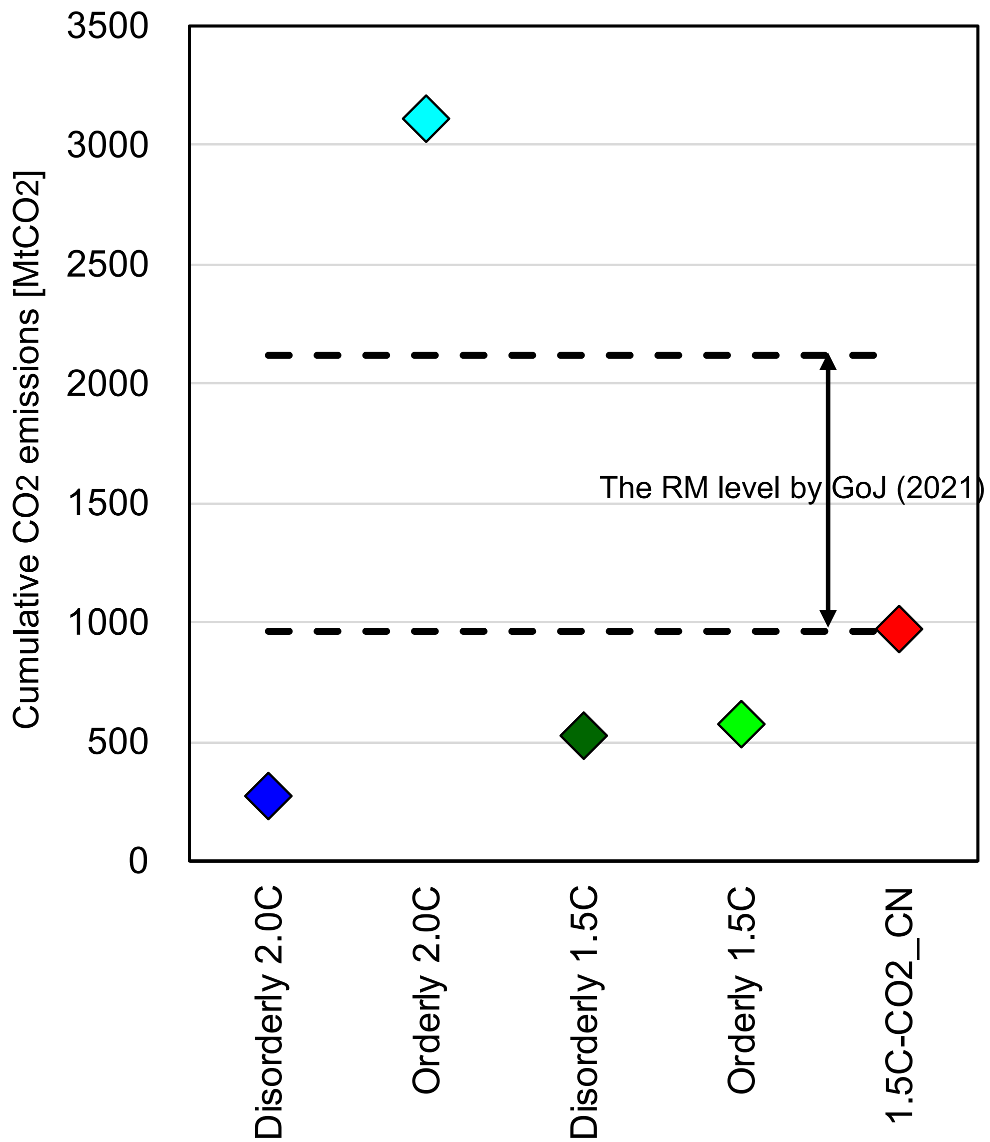
✓ There is no big differences in the trend of CO_2 intensity among Disorderly 1.5°C/2.0°C and Orderly 1.5°C, which assume GHG net zero emissions in 2050, although the power mixes are varied, and achieving CN by around 2040 would be cost-effective as a whole.

CO_2 emissions in power sector (Japan): comparison with the RM by GoJ

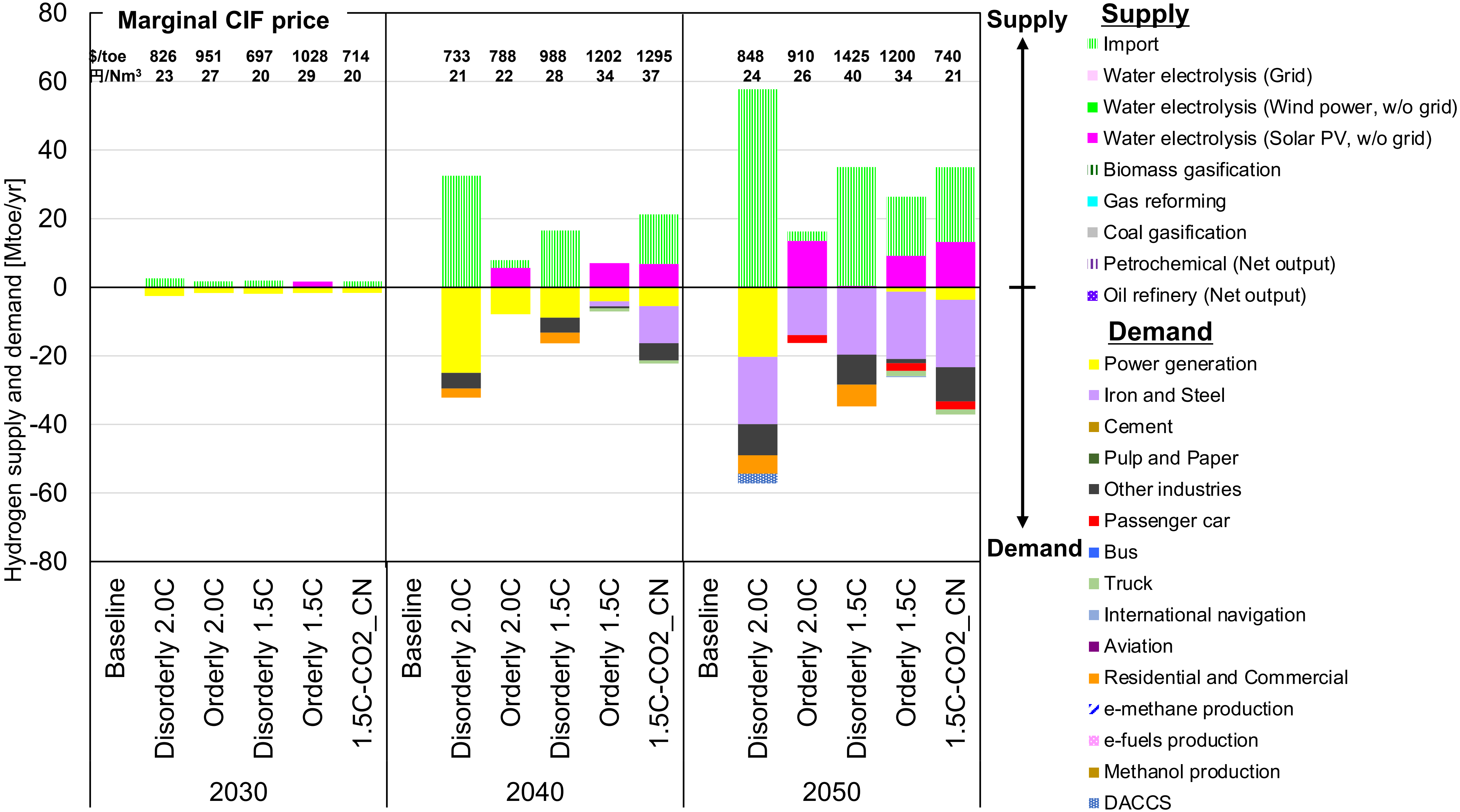
2020–2030



2031–2050

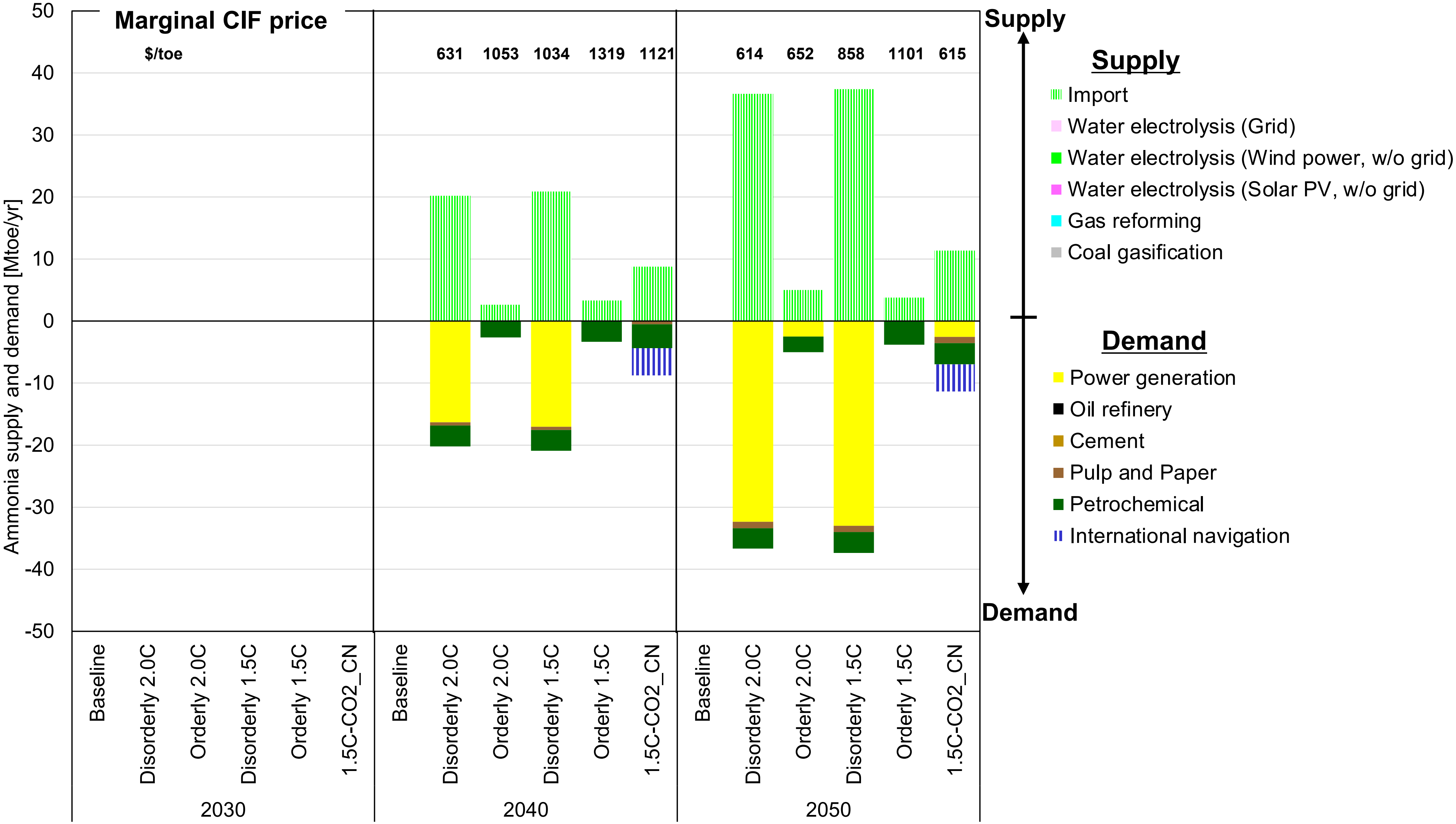


Supply and demand of hydrogen (Japan)



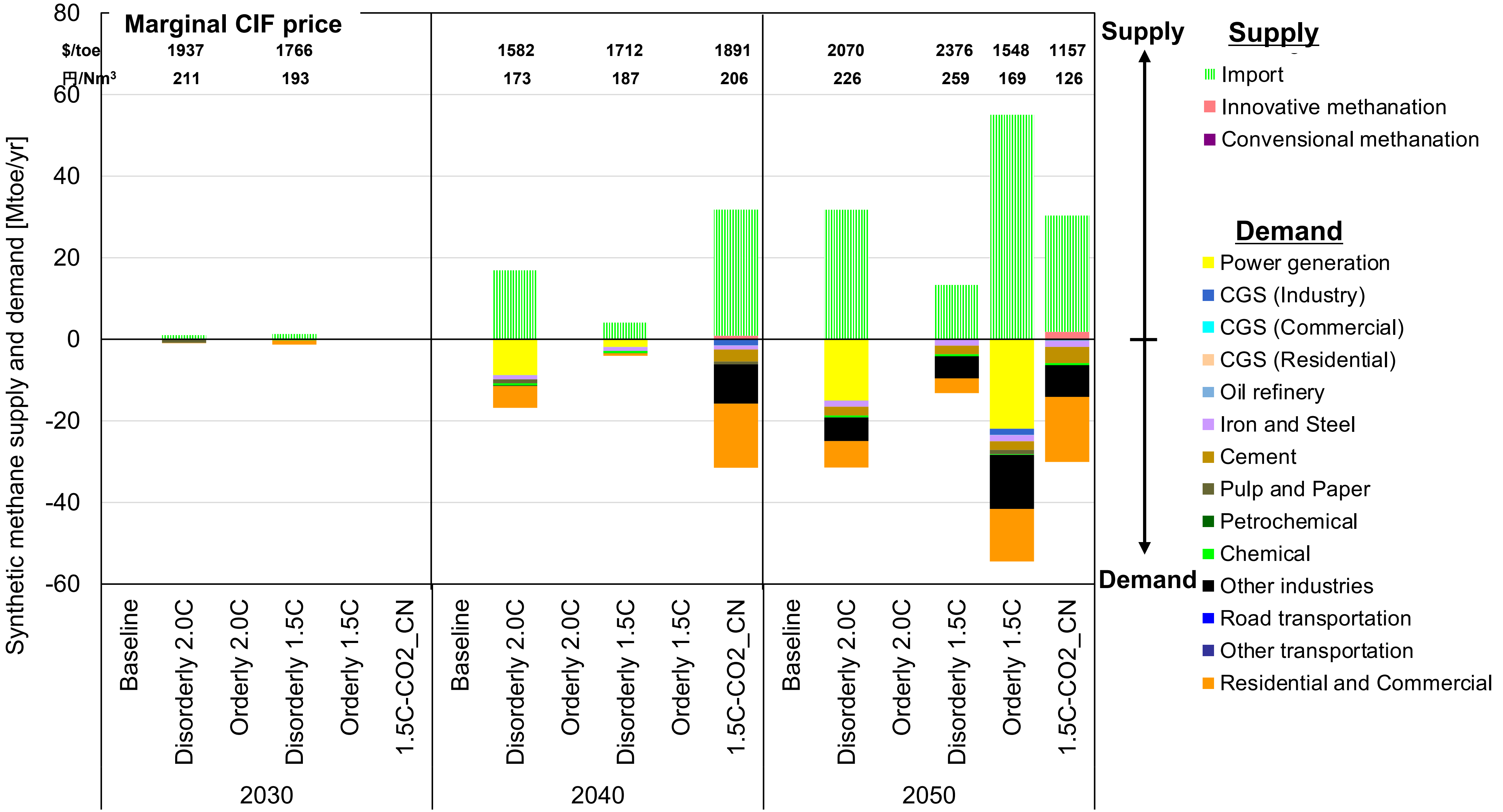
- ✓ **Large hydrogen uses for iron and steel sector are estimated in 2050.**
- ✓ **In the Orderly 1.5°C/2.0°C scenarios, domestic hydrogen productions are also economic, but most of hydrogen is imported in many scenarios.**
- ✓ **The marginal prices of CIF of the 1.5°C scenarios are high due to competitions among countries.**

Supply and demand of ammonia (Japan)



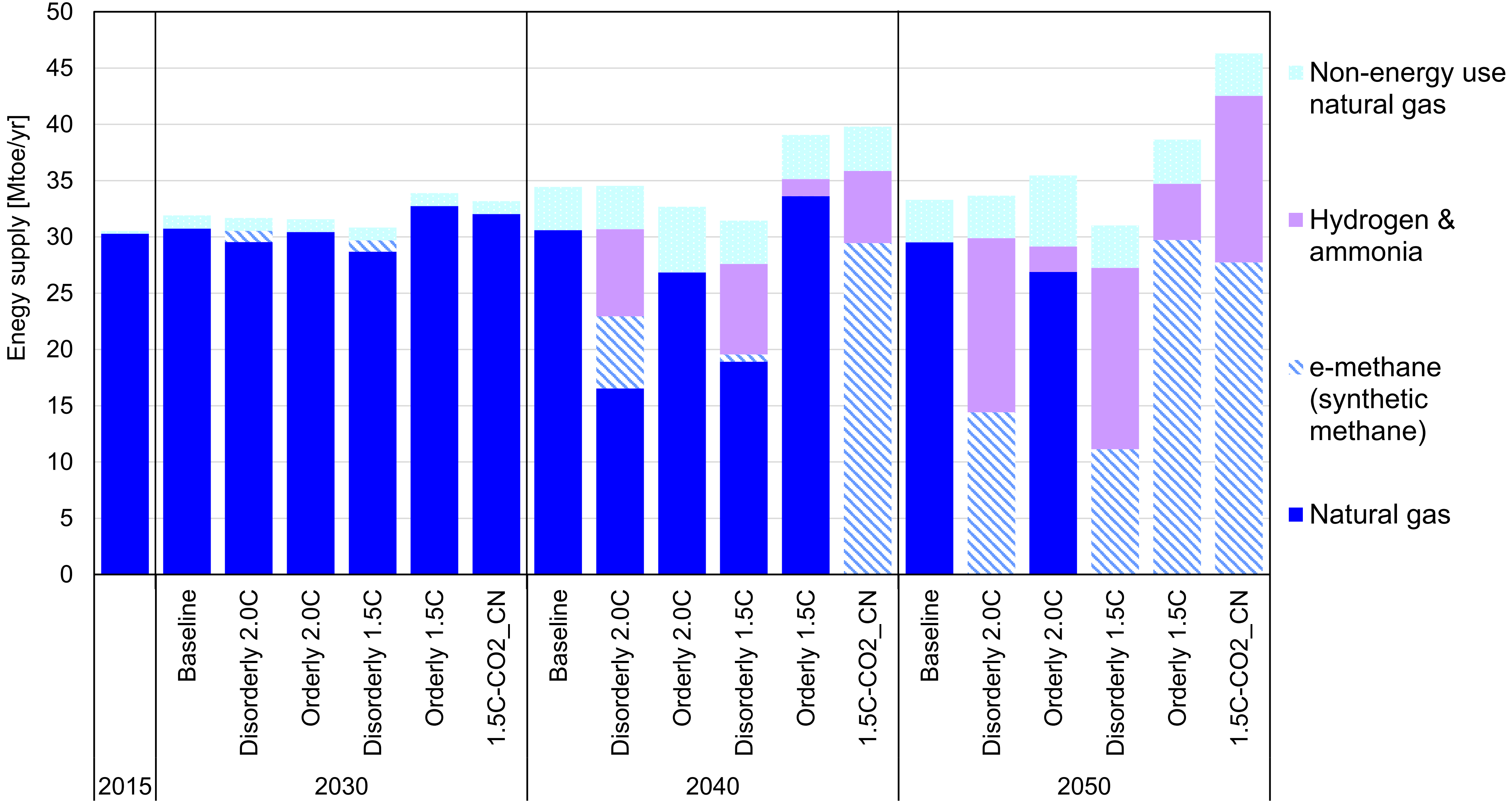
- ✓ **In the Disorderly 1.5°C/2.0°C scenarios, the cost reductions of VRE are gradual, and blue ammonia from overseas plays an important role in the power sector.**
- ✓ **Ammonia uses for industrial sectors are also economical options in Japan.**

Supply and demand of e-methane (synthetic methane) (Japan)



- ✓ e-methane will contribute to power sector as well as building and industrial sectors.
- ✓ Productions of e-methane overseas are dominant due to differences in renewable energy costs.

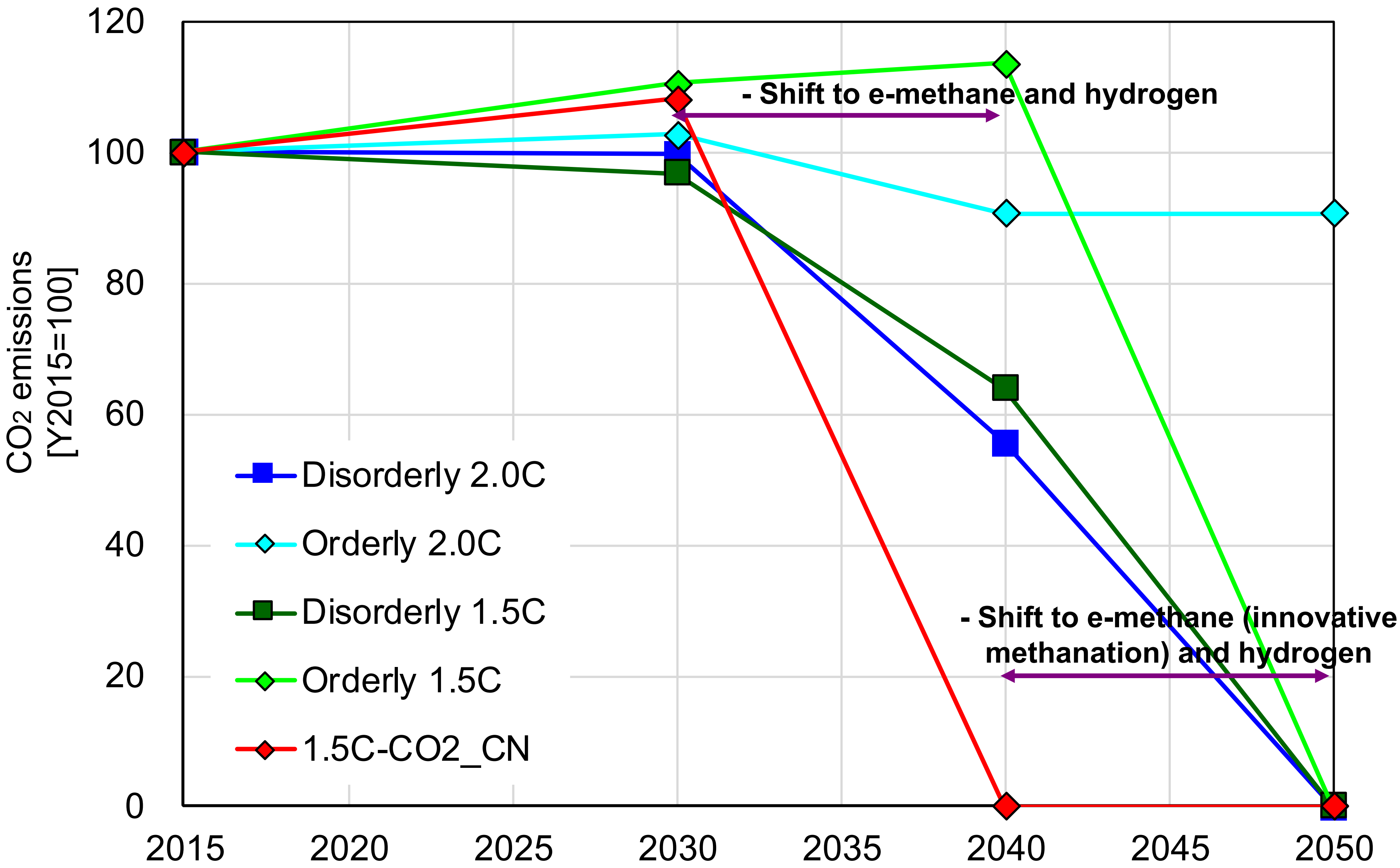
Gas supply (Japan)



Note) The uses in power, iron & steel, and petrochemical sectors are not included here and described in each sectoral analysis.

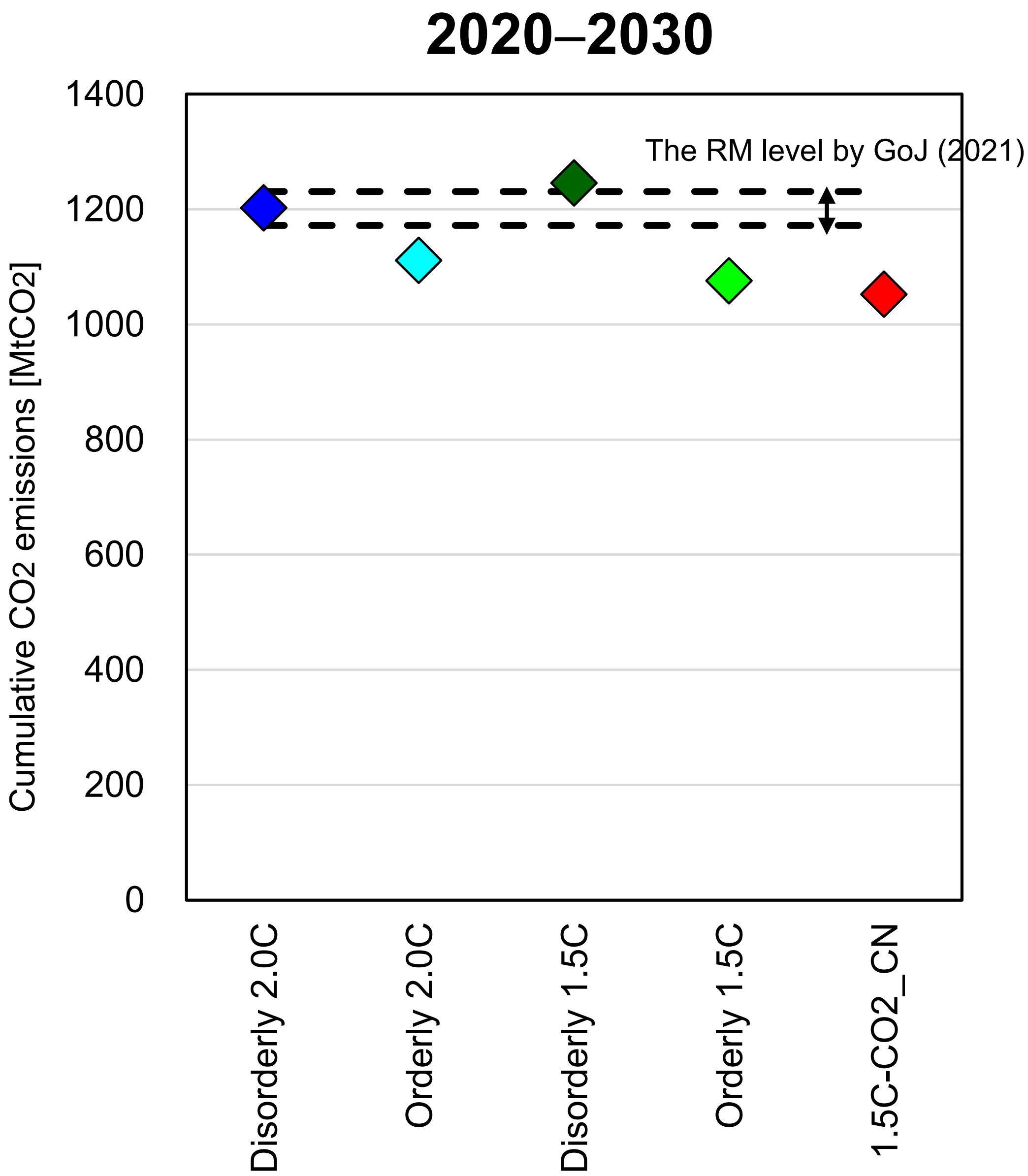
- ✓ **In Orderly 2.0°C, natural gas supply would keep the current level or slightly decrease by 2050. Other scenarios predict greater uses of hydrogen or e-methane after 2040.**
- ✓ **The choice between hydrogen and e-methane is sensitive depending on preconditions, such as the assumption of cost reduction timing.**

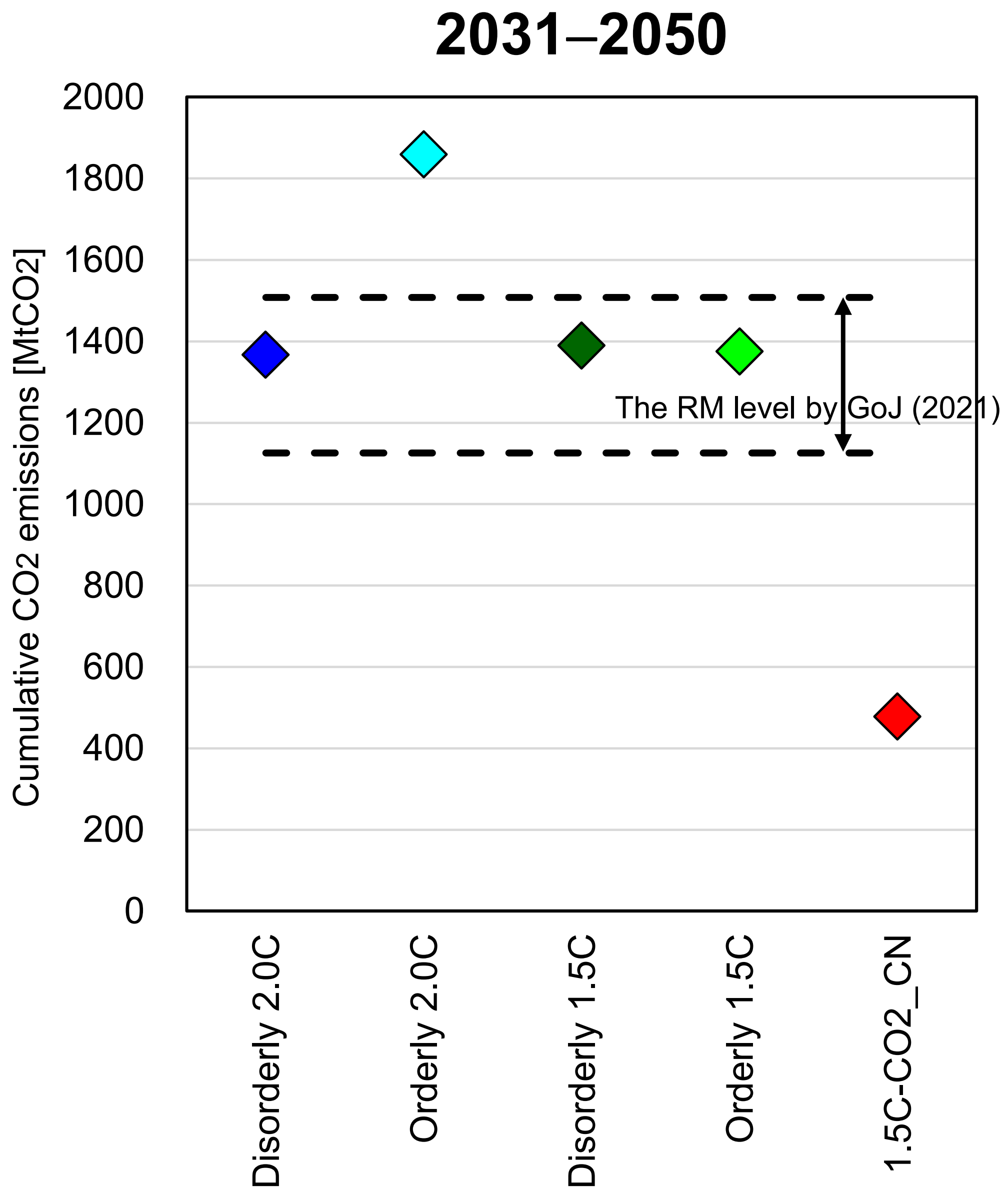
CO_2 emissions from gas (Japan)



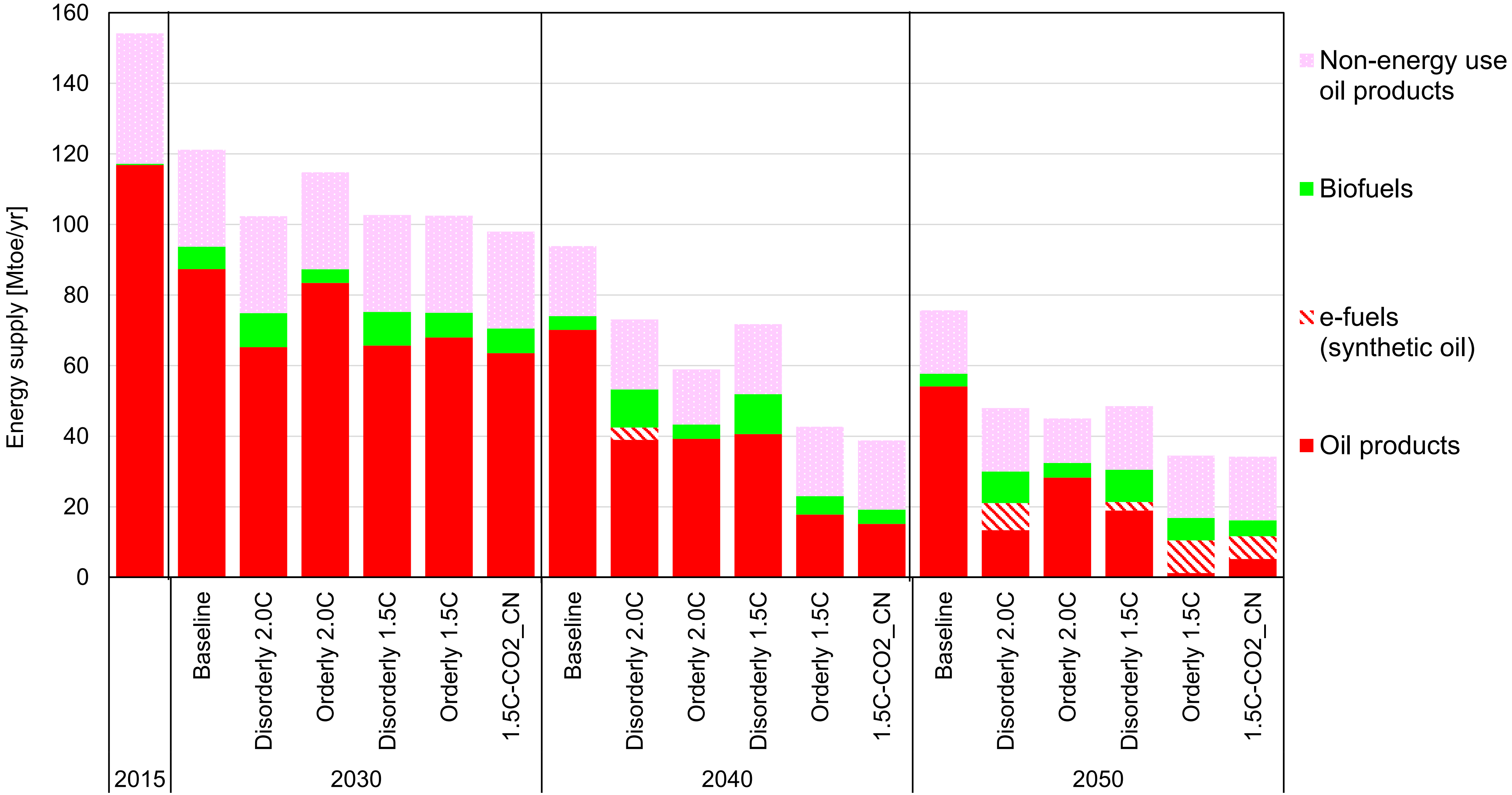
- ✓ **As for Orderly 1.5°C, it can be interpreted that the MAC would be close to those of other countries in 2040, causing competition in importing synthetic fuels and hydrogen (the marginal CIF price is also high), and the CO_2 emissions in 2040 is relatively large.**

CO_2 emissions in gas sector (Japan): comparison with the RM by GoJ





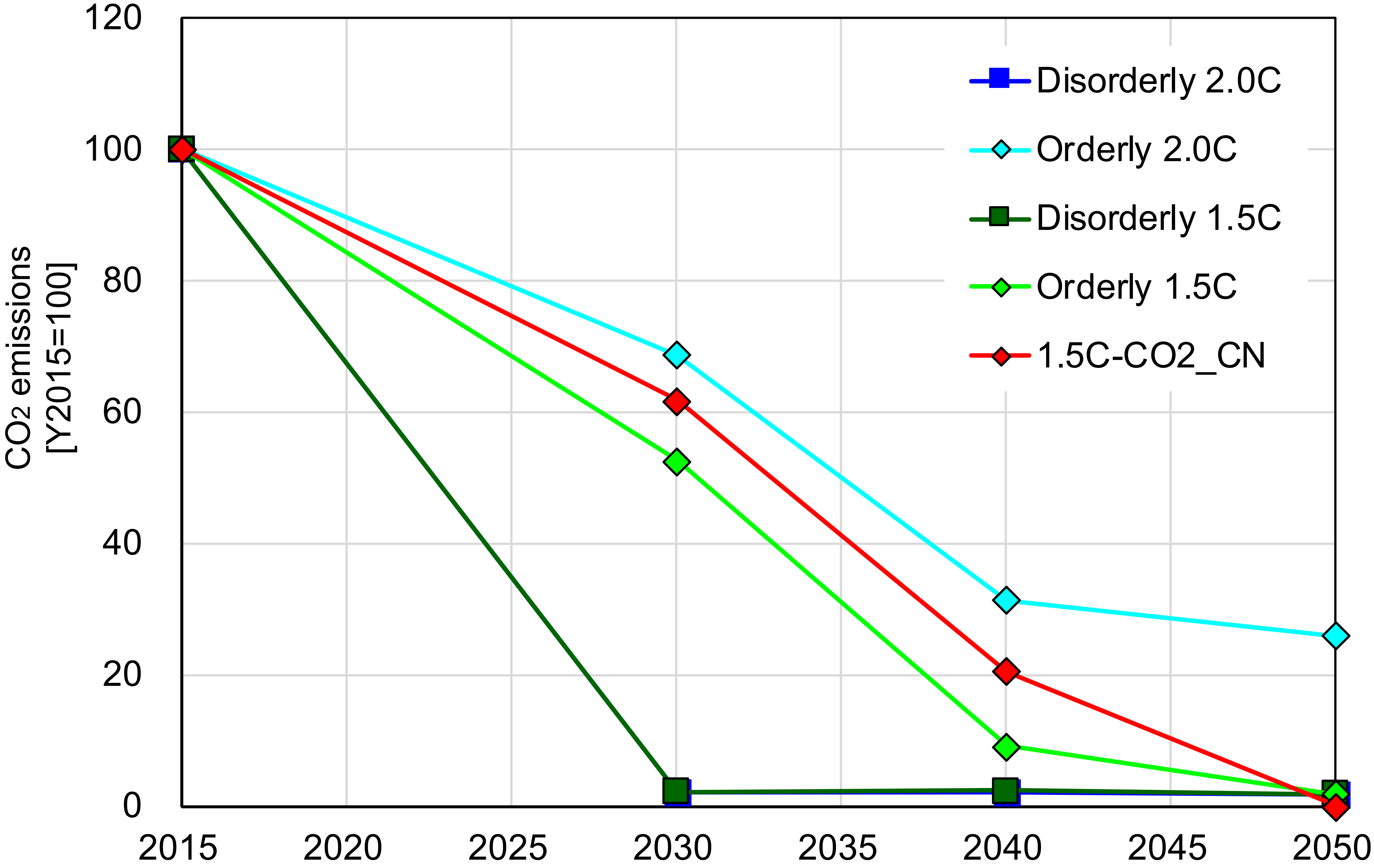
Oil (liquid fuels) supply (Japan)



Note) The use in the power sector is not included.

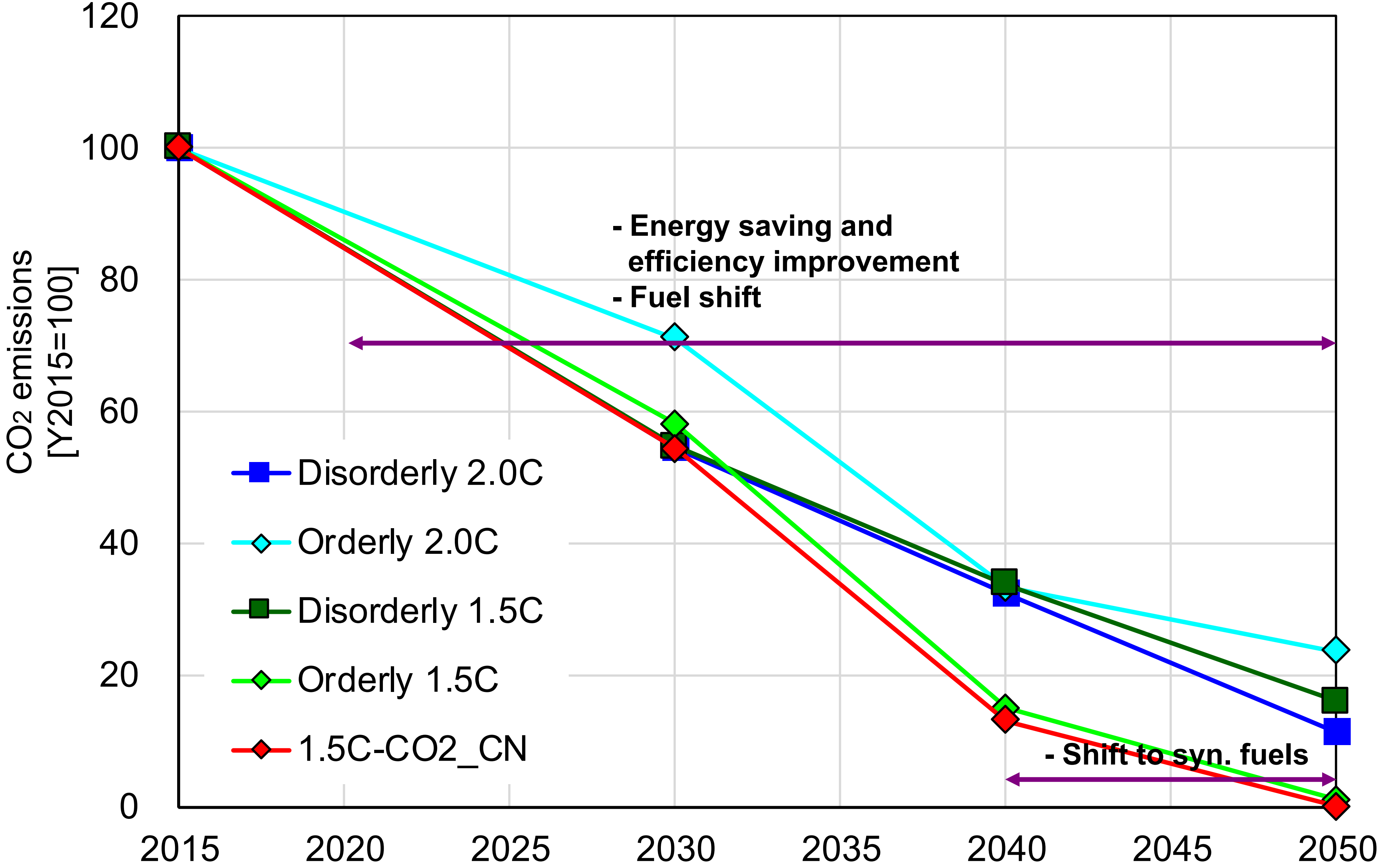
- ✓ **Oil use is considerably decreasing due to efficiency improvement of automobiles, EV diffusion, and so on, in any scenarios. This trend is notable especially in Orderly 1.5°C, which assumes high cost reduction of renewable energy and EV. (Please refer to the results of the transport sector.)**
- ✓ **The use of e-fuels is observed in 2050. In particular, oil would be replaced with e-fuels in Orderly 1.5°C, in which emission offset is limited due to strict constraints on CCS, and the price of e-fuels decreases because of a decline of renewables costs.**

CO_2 emissions in oil refinery: Scope1 (Japan)



✓ **Scope1 emissions are decreasing as oil refining volume decreases. This trend is particularly strong in Disorderly scenarios, where there are large differences in CO_2 MAC with other countries.**

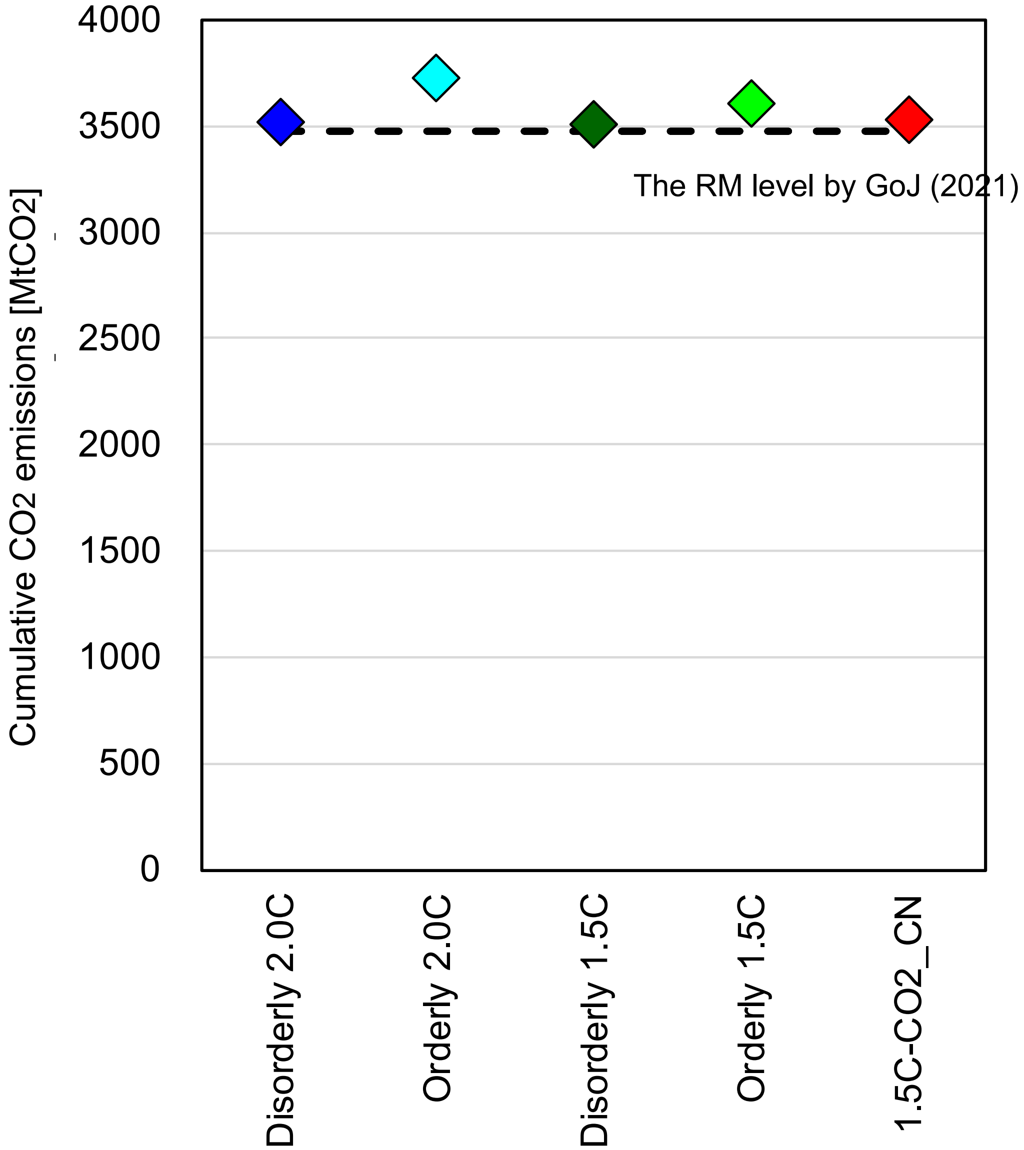
CO_2 emissions from oil (Japan)



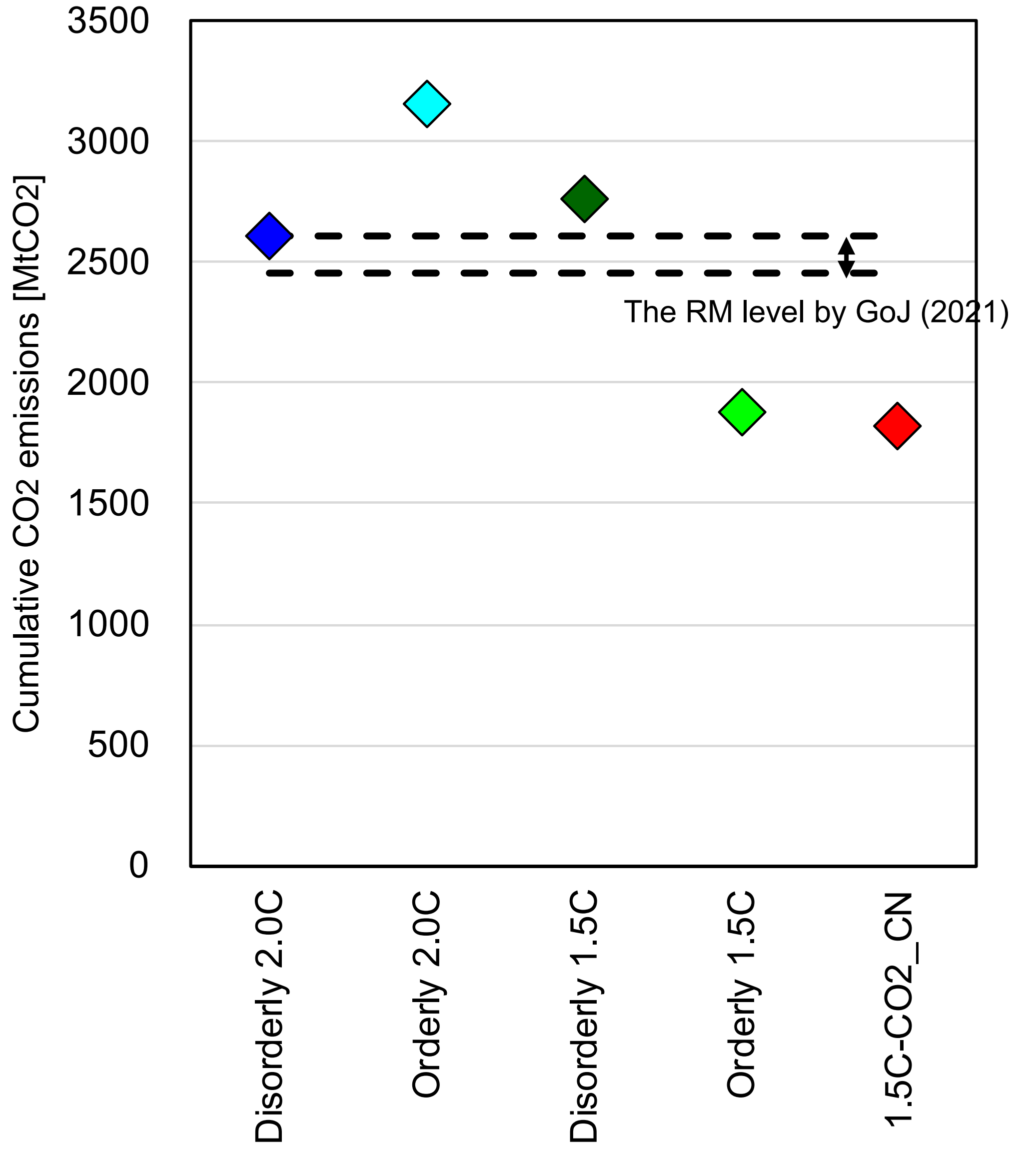
✓ **In Orderly 1.5°C, which assumes strict constraints on CCS, CO_2 emissions in 2050 would be reduced to almost zero because there is a small room for offsetting emissions through DACCS, etc.**

CO_2 emissions in oil sector (Japan): comparison with the RM by GoJ

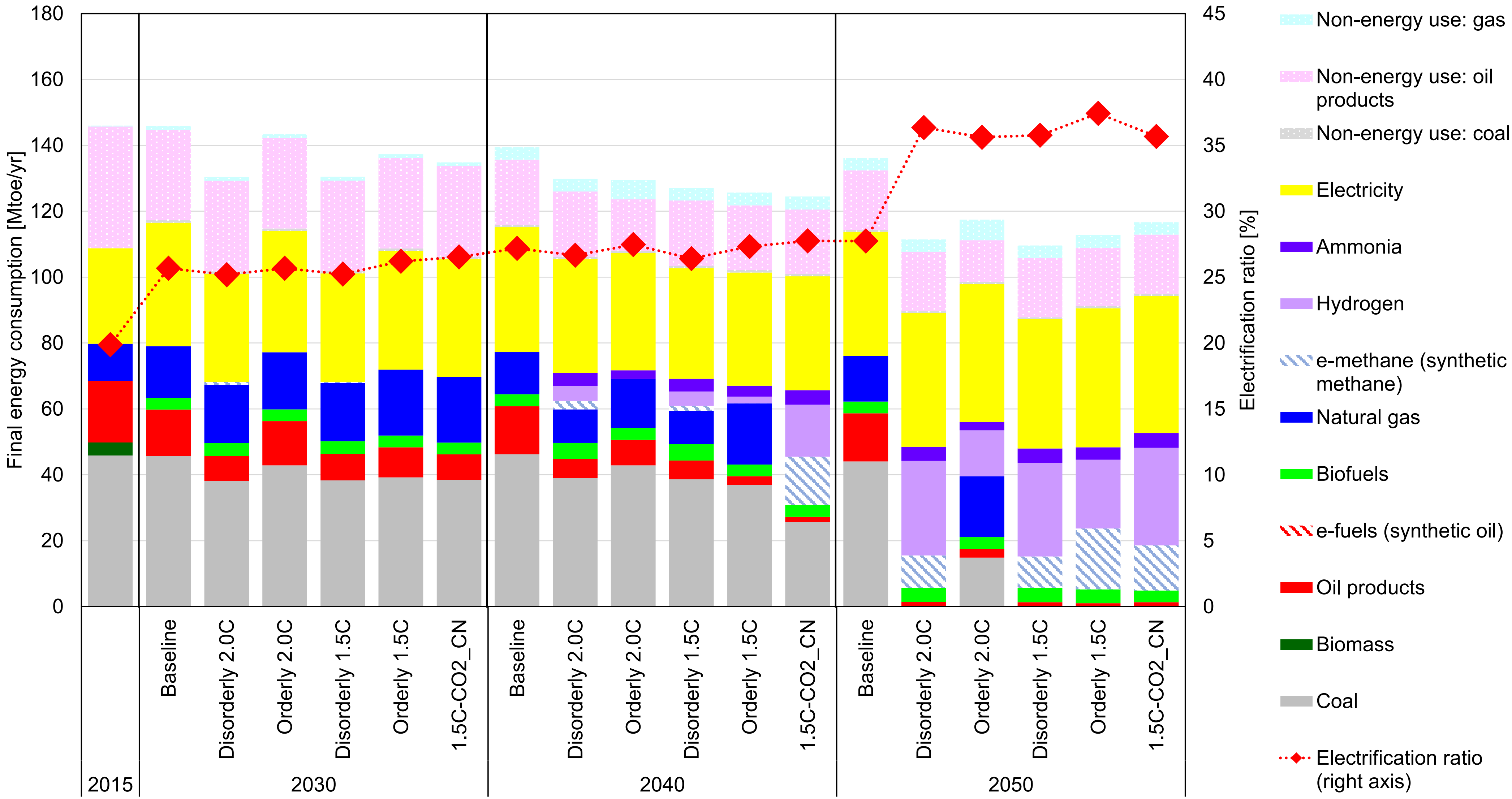
2020–2030



2031–2050

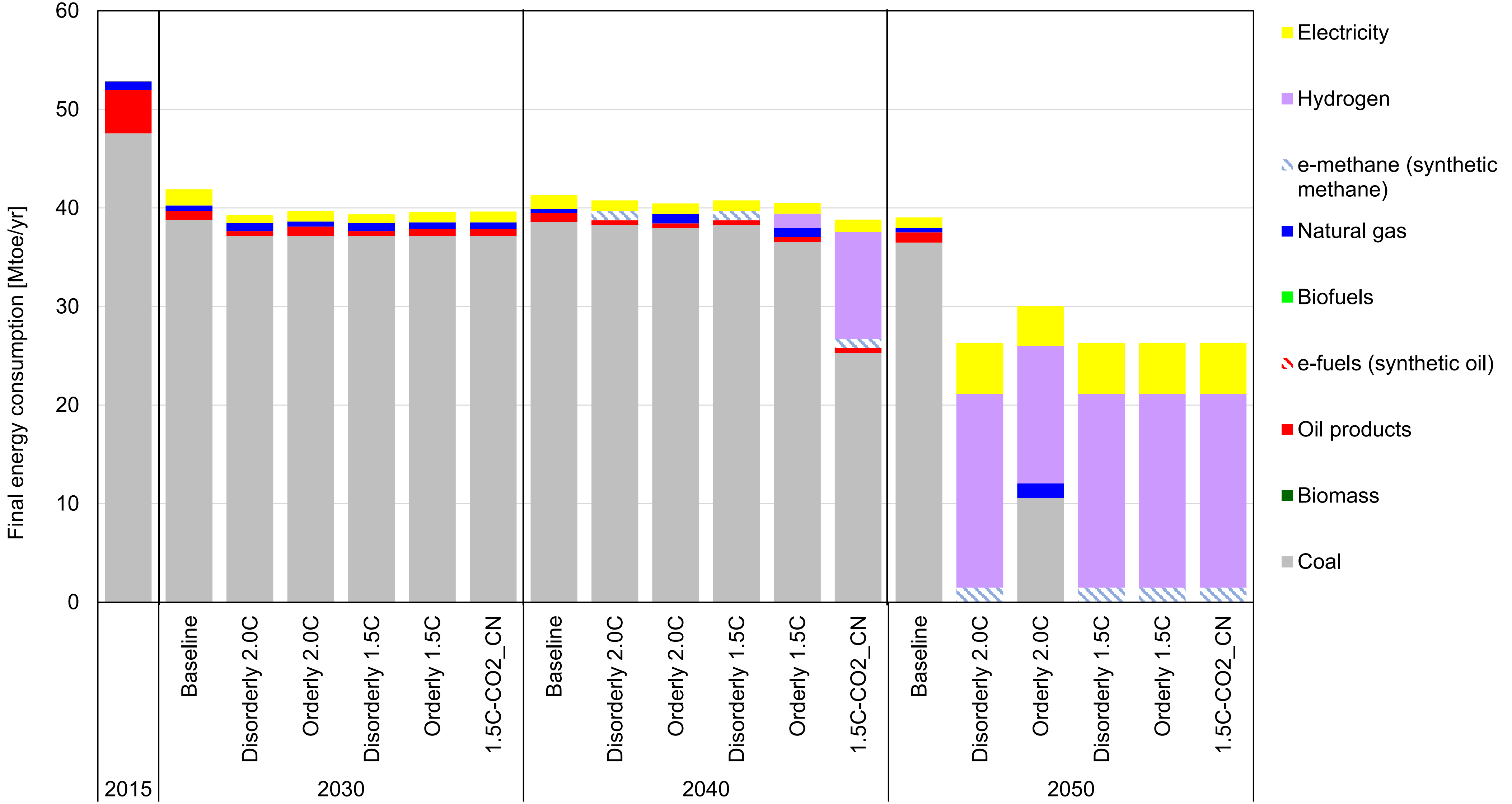


Final energy consumption in industry (Japan)



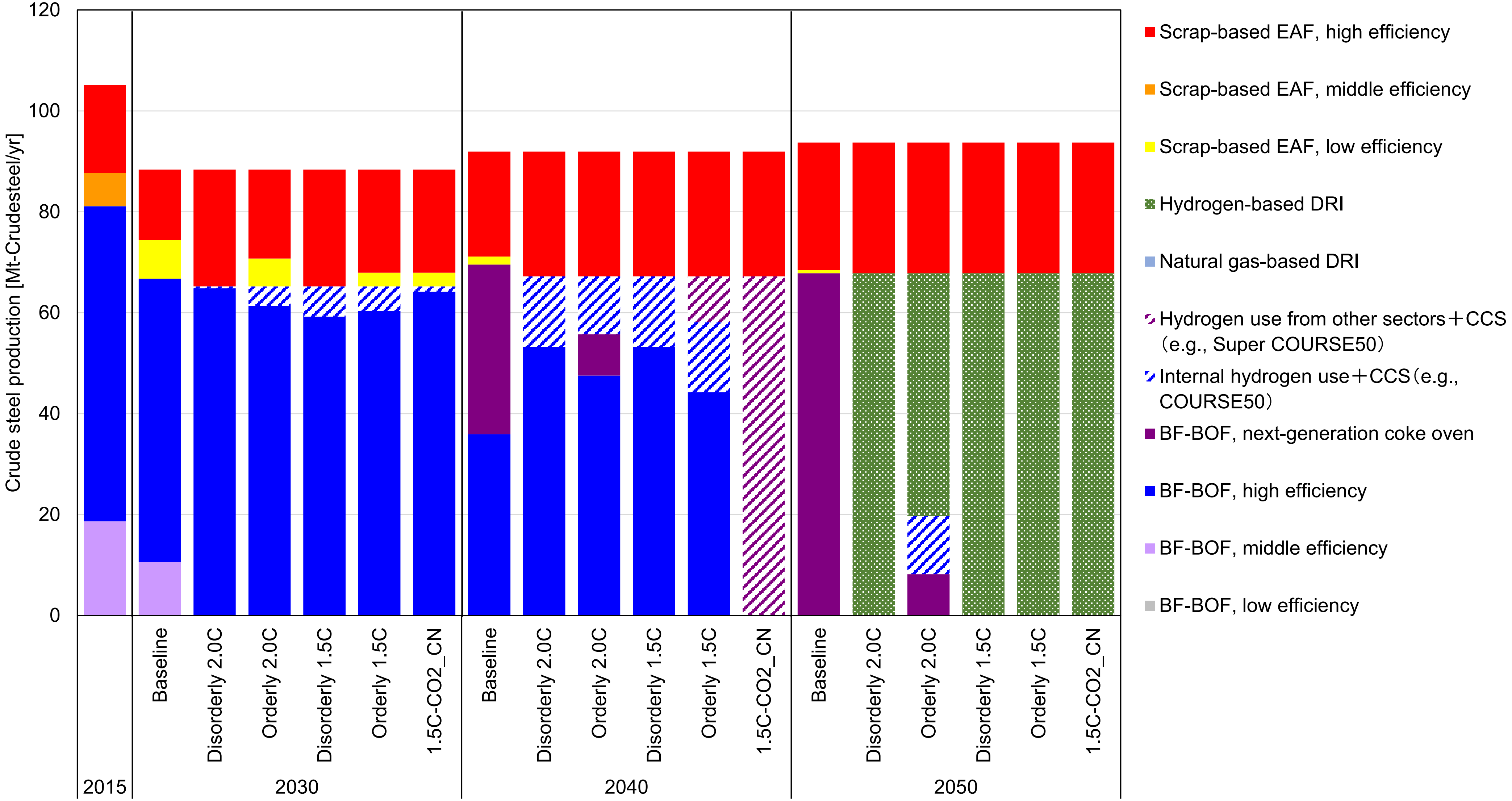
- ✓ **Coal uses remain for BF-BOF in the iron and steel sector in 2040.**
- ✓ **In 2050, coal is not used, and the uses of hydrogen, ammonia, and e-methane are observed in the scenarios other than Orderly 2.0°C.**

Final energy consumption in iron & steel (Japan)



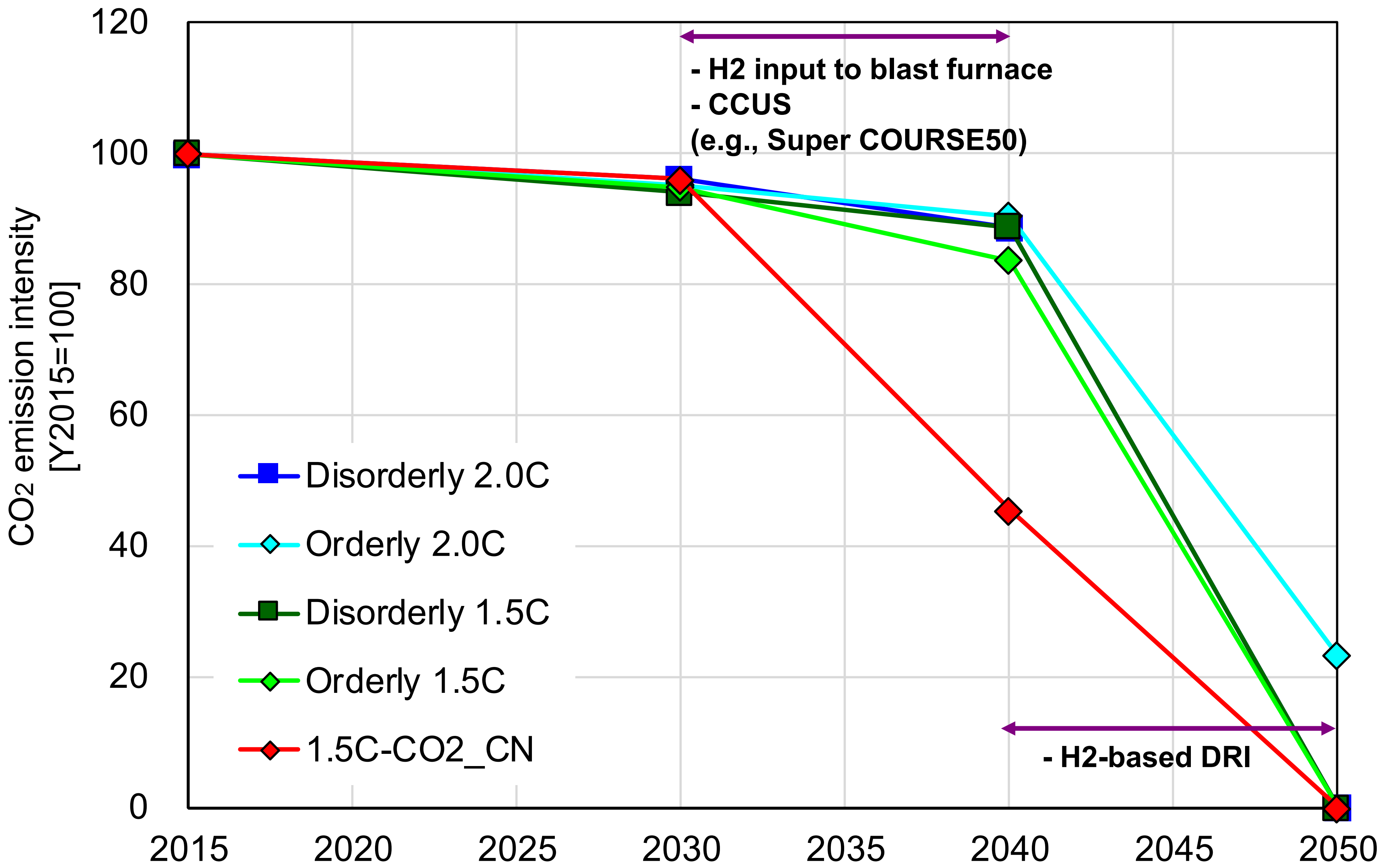
- ✓ Coal is used in BF-BOF in 2040. Hydrogen use from other sectors (Super COURSE50) is also observed.
- ✓ In 2050, coal is not used and replaced with hydrogen-based DRI in other scenarios than Orderly 2.0°C, in which total emission is predicted to be ▲69% relative to 2013. E-methane is used in scrap-based EAF.

Steel production by technology (Japan)



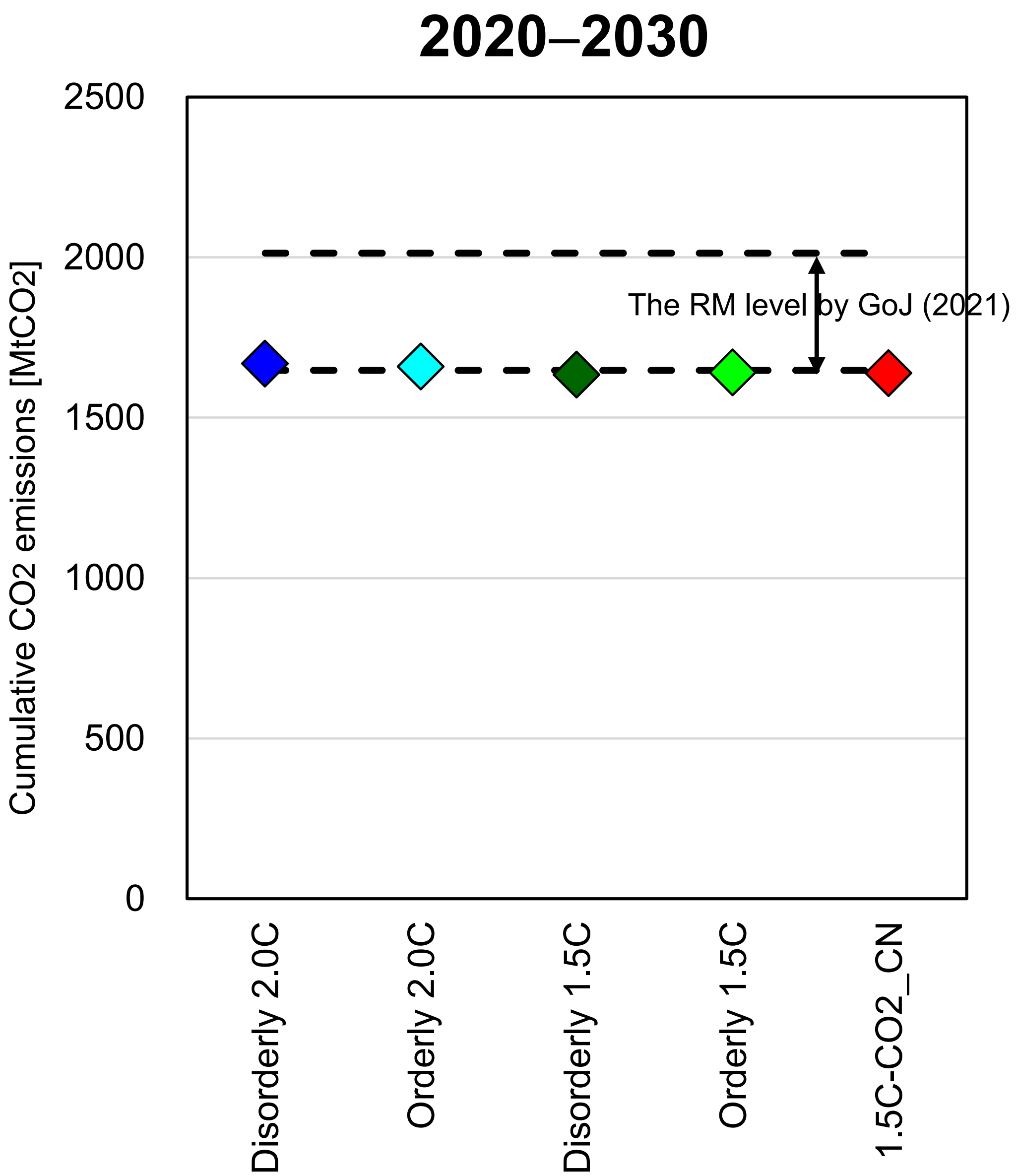
- ✓ **By 2040, CCS will play an important role.**
- ✓ **In 2050, hydrogen-based DRI will play a main role in iron and steel production processes.**
- ✓ **Under the 1.5C-CO_2_CN scenario, hydrogen use from other sectors in BF (e.g., Super COURSE50 like technologies) will be large.**

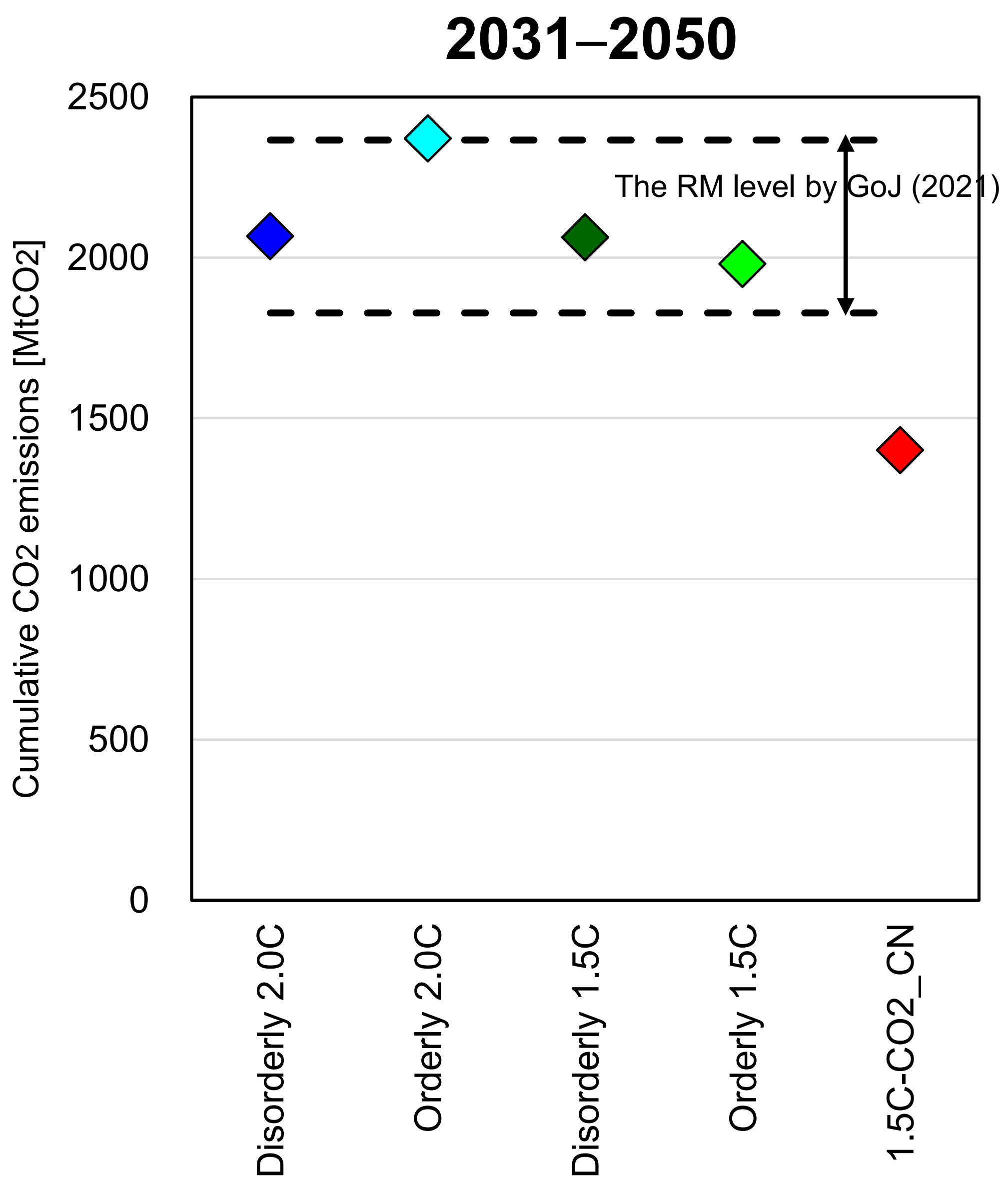
CO_2 intensity of iron and steel sector (Japan)



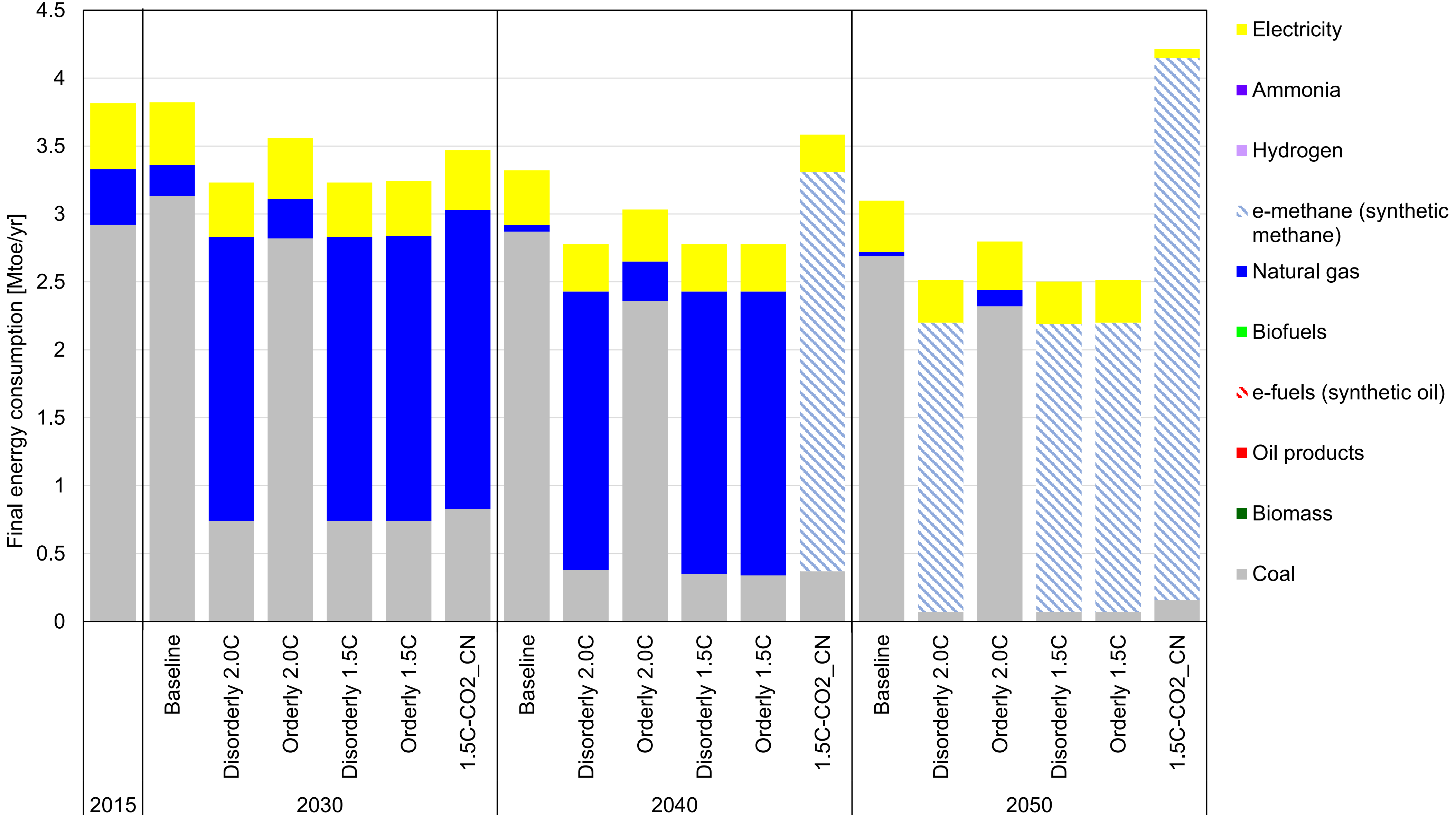
✓ **In any scenarios, nearly zero emissions would be achieved in 2050 by CCUS and hydrogen input to BF after 2030, and by a shift to hydrogen-based DRI after 2040. However, a part of emissions remains in 2050 in Orderly 2.0°C.**

CO_2 emissions in iron & steel sector (Japan): comparison with the RM by GoJ



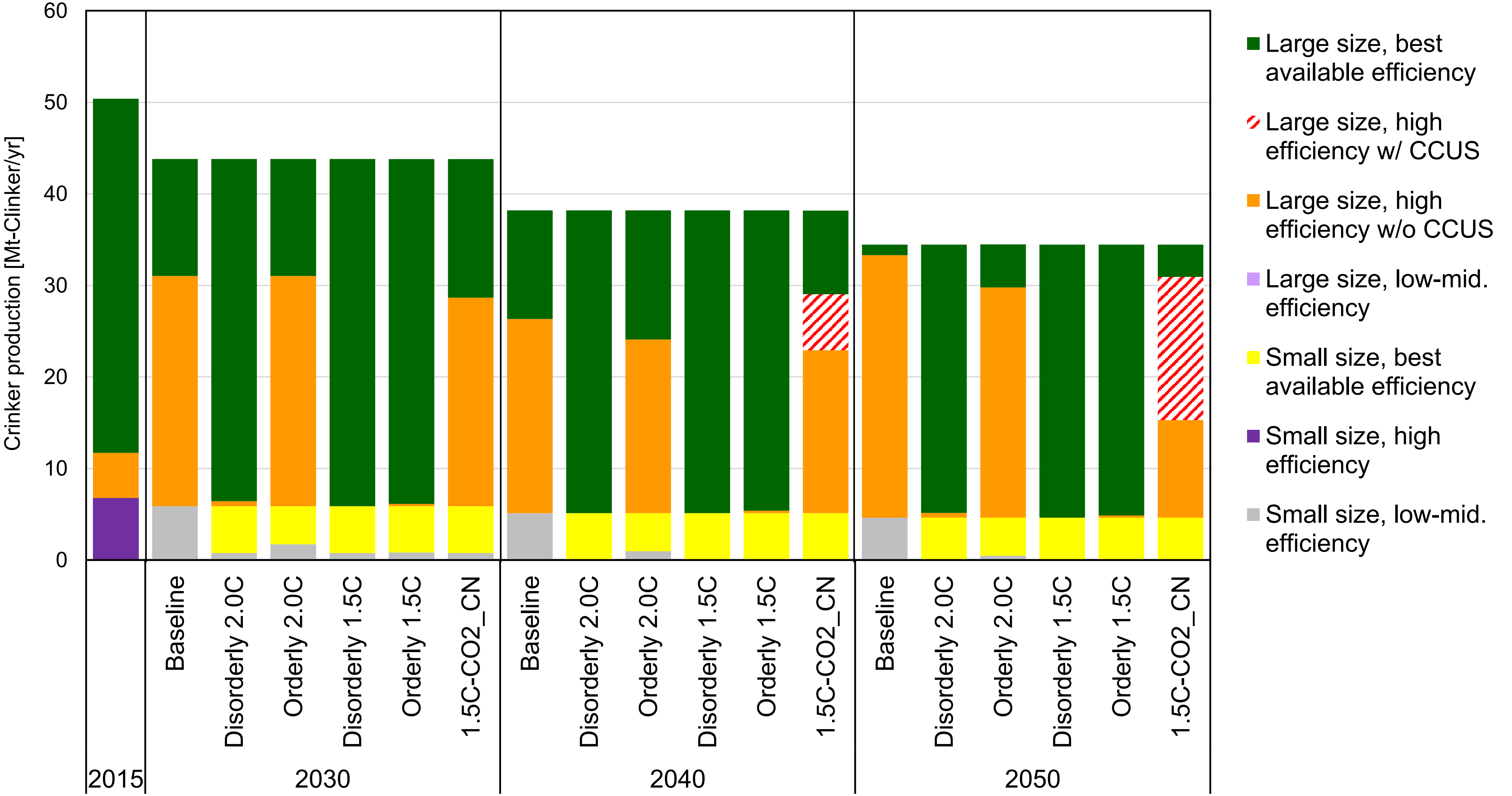


Final energy consumption in cement (Japan)



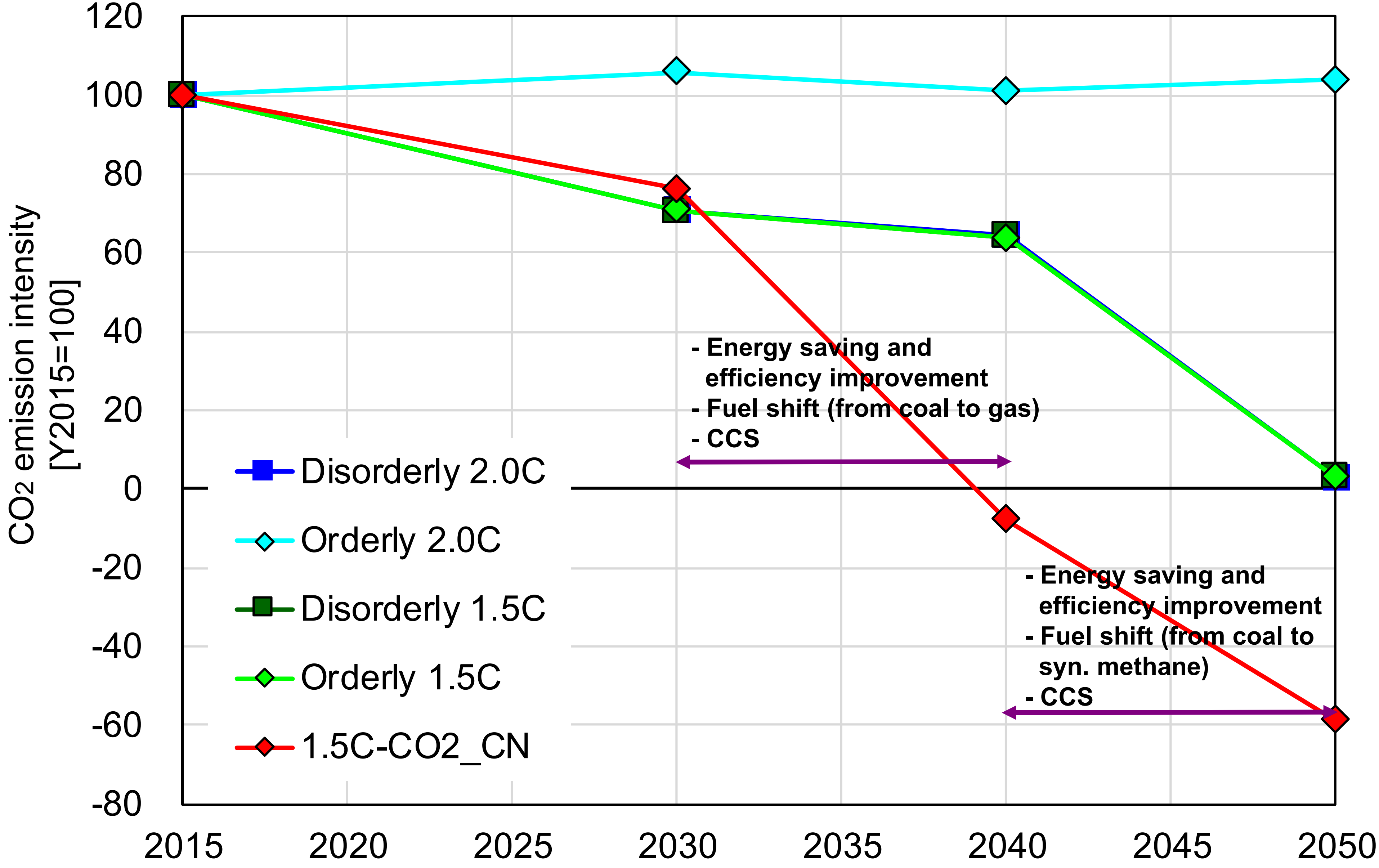
- ✓ **A shift from coal to gas is cost-effective in 2030 except Orderly 2.0°C.**
- ✓ **A further shift to gas is promoted toward 2040, and synthetic methane is evaluated to be cost-effective around 2050 in the scenarios which assume CN in Japan.**

Clinker production by technology in cement sector (Japan)

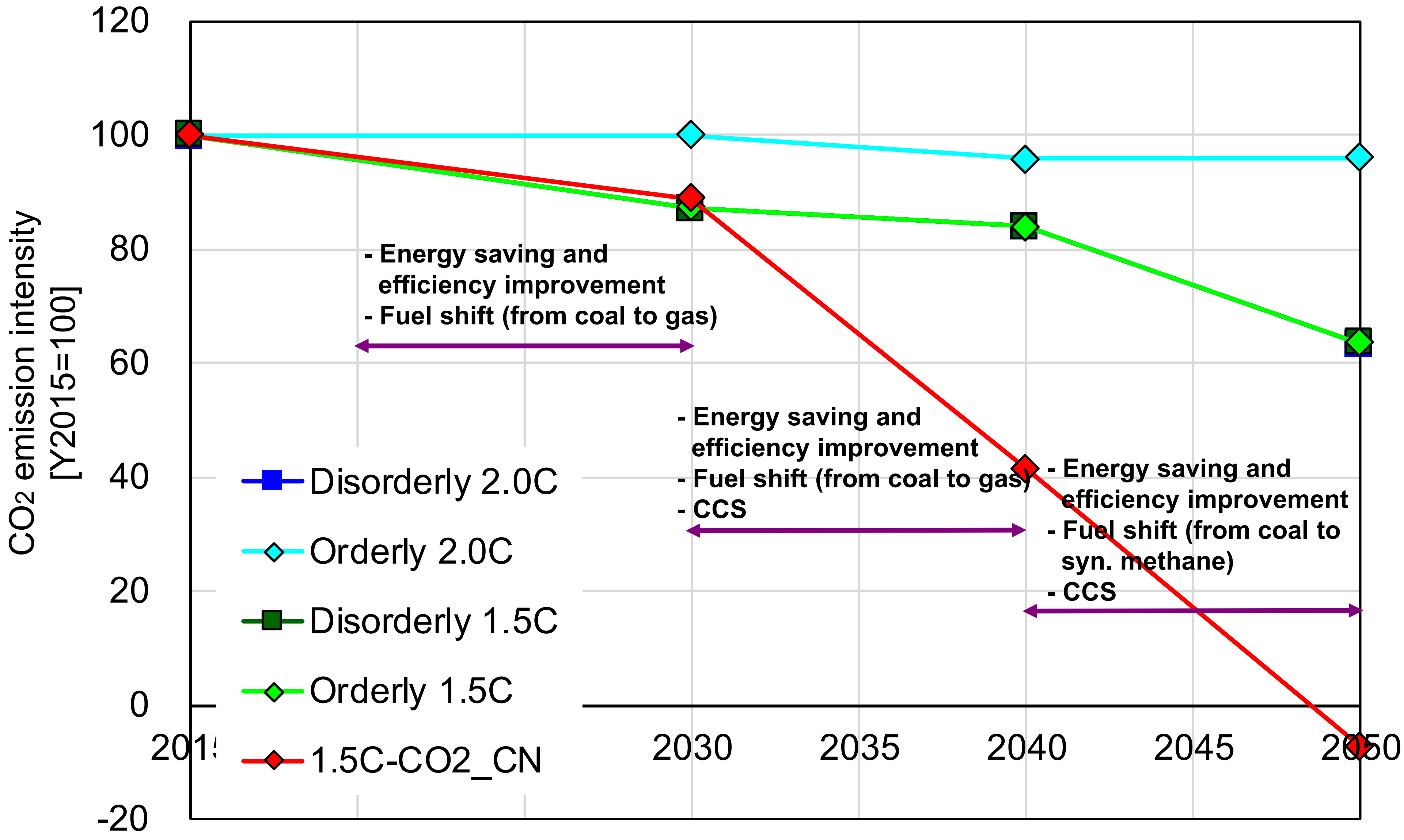


- ✓ **CO_2 capture in clinker production is not selected as a cost-effective measure in Japan in other scenarios than 1.5C-CO_2_CN. Some possible reasons are that CCS cost is relatively high in the cement sector and that negative emission measures, such as DACCS, are prioritized due to the constraint on overall CO_2 storage potential.**
- ✓ **On the other hand, CO_2 capture is also introduced in large size production facility in 1.5C-CO_2_CN.**

Energy-related CO_2 intensity of cement sector (Japan)

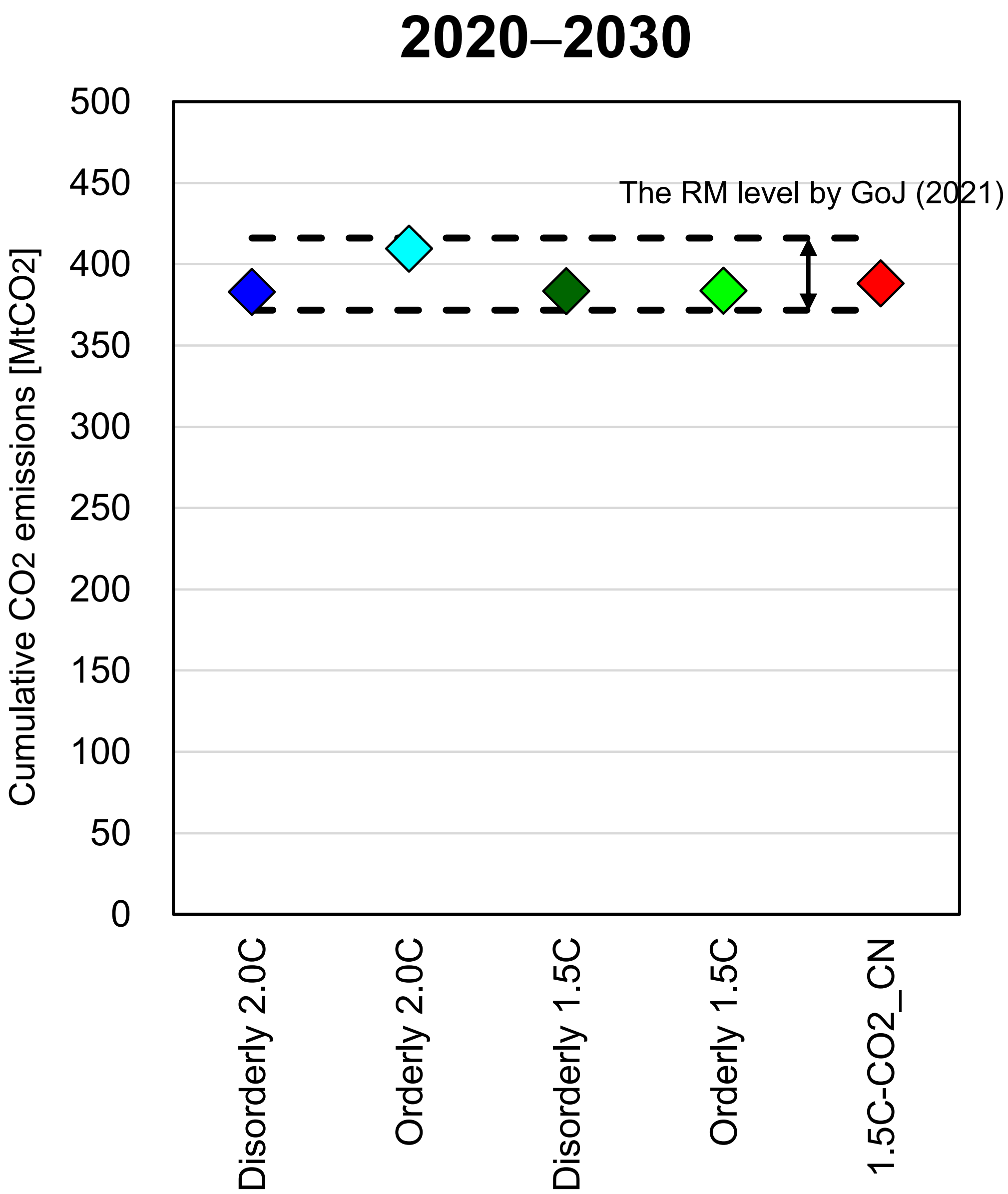


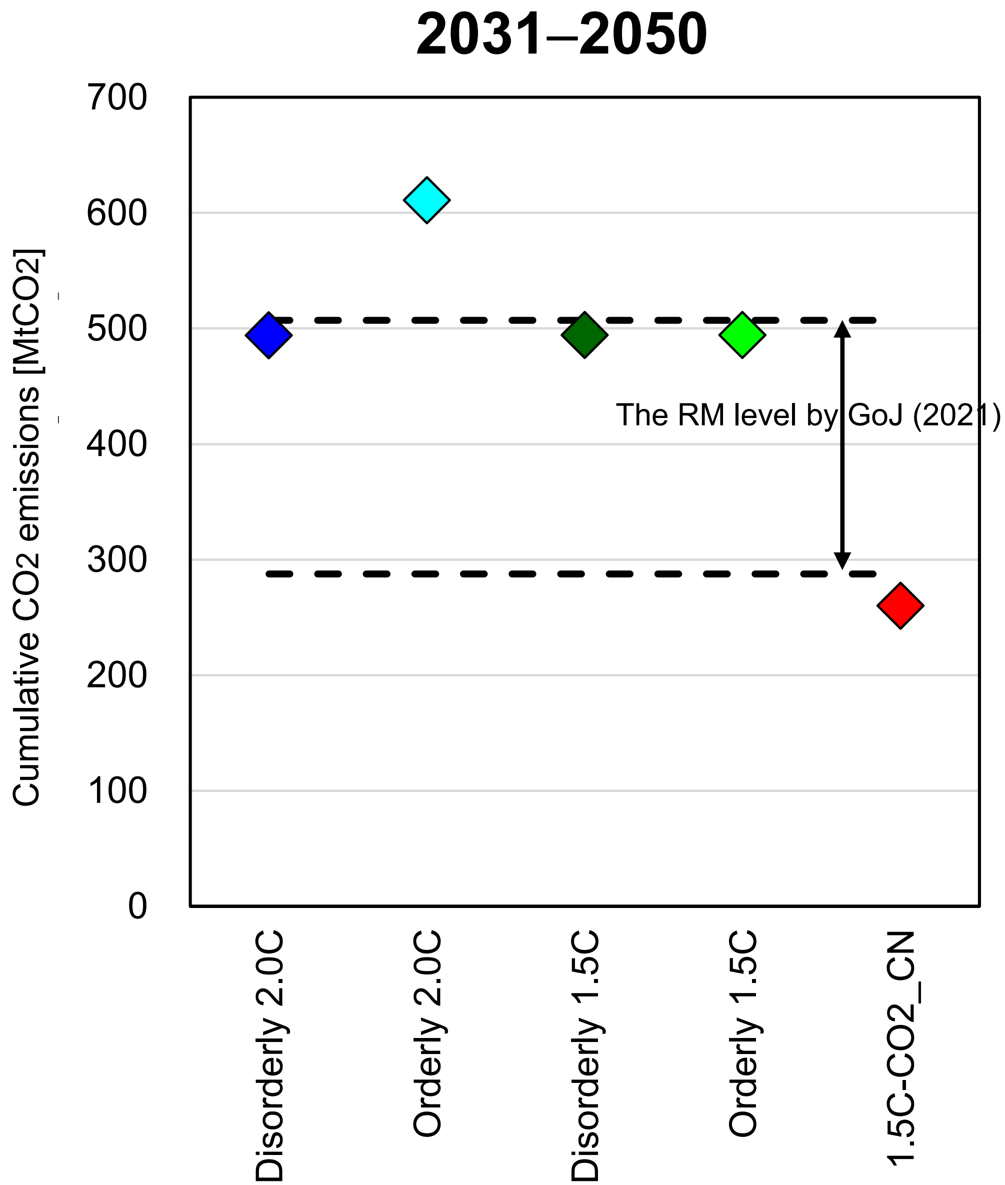
CO_2 intensity of cement sector (Japan)



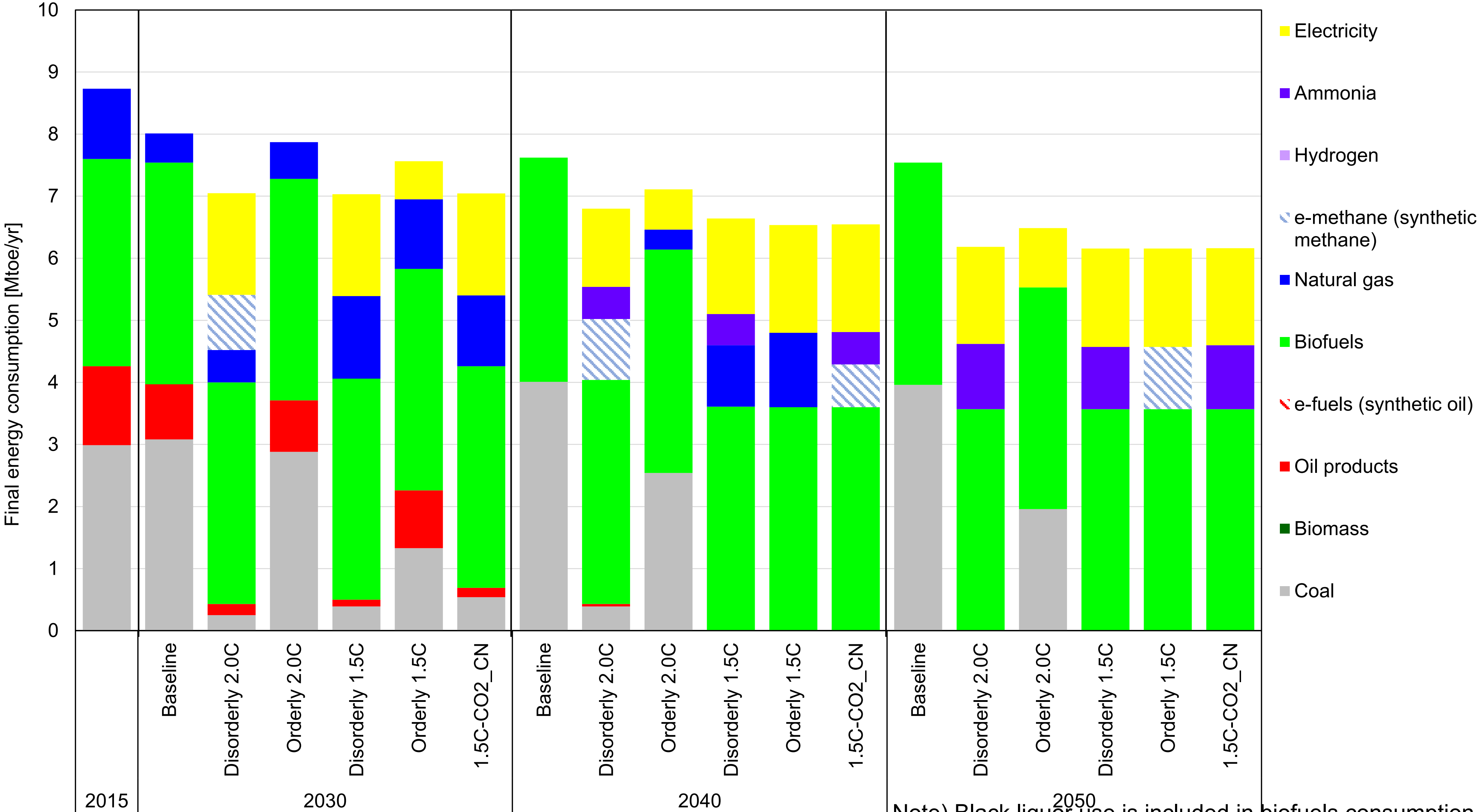
- ✓ In other scenarios than 1.5C-CO_2_CN, emissions from processes still remain in 2050 as there is no CCS deployment.
- ✓ In 1.5C-CO_2_CN, CN is achieved by the introduction of synthetic methane+CCS.

CO_2 emissions in cement sector (Japan): comparison with the RM by GoJ





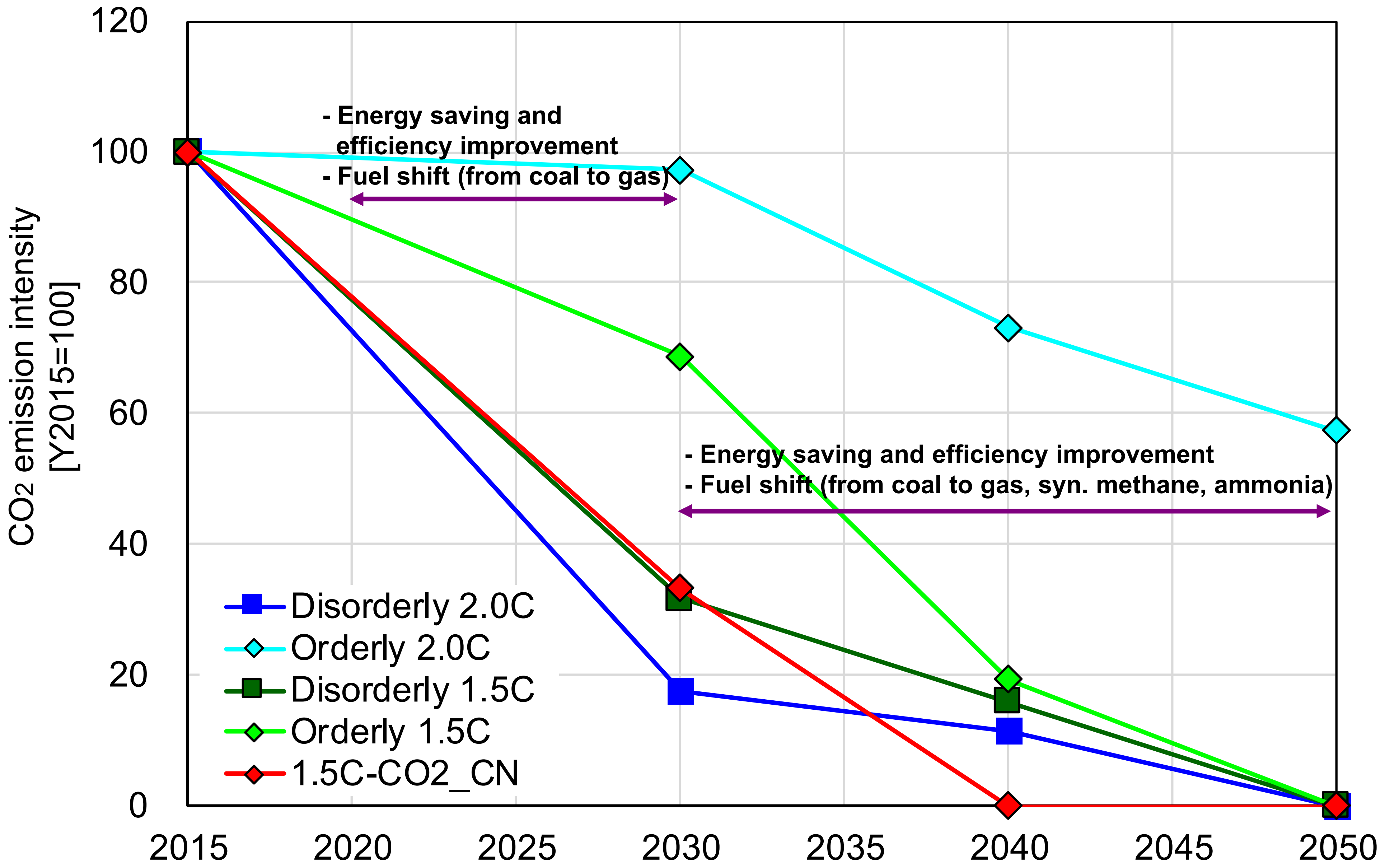
Final energy consumption in paper & pulp (Japan)



Note) Black liquor use is included in biofuels consumption.

- ✓ **A Shift from coal to gas, biomass and electricity are observed in 2030.**
- ✓ **After 2040, a shift to blue ammonia produced overseas in Disorderly 2.0°C/1.5°C, which assumes relatively modest constraints on CCS, and a shift to synthetic methane in Orderly 1.5°C, in which ammonia production is difficult due to relatively strict constraints on CCS, are observed.**

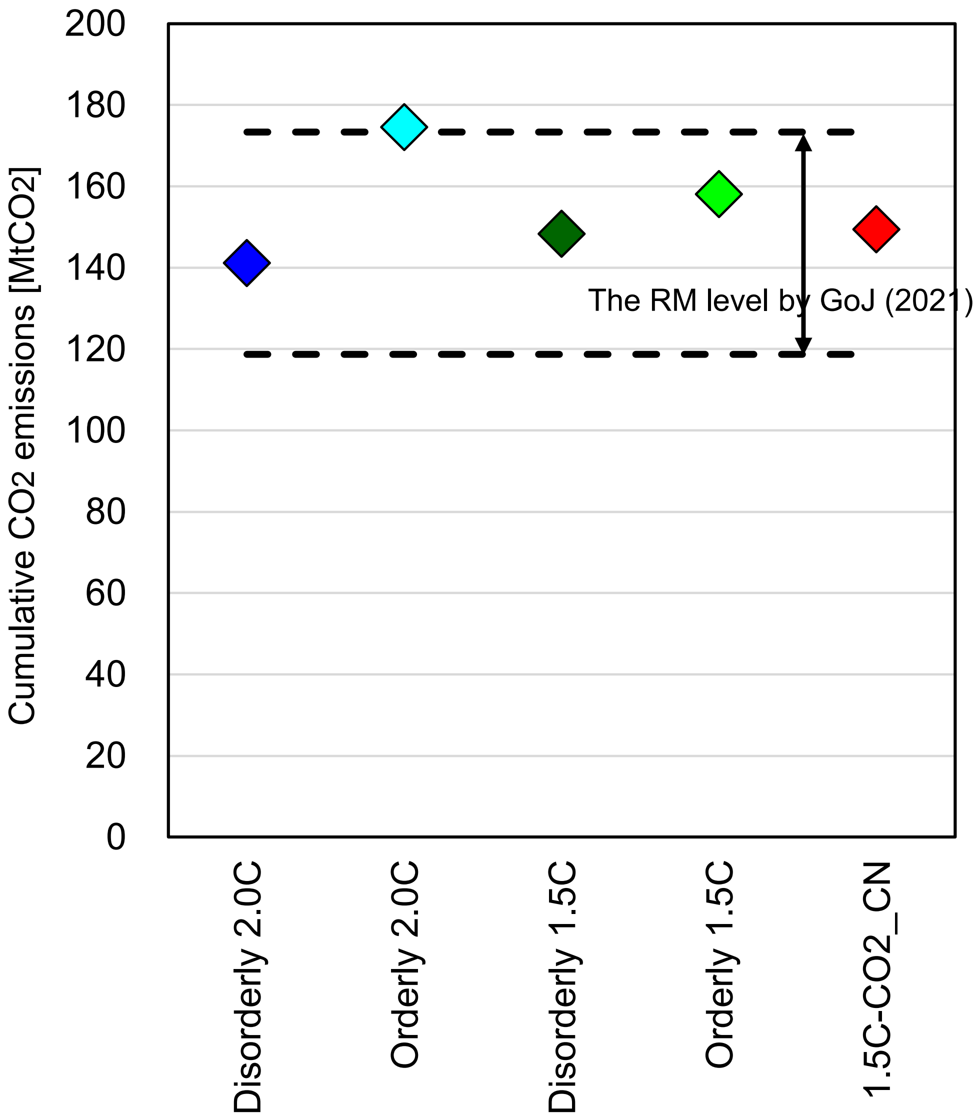
CO_2 intensity of paper & pulp sector (Japan)



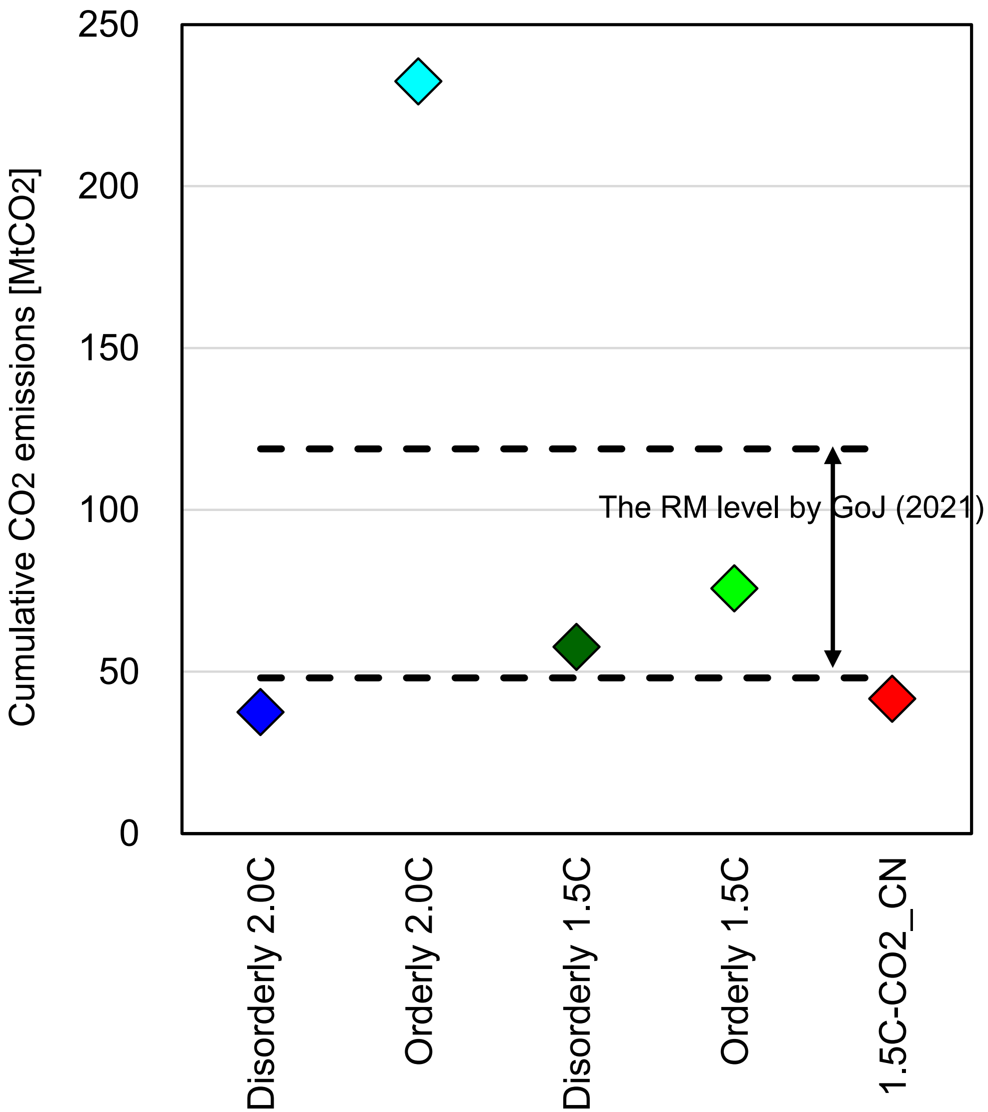
- ✓ A certain amount of emissions remains in Orderly 2.0°C, where emissions reduction is modest.
- ✓ In other scenarios, zero emission is achieved in 2050 by the introduction of synthetic methane or ammonia.

CO_2 emissions in paper & pulp sector (Japan): comparison with the RM by GoJ

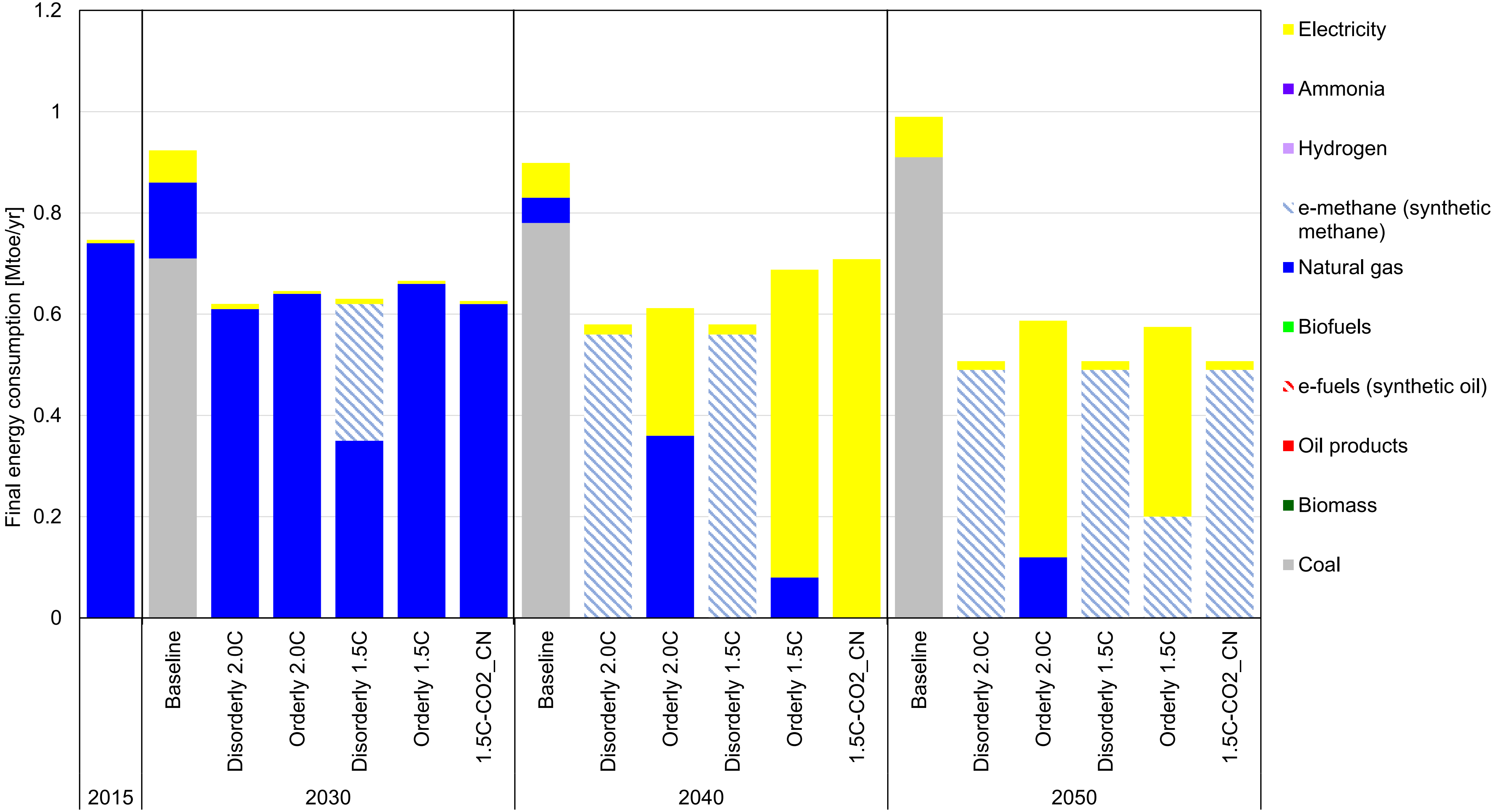
2020–2030



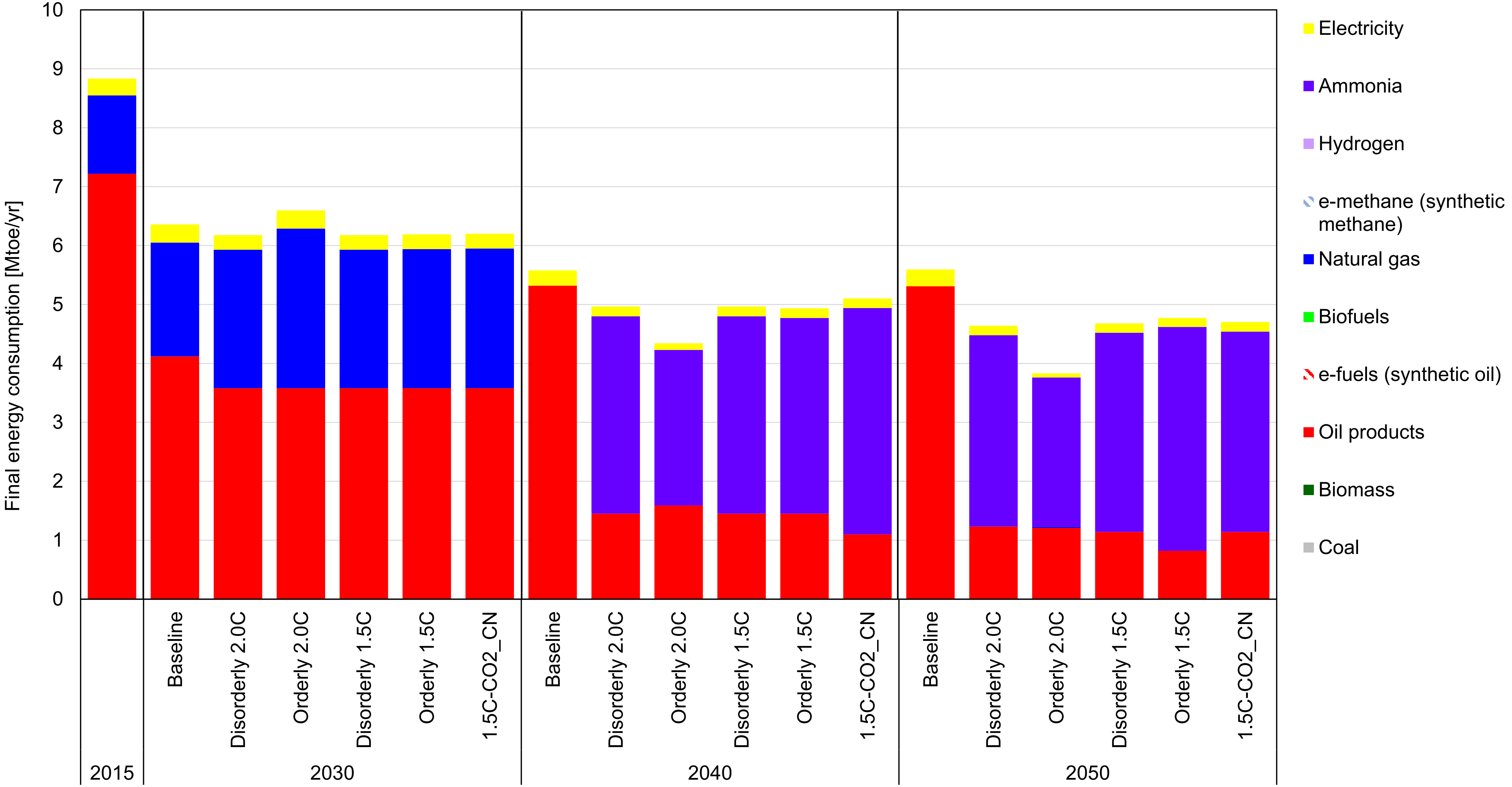
2031–2050



Final energy consumption in ammonia productions of chemical sector (Japan)



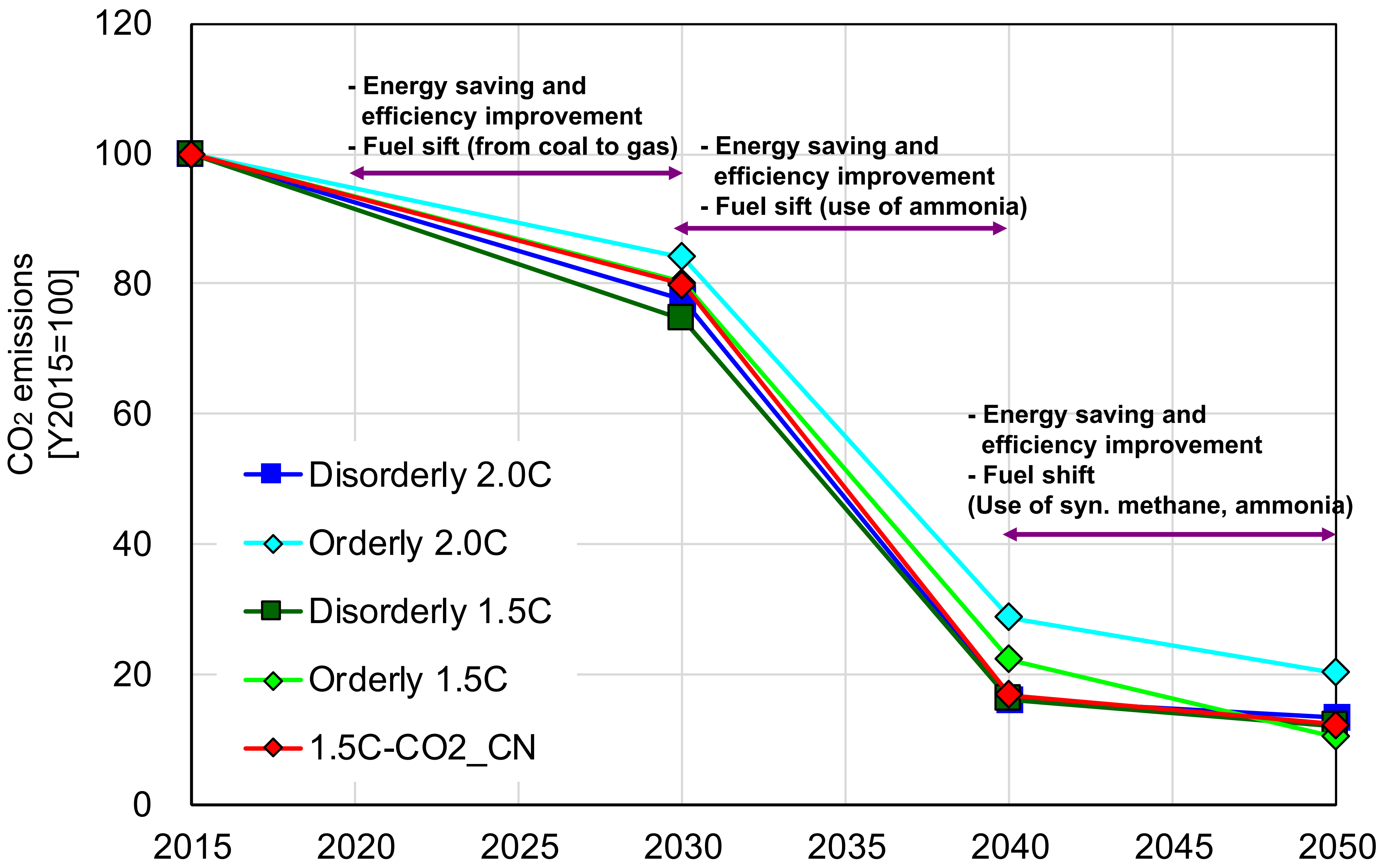
Final energy consumption in ethylene, propylene, and BTX productions of chemical sector (Japan)



Note) Only energy consumption for production is shown, and raw material is not included.

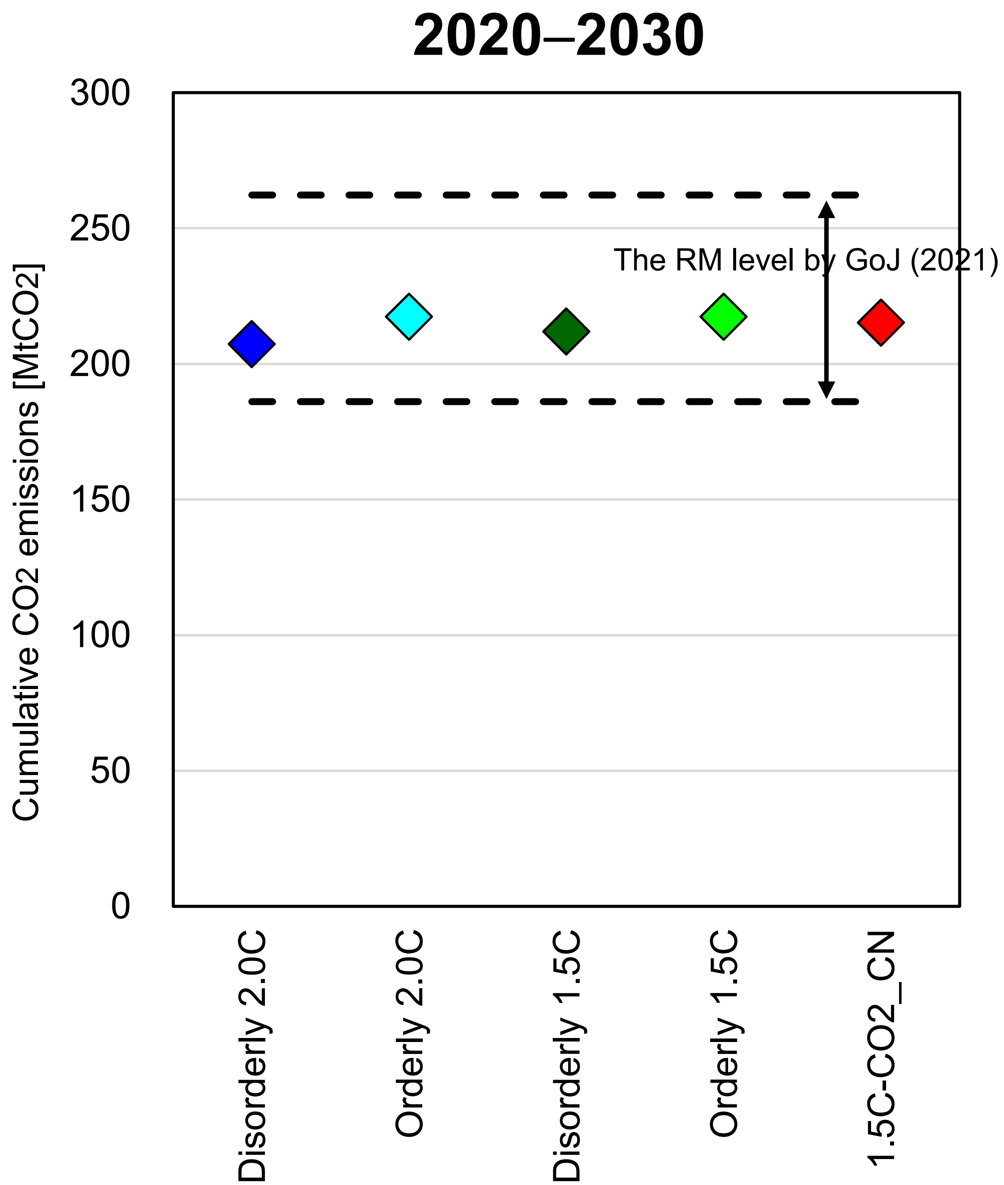
✓ **The use of ammonia expands in 2040 and 2050.**

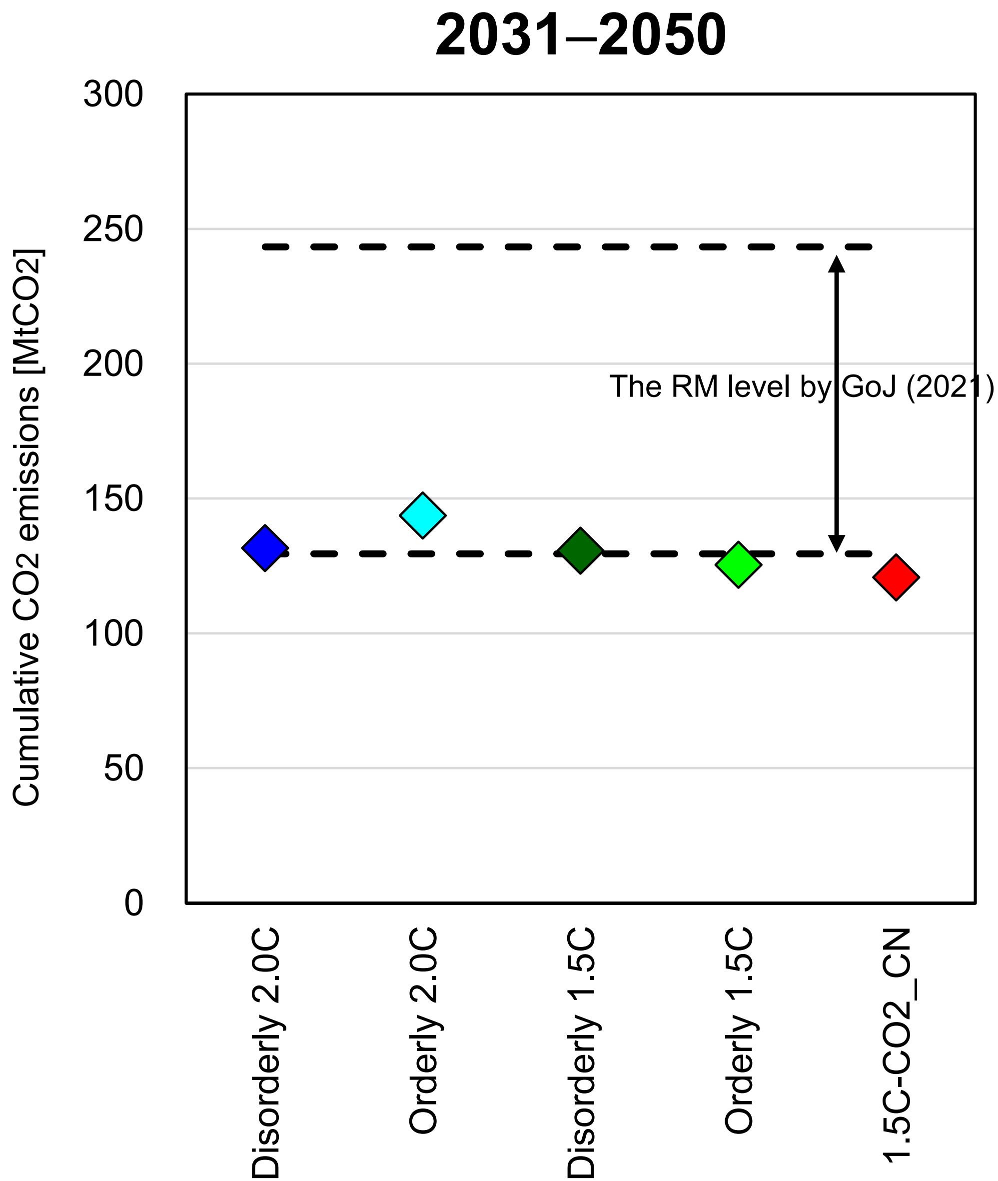
CO_2 emissions in chemical sector (Japan)



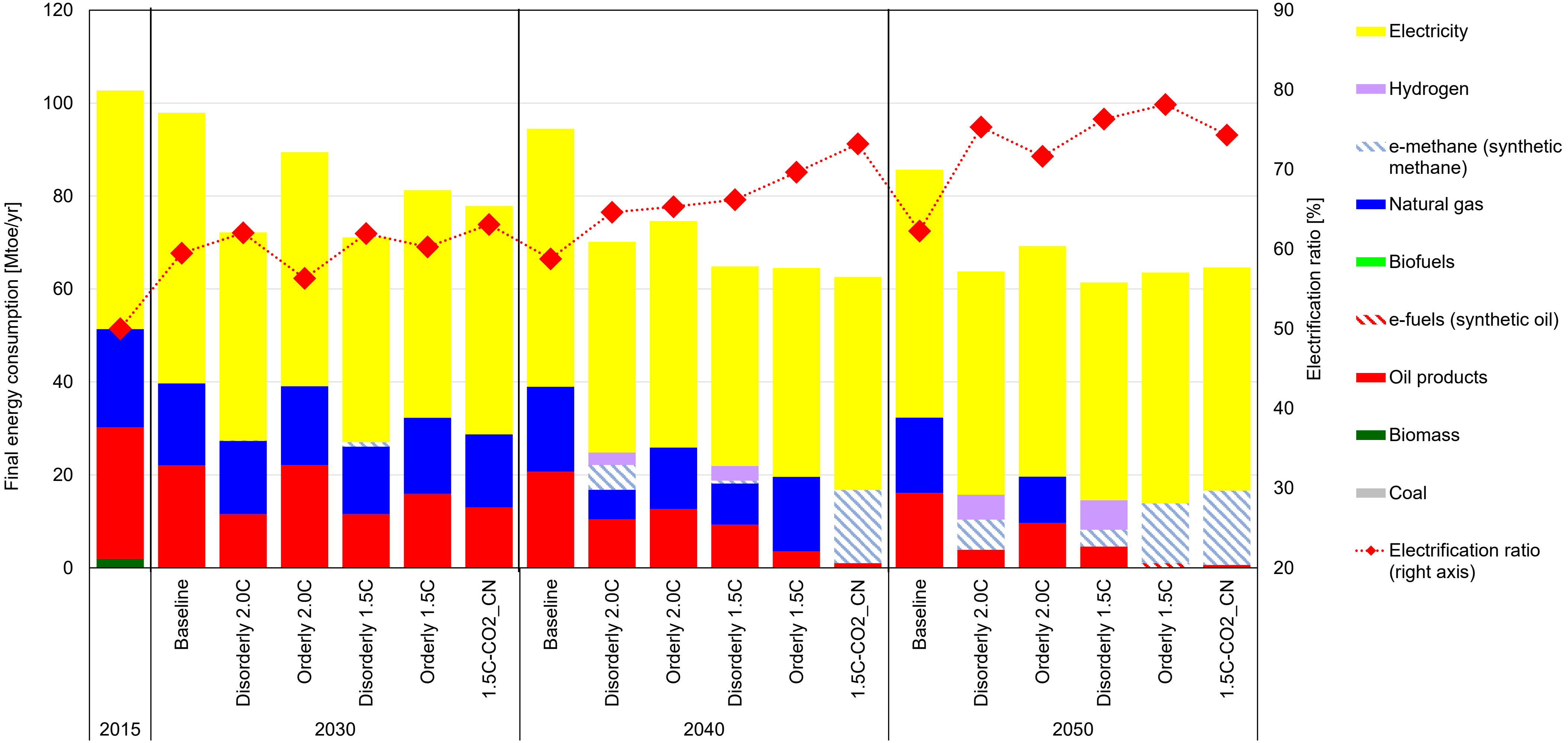
✓ Emissions reduction is progressed by use of ammonia and synthetic methane and electrification.

CO_2 emissions in chemical sector (Japan): comparison with the RM by GoJ



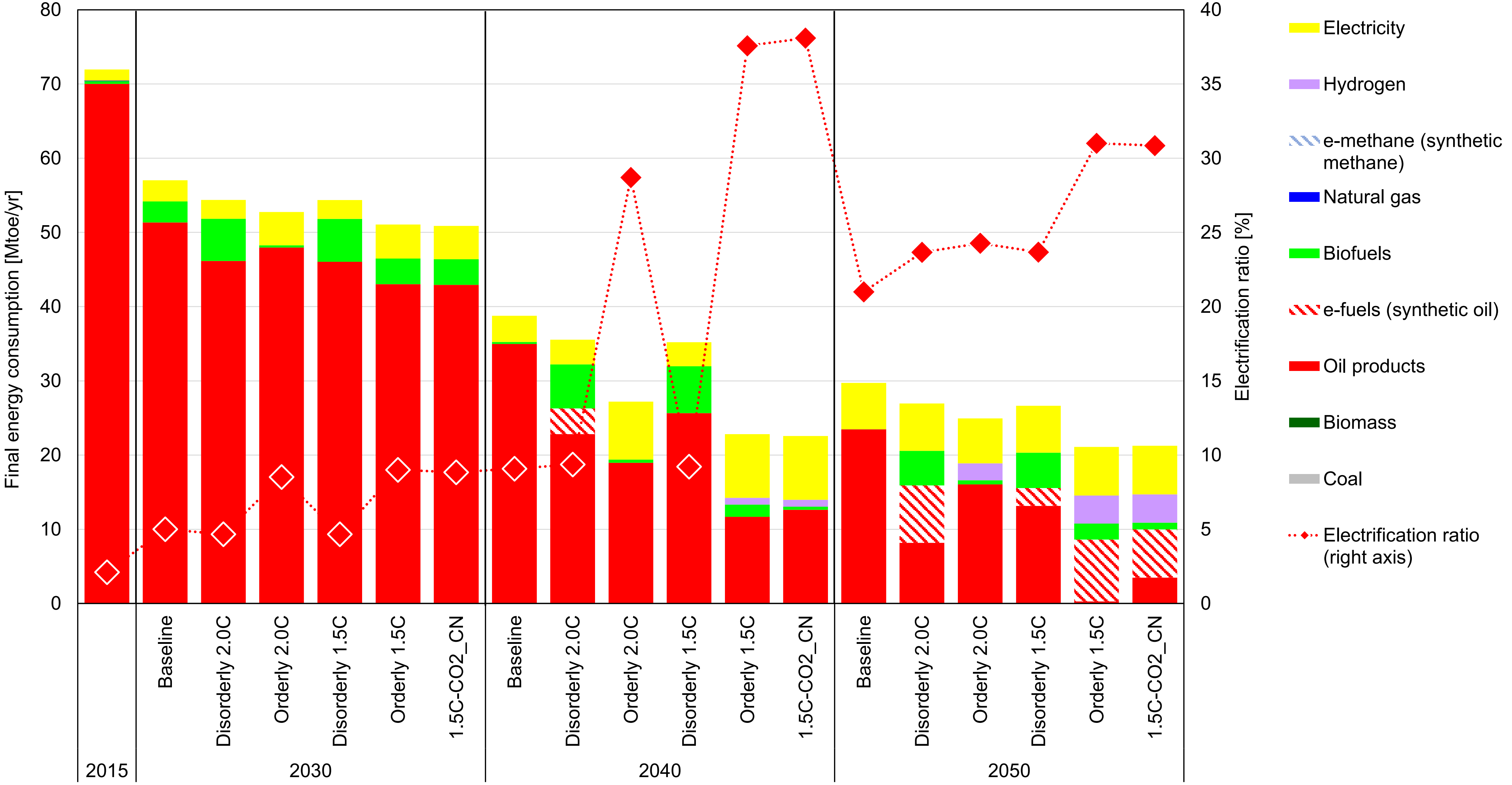


Final energy consumption in building (Japan)



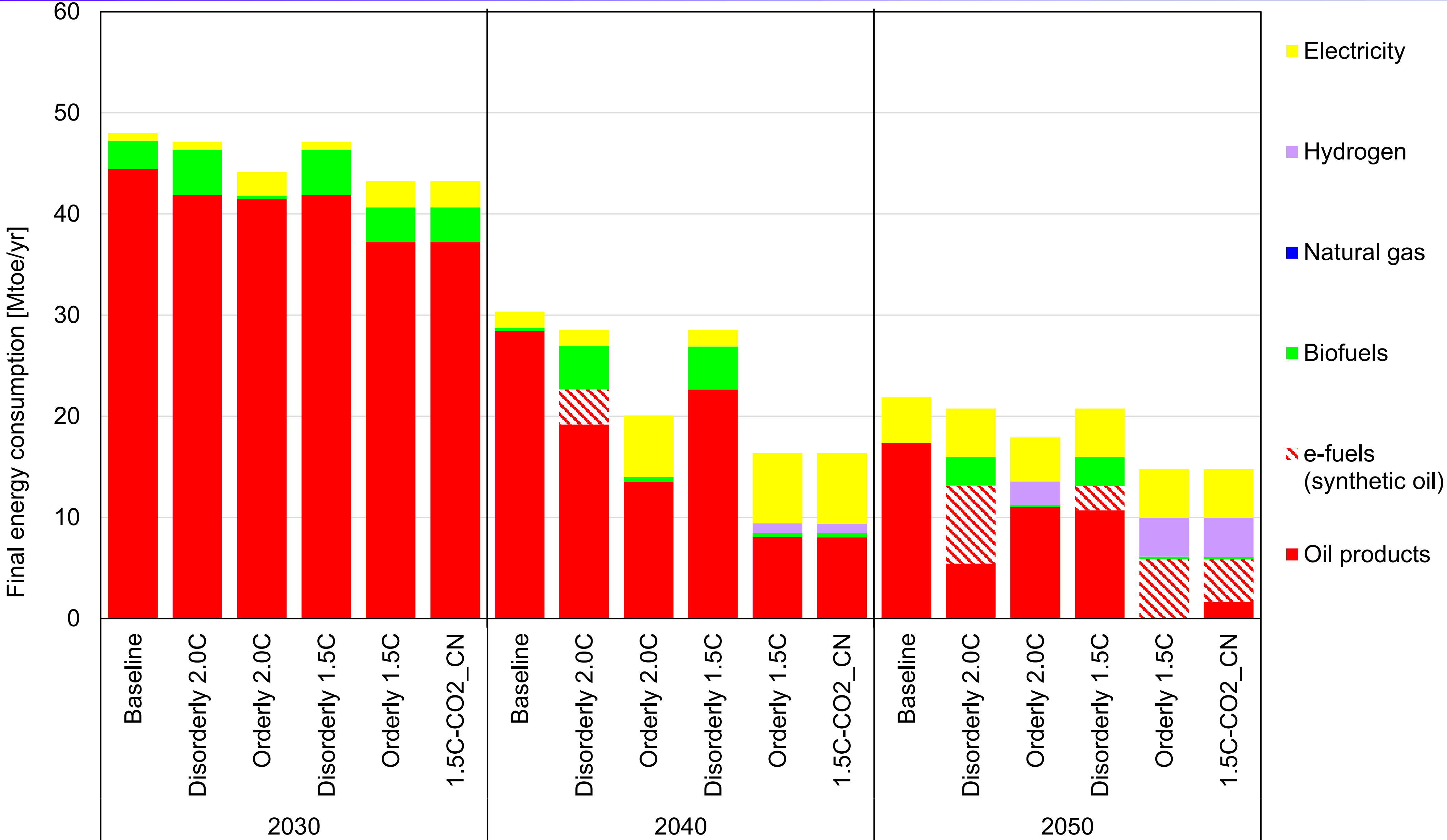
- ✓ The improvement of electrification ratio is cost-effective as emissions reduction is stricter.
- ✓ In Orderly 2.0°C, natural gas remains even in in 2050. It is replaced with synthetic methane in other scenarios.

Final energy consumption in transport (Japan)



- ✓ Oil remains to some extent even in 2050 in the scenarios other than Orderly 1.5°C.
- ✓ The uses of hydrogen and synthetic fuels, etc. are observed after around 2040 toward 2050.

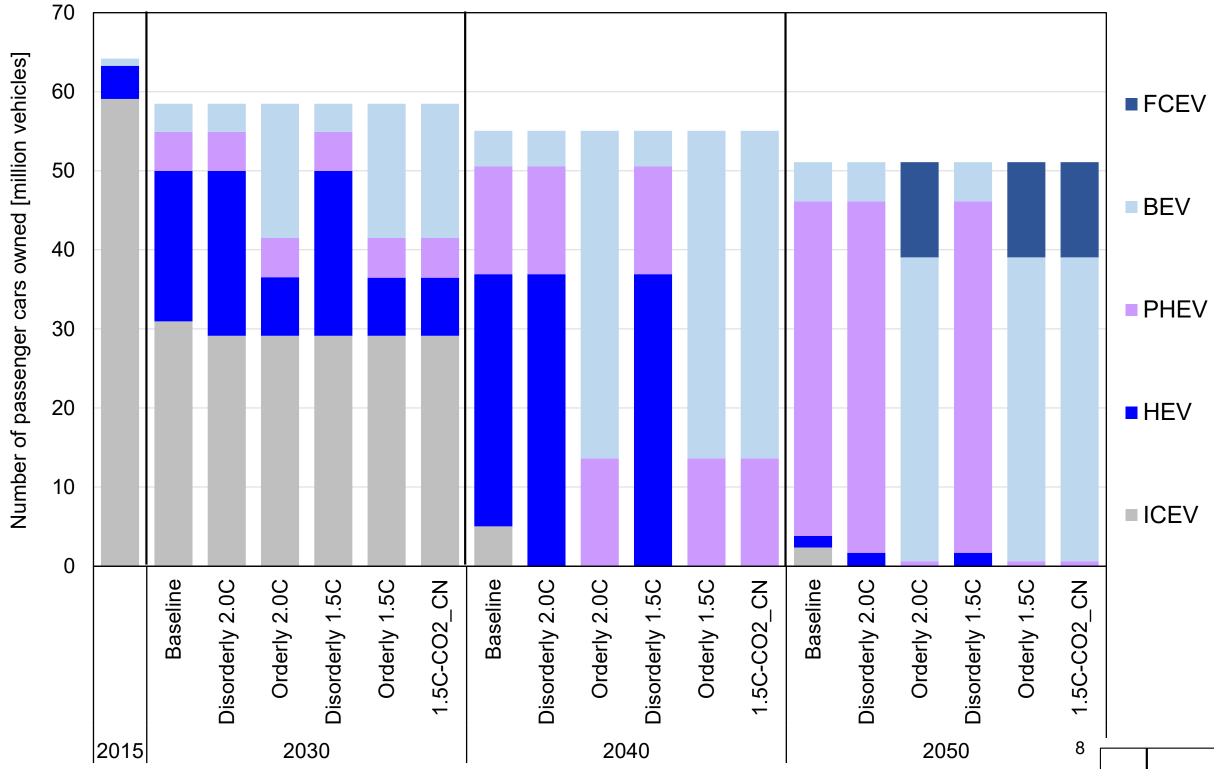
Final energy consumption in road transport (Japan)



- ✓ **Electricity notably increases from around 2040 in Orderly scenarios, which assume significant cost reduction in renewables and EV.**
- ✓ **Synthetic fuels are also used in 2050. Almost all passenger cars would be BEV, and synthetic fuels are used mainly for trucks in Orderly 1.5°C.**

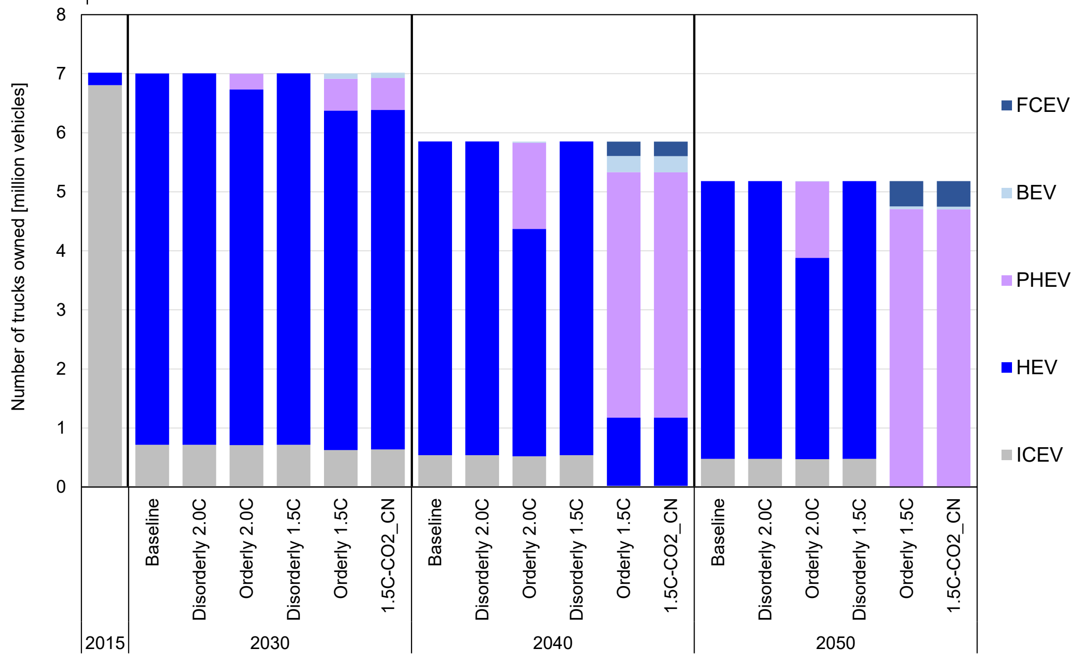
Number of vehicles owned (Japan)

Passenger cars



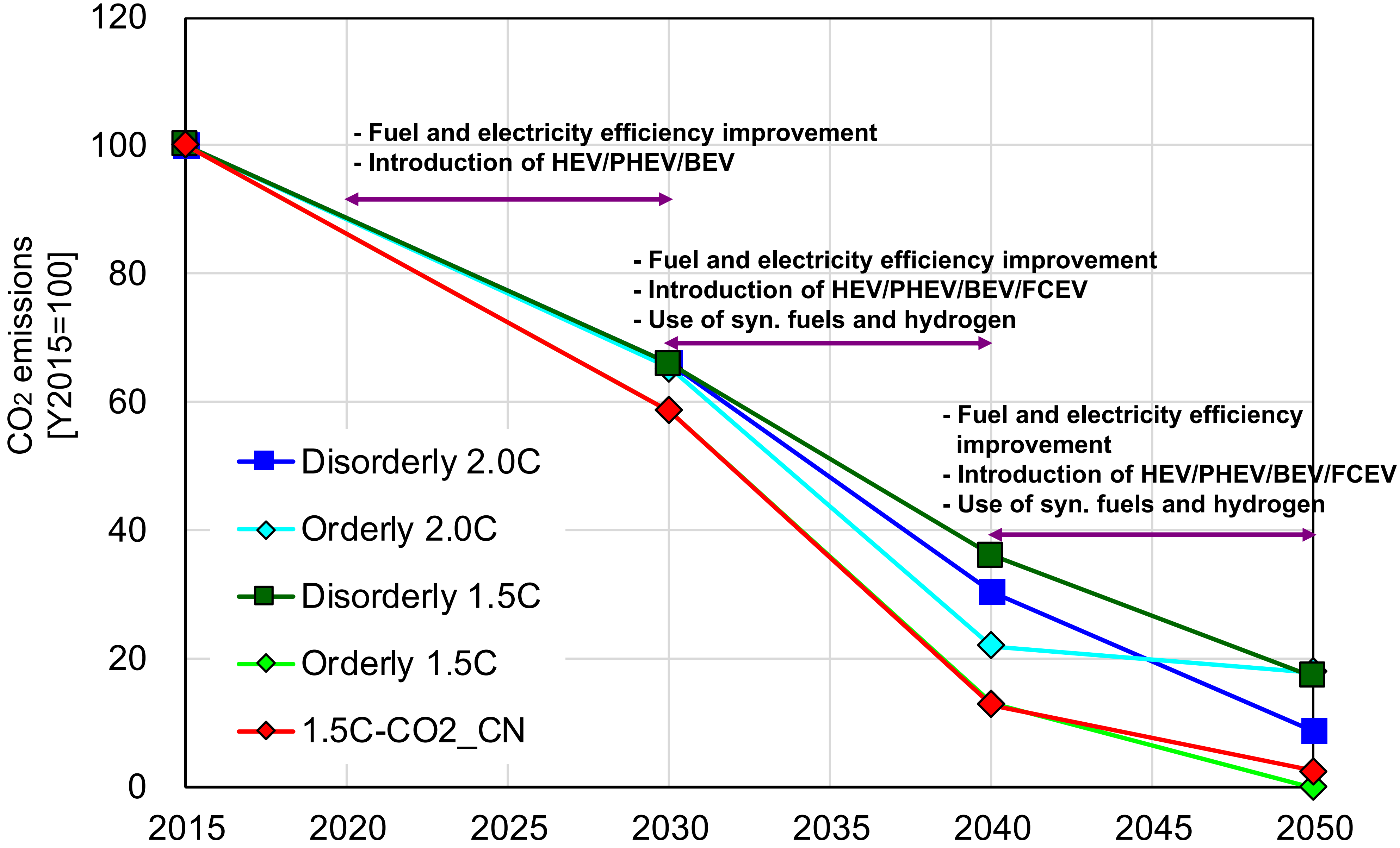
- ✓ In Disorderly scenarios, PHEV is cost-effective.
- ✓ In Orderly scenarios, BEV becomes cost-effective from around 2040, an FCEV can be observed around in 2050.

Trucks



- ✓ For trucks, in Orderly scenarios, most of them are internal combustion trucks, while BEV and FCEV are partly observed.

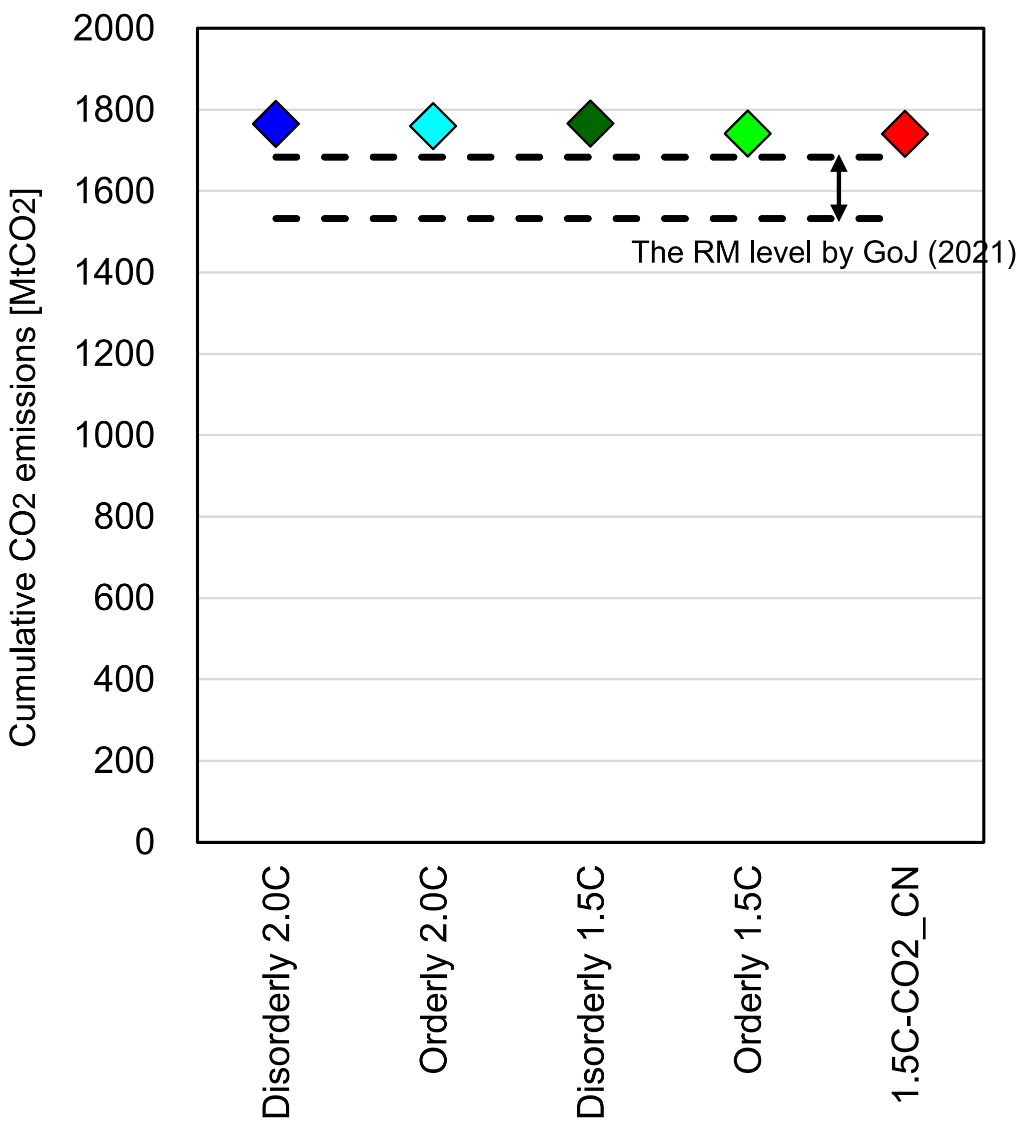
CO_2 emissions in road transport (Japan)



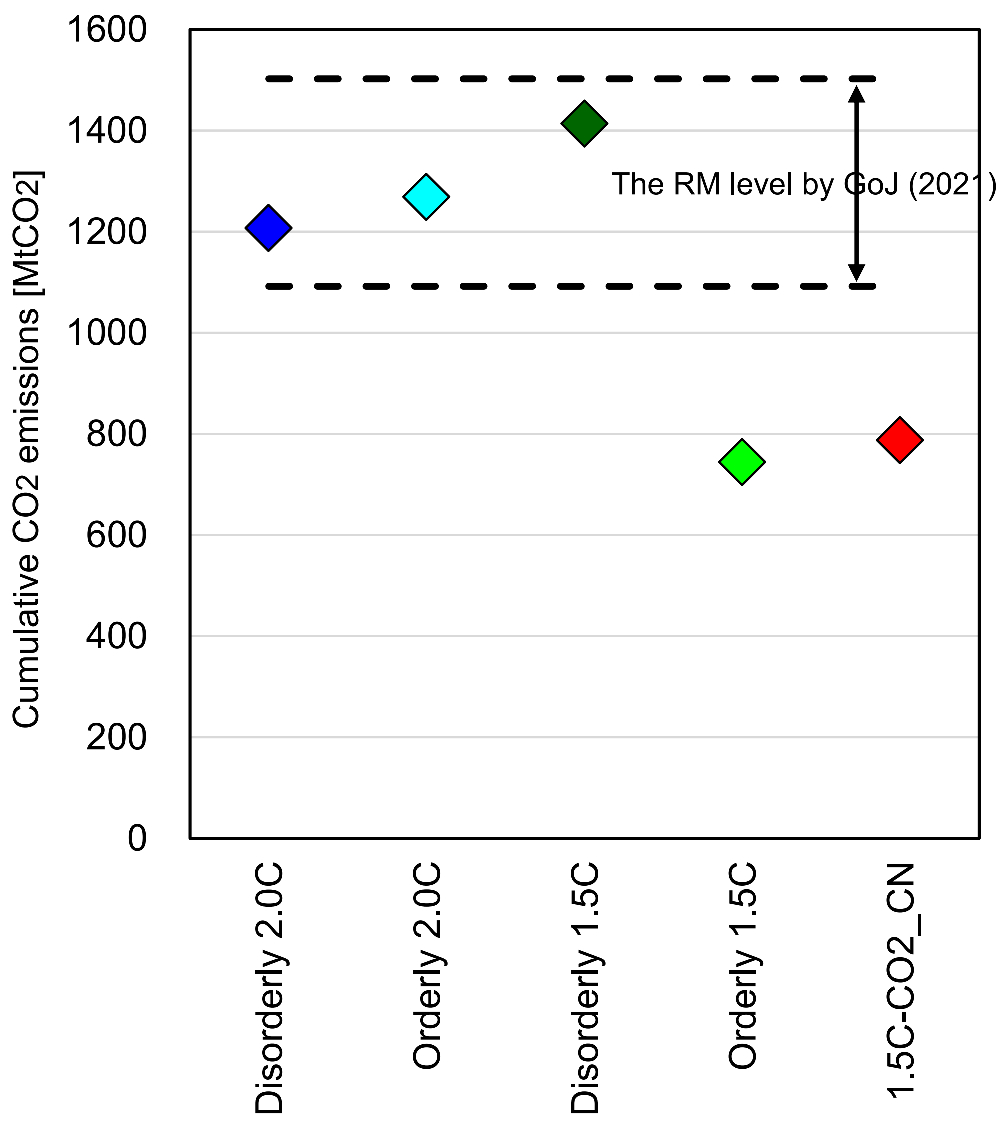
✓ Continuous CO_2 emissions reduction is expected due to the enlarged introduction of HEV/PHEV/BEV.
✓ The use of hydrogen and synthetic fuels is expected from around 2040.

CO_2 emissions in road transport sector (Japan): comparison with the RM by GoJ

2020–2030

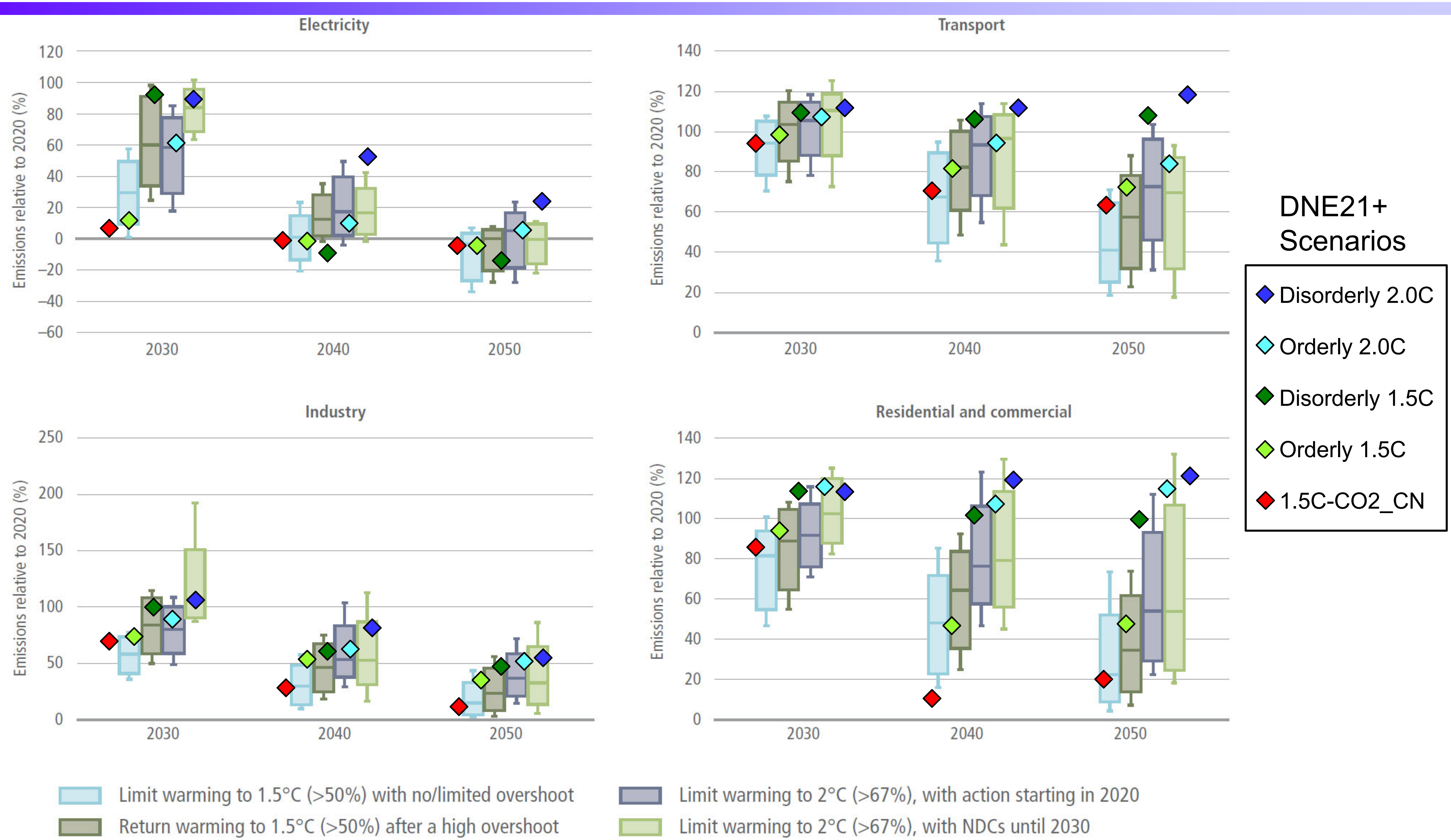


2031–2050



3. The Scenarios Developed by Using DNE21+ Model and the Comparison with Other Scenarios

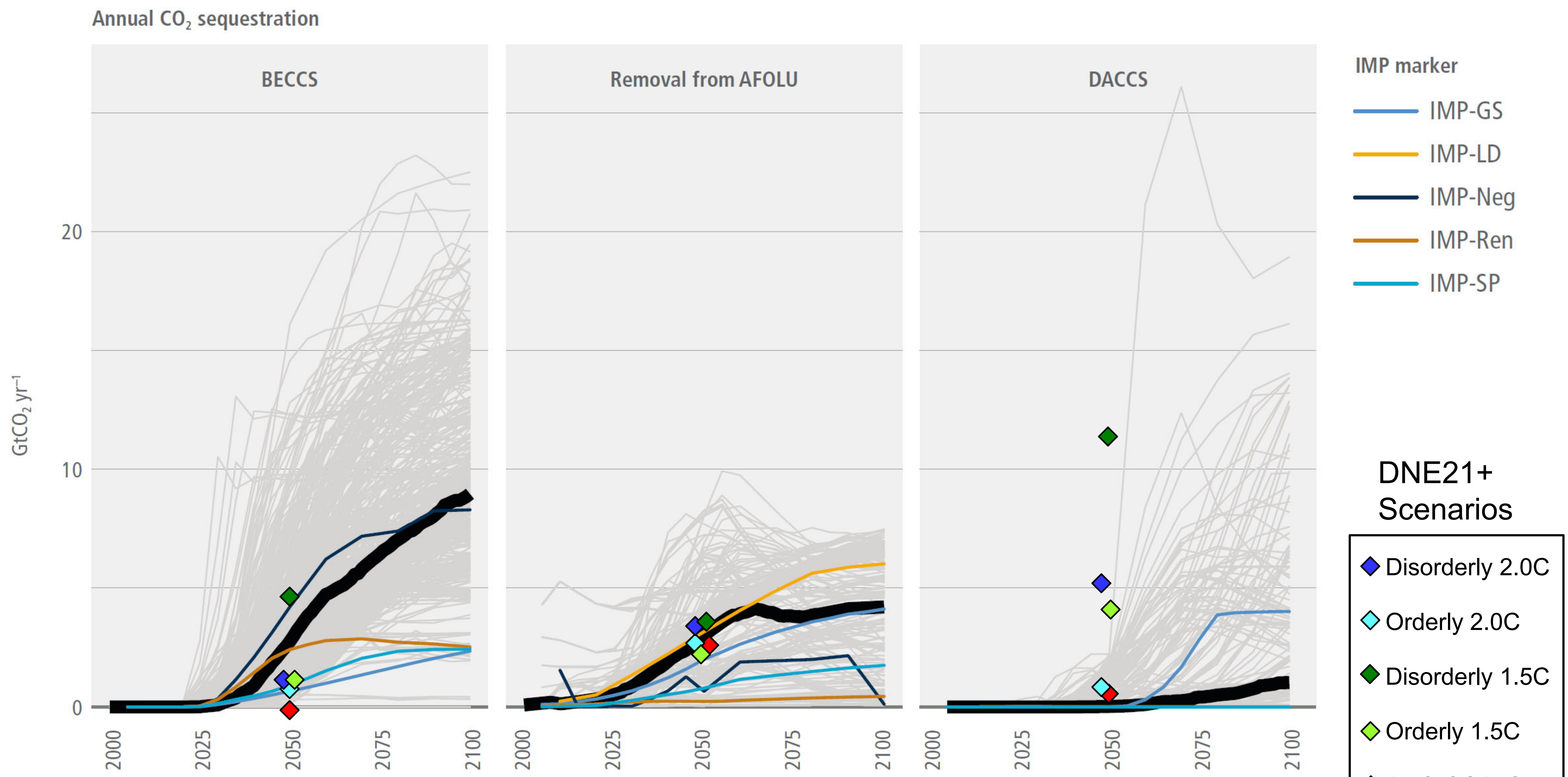
Comparison with global CO_2 emission scenarios of IPCC



Source) DNE21+ scenarios are plotted on the figures of IPCC AR6 (2022).
Note) Boxes indicate 25th and 75th percentiles, while whiskers indicate 5th and 95th percentiles in IPCC scenarios.

The DNE21+ scenarios are almost consistent with those of IPCC, covering their ranges of upper and lower limits. Some parts are slightly out of the range, probably due to the assumption of DACCS.

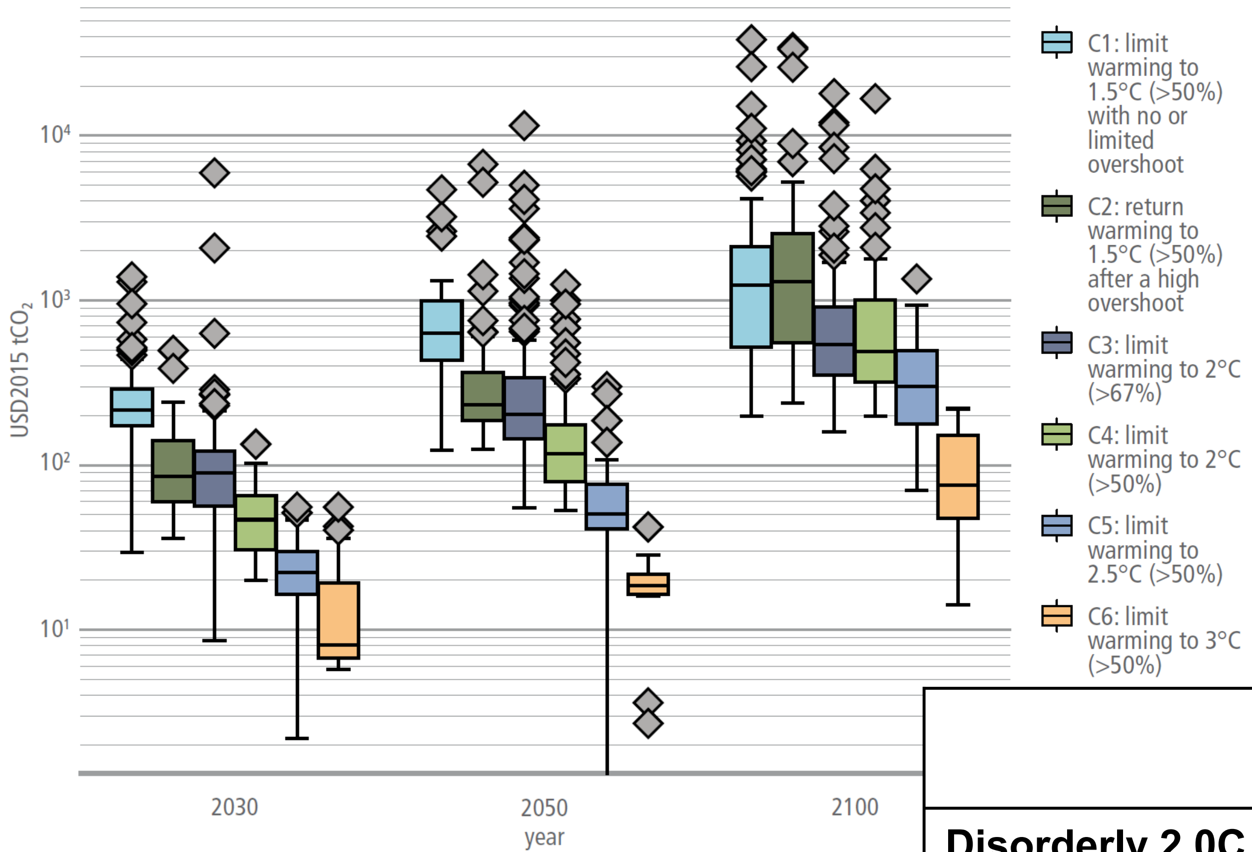
Comparison with global CDR scenarios of IPCC



Source) DNE21+ scenarios are plotted (only for 2050) on the figures of IPCC AR6 (2022).
Note) As for IPCC AR6, only the scenarios categorized as C1-C3 are shown.

The CO_2 amounts for DACCS in Disorderly 1.5°C are around at the upper most level of those in IPCC scenarios, and the amounts for DACCS in other scenarios and for BECCS and Removal from AFOLU are around at the middle of those in IPCC scenarios. (Slightly higher in DACCS while slightly lower in BECCS.) It can be said that RITE scenarios are quite reasonable considering that not many models explicitly evaluate DACCS in IPCC AR6.

CO2 marginal abatement costs: compared with IPCC and IEA



AR6, Fig. 3.33

IEA WEO2022 NZE
【corresponding to the IPCC C1】
Carbon price in 2050：180～250 $/tCO2 (which is quite cheaper than those of IPCC and DNE21+ scenarios)

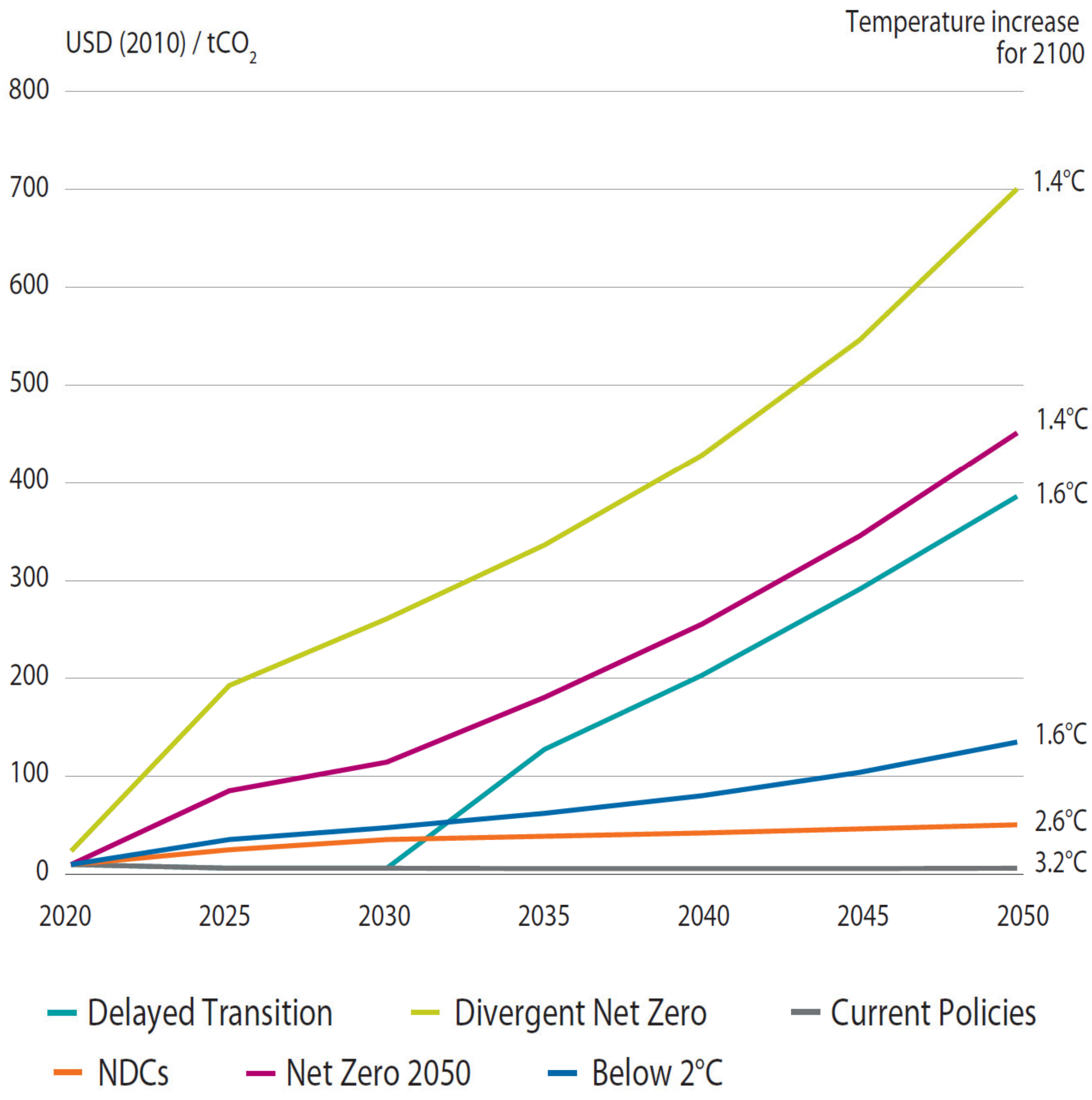
Note) The MAC having the ranges of DNE21+ are differences across countries.

DNE21+ and IPCC scenarios in 2050 (USD/tCO2eq)

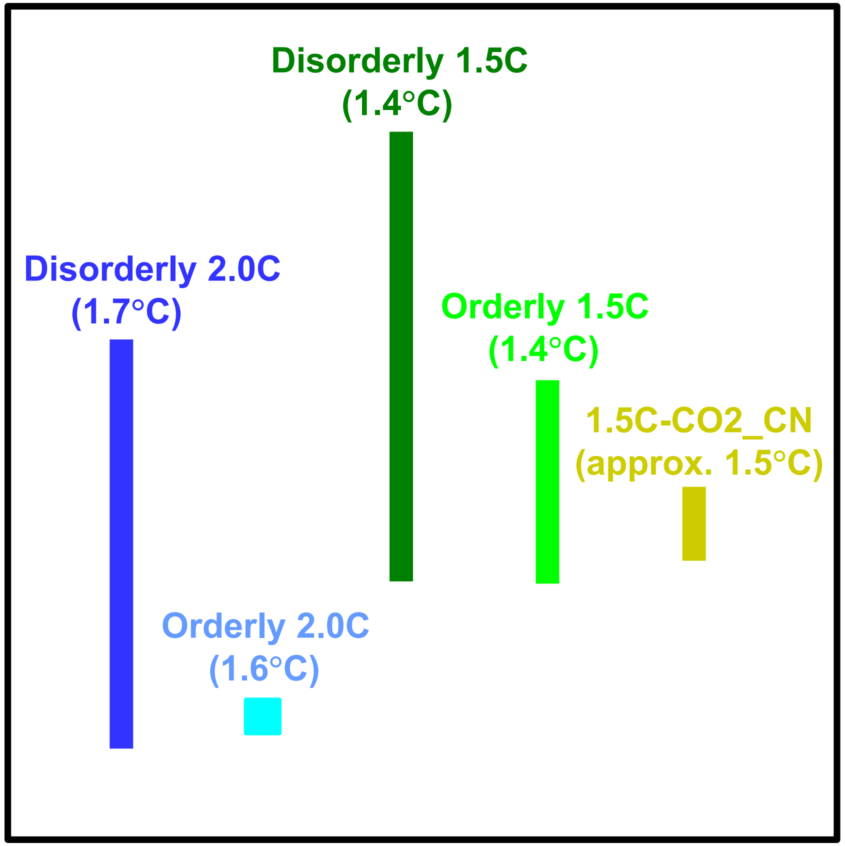
	DNE21+	IPCC (25-75 percentile, approx.)	
Disorderly 2.0C	119～500	C3	150～350
Orderly 2.0C	158	C3	
Disorderly 1.5C	268～685	C2	200～350
Orderly 1.5C	268～465	C1	450～1000
1.5C-CO2_CN	293～351	C1	

- **Most of the carbon prices in the IPCC reports had been estimated under the equal MAC across countries. The prices of DNE21+ scenarios are consistent with those of the IPCC report.**
- **Most of the IPCC scenarios had not considered DACCS explicitly, while DNE21+ considers. Thanks to DACCS, the carbon prices of DNE21+ for the C1 categories are sligly lower than those of the IPCC.**

CO_2 marginal abatement costs: compared with NGFS



DNE21+ scenarios in 2050



Note) the parentheses numbers are temperature rise in 2100

- ✓ **Thanks to DACCS, the carbon prices of DNE21+ for the 1.5°C scenarios are slightly lower than those of NGFS scenarios.**
- ✓ **Generally, the carbon prices (MAC) are consistent with the NGFS's.**

4. Conclusion and Future Works

Conclusion and future works

[Conclusion]

- We developed five scenarios consistent with the 2℃ and 1.5℃ targets, which are comparable with the NGFS and IEA scenarios to derive sector-specific measures, including transitions to carbon neutrality, using the DNE21+ model that enables quantitative and consistent analysis.
- Emission pathways vary widely from sector to sector. They also vary widely depending on the assumed scenario. In particular, there can be considerable differences depending on the projection of CDR.
- Among them, in relative terms, CO2 intensity reduction in the power sector is required to be reduced relatively quickly (consistent with IPCC and IEA scenarios, etc.).
- Japan's sectoral roadmap is generally consistent with the sectoral roadmap prepared by the Japanese government in 2021-22, although there are differences depending on the scenario. In other words, the government roadmap is generally consistent with not only 2℃ but also 1.5℃.
- Taking cost-effective measures from among a wide range of countermeasure options as much as possible will be a closer path to achieving CN at an earlier stage, and this scenario analysis and roadmap will be effective for such a strategy.

[Future works]

- Continue to monitor technological trends, etc., and update as appropriate.
- Prepare roadmaps for individual countries and regions other than Japan to contribute to the promotion of use in a wide range of countries.

Appendix 1:
The Model Assumptions

Examples of literature for DNE21+ model

[Peer-reviewed papers]

K. Akimoto, F. Sano, T. Homma, J. Oda, M. Nagashima, M. Kii, Estimates of GHG emission reduction potential by country, sector, and cost, Energy Policy, 38-7 (2010) 3384–3393.

K. Akimoto, T. Homma, F. Sano, M. Nagashima, K. Tokushige, T. Tomoda, Assessment of the emission reduction target of halving CO2 emissions by 2050: macro-factors analysis and model analysis under newly developed socio-economic scenarios, Energy Strategy Reviews, 2(3-4) (2014) 246-256.

T. Nagata, F. Sano, K. Akimoto

Analyses on the Contribution of Natural Gas in the World and Japan as Medium- and Long-term Global Warming Countermeasures, Journal of Japan Society of Energy and Resources 41-5 (2020).

F. Sano, T. Nagata, K.Akimoto

Role of Hydrogen and Synthetic Methane under Long-term Scenarios toward Carbon Neutrality, Journal of Japan Society of Energy and Resources 42-1 (2021).

K. Akimoto, F. Sano, J. Oda, H. Kanaboshi, Y. Nakano, Climate change mitigation measures for global net-zero emissions and the roles of CO2 capture and utilization and direct air capture, Energy and Climate Change, 2, 100057 (2021).

K. Akimoto, F. Sano, Y. Nakano, Assessment of comprehensive energy systems for achieving carbon neutrality in road transport, Transportation Research Part D: Transport and Environment, 112, 103487 (2022).

K. Akimoto, Assessment of road transportation measures considering comprehensive energy systems under global net-zero emissions, IATSS Research, IATSSR, 47-2 (2023) 196-203.

K. Akimoto, F. Sano, T. Homma, M. Nagashima, N. Onishi, Analysis of the 2030 emissions reduction targets of the previous and current nationally determined contributions of Japan, and a comparison between countries using energy-technology and energy-economic models, Asia-Pacific Sustainable Development Journal, 30-1 (2023).

[Others]

K. Akimoto, F. Sano "Scenario analysis towards achieving carbon neutrality in 2050 (interim report)",

Agency for Natural Resources and Energy, Strategic Policy Committee, May 13, 2021

https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/2021/043/043_005.pdf

Assumed socioeconomic scenarios (Overview)

Shared Socioeconomic Pathways, SSP1 to 5, are developed in response to a call from IPCC. Among the quantitative scenarios developed by RITE in line with these SSPs storylines, this study assumes SSP2 "middle of the road" scenario to deliver the analyses.

[World]

	2030	2050	2100
Population (billion people)	**8.36** (8.14-8.59)	**9.21** (8.61-10.05)	**9.31** (7.00-12.73)
GDP (%/year)	**2.7** (2.4-3.1) [2010-]	**2.2** (1.3-2.8) [2030-]	**1.4** (0.6-2.2) [2050-]
Crude steel production (billion ton)	**1.96** (1.88-2.00)	**2.13** (1.93-2.27)	**2.29** (1.47-2.65)
Cement production (billion ton)	**4.16** (3.90-4.30)	**4.40** (3.85-4.66)	**4.47** (2.94-5.91)
Passenger transport demand in Road sector (trillion p-km)	**30.2** (31.2-37.3)	**60.0** (56.8-74.2)	**83.3** (66.8-88.8)

[Japan]

	2030	2050	2100
Population (billion people)	**0.118** (0.116-0.126)	**0.102** (0.096-0.122)	**0.084** (0.047-0.105)
GDP (%/year)	**1.6** (1.3-1.9) [2010-]	**0.4** (-0.1-1.2) [2030-]	**0.4** (-0.9-1.5) [2050-]
Crude steel production (billion ton)	**0.09** (0.081-0.097)	**0.095** (0.073-0.111)	**0.085** (0.045-0.090)
Cement production (billion ton)	**0.054** (0.050-0.068)	**0.044** (0.031-0.075)	**0.040** (0.023-0.065)
Passenger transport demand in Road sector (trillion p-km)	**0.77** (0.69-0.85)	**0.64** (0.61-0.82)	**0.61** (0.51-0.70)

Note: The values in parentheses show the scenario ranges among SSP1-SSP5. Energy demands and electricity generation are endogenously calculated in the model.

Assumptions on facility costs of power generation

Note 1) The DNE21 + employs the 2000 price, which is the initial year of the model. The 2018 price shown is converted using the US GDP deflator.
Note 2) Facility costs are assumed to decrease over time within the range shown in the table.
Note 3) This figure is an assumed value for the United States, and is multiplied by the location factor depending on the country/region, and there is a slight difference (up to + 3% in Japan). The assumptions on renewable energy are shown in other slides.

			Capital costs in 2000 [US$/kW]	Capital costs in 2018 [US$/kW]
Coal power	Low efficiency (e.g., Conventional (sub-critical), currently used in developing countries)		1000	1458
	Middle efficiency (e.g., mainly used in developed countries (super-critical) – Combined power generation including Integrated Coal Gasification (IGCC) in the future)		1500	2187
	High efficiency (e.g., mainly used in developed countries (super-critical) – Combined power generation including IGCC and Integrated Coal Gasification Fuel cell Combined Cycle (IGFC) in the future)		1700	2479
Co-firing of biomass in coal power	(Additional cost to medium and high efficiency coal power generation)	Co-firing ratio: up to 5%	+85	+124
		Co-firing ratio: up to 30%	+680	+992
Co-firing of ammonia in coal power	(Additional cost to medium and high efficiency coal power generation)	Co-firing ratio: up to 20%	+264-+132	+385-+193
		Co-firing ratio: up to 60%	+271-+135	+395-+197
Oil power	Low efficiency (e.g., diesel)		250	365
	Middle efficiency (sub-critical)		650	948
	High efficiency (super-critical)		1100	1604
	CHP		700	1021
Gas power	Low efficiency (steam turbine)		300	437
	Middle efficiency (combined cycle)		650	948
	High efficiency (combined cycle with high temperature)		1100	1604
	CHP		700	1021
Co-firing of Natural gas / hydrogen	(Additional cost to medium and high efficiency natural gas power generation)	Co-firing ratio: up to 20%	+55	+80
Biomass power	Low efficiency (steam turbine)		2720–2400	3967–3500
	High efficiency (combined cycle)		3740–3030	5454–4419
Nuclear power			2743	4000
IGCC/IGFC with CO_2 Capture			2800–2050	4083–2989
Natural gas oxy-fuel power			1900–1400	2771–2042
Hydrogen power（FC/GT）			1160	1692
Ammonia power generation (single fuel firing)			3040-1444	4433-2106
Electricity storage (e.g., pumping-up)			1000	1458

Assumptions on conversion efficiency for thermal power

Generating efficiency (%LHV)

		2010	2020	2030	2050
Coal power	Low efficiency (e.g., Conventional (sub-critical), currently used in developing countries)	23.0	24.0	25.0	27.0
	Middle efficiency (e.g., mainly used in developed countries (super-critical) – Combined power generation including Integrated Coal Gasification (IGCC) in the future)	37.8	39.6	41.4	45.0
	High efficiency (e.g., mainly used in developed countries (super-critical) – Combined power generation including IGCC and Integrated Coal Gasification Fuel cell Combined Cycle (IGFC) in the future)	44.0	46.0	48.0	58.0
	IGCC/IGFC with CO_2 Capture	34.0	35.5	38.5	50.3
Oil power	Low efficiency (e.g., diesel)	23.0	24.0	25.0	27.0
	Middle efficiency (sub-critical)	38.6	40.2	41.8	45.0
	High efficiency (super-critical)	52.0	54.0	56.0	60.0
	CHP[*1]	39.0	41.0	43.0	47.0
Gas power	Low efficiency (steam turbine)	27.2	28.4	29.6	32.0
	Middle efficiency (combined cycle)	39.8	41.6	43.4	47.0
	High efficiency (combined cycle with high temperature)	54.0	56.0	58.0	62.0
	CHP[*1]	40.0	42.0	44.0	48.0
	Natural gas oxy-fuel power	40.7	41.7	43.7	48.7
Biomass power	Low efficiency (steam turbine)	22.0	22.5	23.5	25.5
	High efficiency (combined cycle)	38.0	40.0	42.0	46.0
Hydrogen power (GT/FC)		54.0	56.0	58.0	62.0

*1 Exhaust heat recovery efficiency is assumed to be 5 to 20% that varies by region, considering supply and demand balance.

Assumptions on nuclear power generation cost

Year	Facility cost ($/kW)		Unit price of electricity ($/MWh)	
	2000 price	2018 price	2000 price	2018 price
2020	2763	4029	75	110
2030	2779	4053	76	111
2050	2794	4075	78	114
2100	2824	4117	79	115

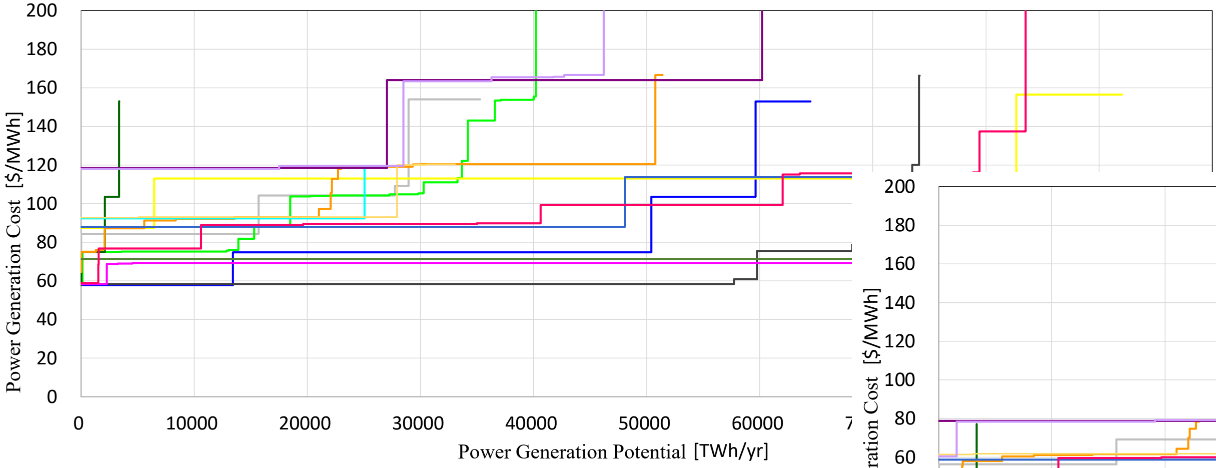
*1 The figures in the table are assumed values for Japan. For the rest of the world, location factors are multiplied, resulting in slightly different assumptions.

*2 Since the base year of the model is 2000, the 2000 price is also shown; the conversion from the 2000 price to the 2018 price is multiplied by 1.46 (based on CPI of U.S.).

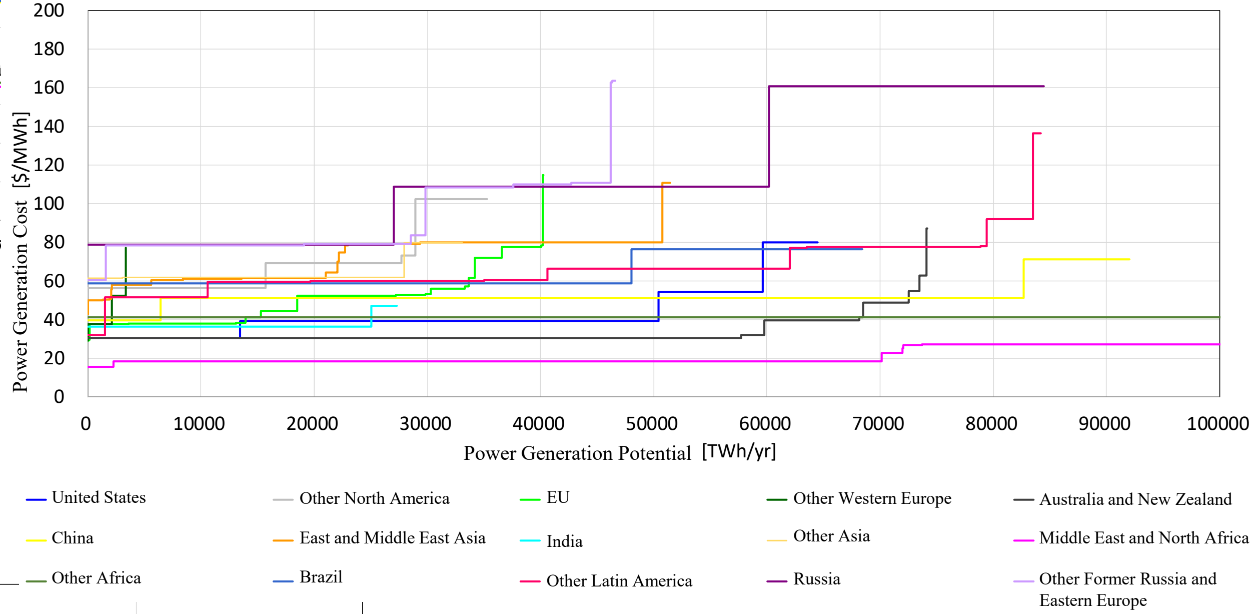
*3 The unit prices of electricity shown in the table are converted using a capacity factor of 85%.

Assumptions on the costs and potentials of solar PV and wind power

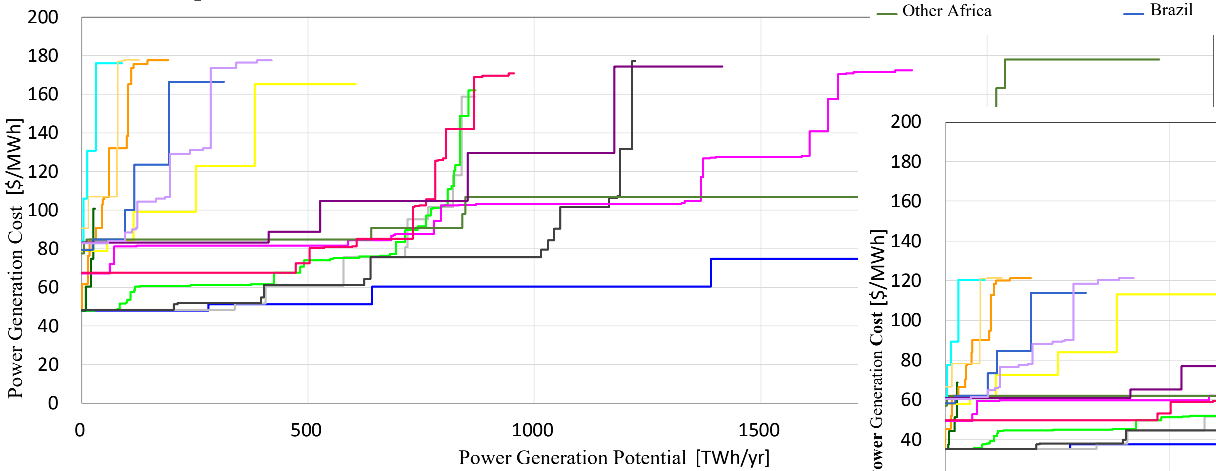
Solar PV: standard scenario



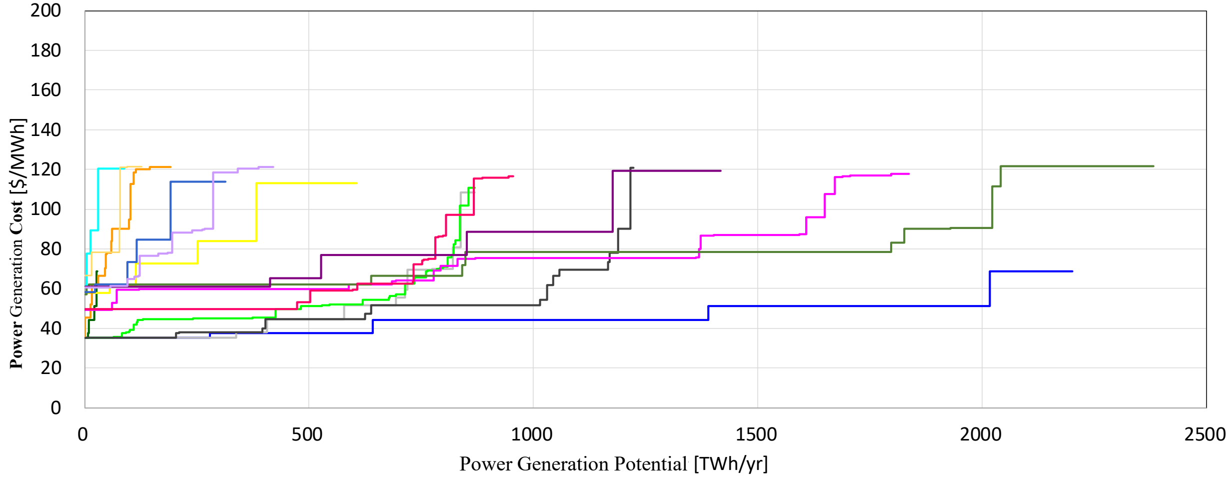
Solar PV: high cost reduction



Wind power: standard scenario



Wind power: high cost reduction



Assumptions on co-generation system (CGS)

Facility Cost ($/kW, Price in 2000)

	2015	2030	2050
Industry (equivalent to 5 MW)		1250	
Business 1 (1-2 MW)		1875	
Business 2（0.5MW）		2500	
Household（PEFC/SOFC）	15167	3575	3575

Note) The listed price is the price in 2000. The US consumer price index is 1.46 in 2015 if year 2000 is 1.

Efficiency Assumption (LHV%)

		2015	2030	2050
Industry (equivalent to 5 MW)	PGE	49.0	51.0	54.5
	HRE	36.2	34.8	31.2
Business 1 (1-2 MW)	PGE	42.3	47.5	50.7
	HRE	36.2	31.0	27.8
Business 2（0.5MW）	PGE	41.0	44.0	47.0
	HRE	34.0	31.0	28.0
Household（PEFC/SOFC）	PGE	39.7	47.8	55.0
	HRE	55.3	45.0	37.8

Note) PGE = Power Generation Efficiency, HRE=Heat Recovery Efficiency

Assumptions on CO_2 capture technology

	Capital costs (price in 2000) ($/kW)	Generating efficiency (LHV%)	CO_2 capture ratio (%)
IGCC/IGFC with CO_2 Capture*1	2800 – 2050	34.0 – 58.2	90 – 99
Natural gas oxy-fuel power*1	1900 – 1400	40.7 – 53.3	90 – 99
	Capital costs (price in 2000) (1000$/(tCO2/hr))	**Required electricity (MWh/tCO2)**	**CO_2 capture ratio (%)**
Post-combustion CO_2 capture from coal-fired power plants*1	851 – 749	0.308 – 0.154	90
Post-combustion CO_2 capture from natural gas-fired power plants*1	1309 – 1164	0.396 – 0.333	90
Post-combustion CO_2 capture from biomass-fired power plant*1	1964 – 1728	0.809 – 0.415	90
CO_2 capture from gasification*1	62	0.218	90 – 95
CO_2 capture from steelworks blast furnace gas*1	386 - 319	0.171 – 0.150	90
	Capital costs (price in 2000) (1000$/(tCO2/hr))	**Required fuels (GJ/tCO2) Recovered electricity (MWh/tCO2)**	**CO_2 capture ratio (%)**
CO_2 capture from clinker manufacturing*2	2485 - 2246	4.87 – 3.66 0.199 – 0.150	90

*1 The range of values in the table indicates improvement from 2015 to 2100.
*2 It is assumed that the assumed values have a range shown in the table depending on the fuel type used in the kiln body, CO2 capture, and compression equipment.
Note) It is 2000 price. The US consumer price index (CPI) in 2018 is 1.46 when the CPI in 2000 is 1.

Not only the CO_2 capture technologies in the power sector, but also CO_2 capture from fossil fuel gasification (in hydrogen production processes), from blast furnace gas in steel making processes, and in clinker production processes, are explicitly modeled.

The assumptions on the costs and potentials of CO_2 geological storage

	CO_2 storage potentials ($GtCO_2$)		【References】 IPCC SRCCS (2005) (GtCO2)	Storage costs ($/$tCO_2$)*1
	Japan	World		
Depl. oil well (EOR)	0.0	112.4	675–900	92 – 227*2
Depl. gas well	0.0	147.3 – 241.5		10 – 32
Deep saline aquifer	11.3	3140.1	10^3–10^4	5 – 85
Coalbed (ECBMR)	0.0	148.2	3–200	47 – 274*2

Note 1: It is assumed that the CO2 storage potentials of depl. gas well could be expanded to the upper limit in the table with the increase of future mining volume.
Note 2: It is assumed that the storage costs could rise within the range in the table with the increase of accumulated storage amount.
*1 The costs for CO_2 capture are not included. They are assumed separately.
*2 Oil and gas profits from enhanced oil recovery and enhanced methane recovery are not included in this figure, but they are assumed separately.

The constraint on CO_2 storage expansion is assumed considering the difficulties such as limited number of available drilling rigs, i.e., in Orderly scenario, the CCS is assumed available since 2026 onwards and CO_2 storage growth is based on 0.004%/yr to gross domestic/regional CCS implementation(maximum storage potential in 2050 in Japan's case is 11MtCO2/yr). CCS is assumed available since 2026 onwards for Disorderly and 1.5C-CO2-CN scenarios as well however, the storage amount is assumed to grow by 0.01%/yr until 2030 and by 0.02%/yr onwards(maximum storage potential in 2050 is 51Mt CO_2 /yr in Japan's case).

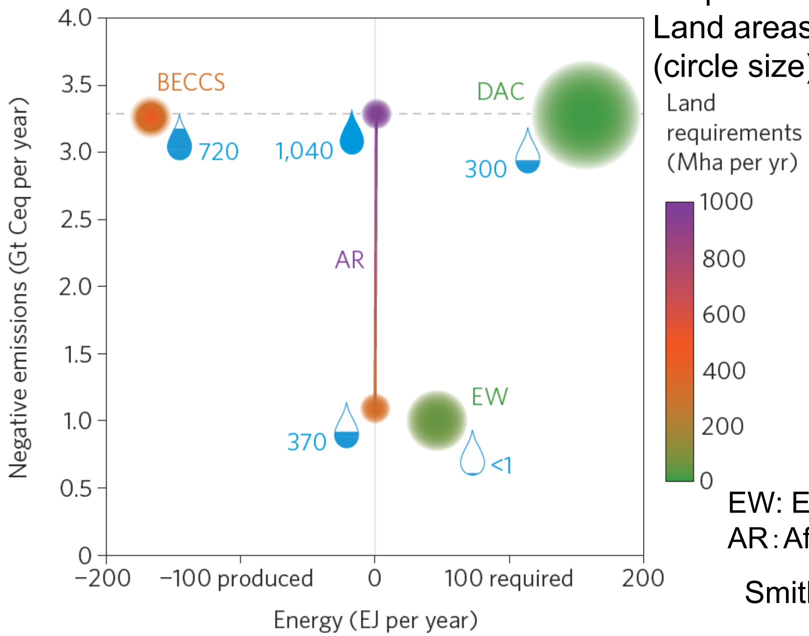
【CO2 transportation cost】

- **The CO2 transportation costs from the sources to the reservoirs are assumed separately as 1.36$/tCO2 (per 100km) and 300km for average transport distance in Japan's case.**
- **For large area countries which are disaggregated in the models (US, Russia, China and Australia), the interregional CO2 transportation costs are estimated according to the transportation distance.**
- **Cross-border CO2 transport is also assumed. Annual export ceiling of 91 Mt CO_2 is set for Japan.**

Assumption for Direct Air Capture (DAC)

- DAC is a technology to capture atmospheric CO_2 at low level of about 400ppm, requiring more amounts of energy than capturing exhaust gas emissions from fossil fuels combustion.
- On the other hand, DACCS (including CO_2 storage) can achieve negative emissions.
- It is economical to deploy in area close to CO_2 storage and where energy supply is available at low cost such as low cost PV.

Climeworks



Required energy (horizontal axis), Land areas (color), Investments (circle size) etc.

EW: Enhanced weathering
AR : Afforestation and reforestation

Smith et al. (2015)

Assumed energy consumption and facility costs of DAC in 2020 based on M. Fasihi et al., (2019):

<u>**This analyses adopt "Conservative" among 2 scenarios, "Base" and "Conservative", by Fasihi et al.**</u>

	Energy consumption (/tCO2)			Facility costs (Euro/(tCO2/yr))	
		2020	2050	2020	2050
High temperature (electrification) system (HT DAC)	Elec. (kWh)	1535	1316	815	222
Low temperature systems (LT DAC): use of hydrogen or gas for heat	Heat (GJ)	6.3 (=1750 kWh)	4.0	730	199
	Elec. (kWh)	250	182		

Assumption: Negative Emission Technologies（NETs）･Carbon Dioxide Removal（CDR）Technology

- The implementation of BECCS and DACCS will be at a low level in the Orderly scenario because imposing constraints on the expansion rate of CO2 storage (refer to page 119) is used.

- The maximum supply of commercial biomass is assumed to be 50EJ/yr in the Orderly scenario and the 1.5C-CO2-CN scenario, considering the impact on food prices and biodiversity. BECCS implementation will be low in these scenarios due to biomass utilization constraints.

- Since reproducing a scenario close to the IEA NZE scenario in 1.5C-CO2_CN, significant constraints are imposed on negative emission technologies (NETs). It is assumed there will be no use of DACCS, biomass-only power generation + CCS, and e-methane + CCS power generation, which is one of the NETs, in 1.5C-CO2_CN. (Coal co-firing biomass power generation + CCS is possible if there is a condition for establishing economic efficiency as a transition.).

Assumption for hydrogen production and energy transport technologies

Hydrogen production technologies

	Facility cost (US$/(toe/yr))	Conversion efficiency (%)
Coal gasification	1188 - 752	60%
Gas reforming	963 - 733	70%
Biomass gasification	1188 - 752	60%
Water electrolysis	2050 - 667	64 - 84%

Liquefaction technology

	Facility cost (US$/(toe/yr))	Electricity consumption (MWh/toe)
Natural gas/Synthetic methane	226	0.36
Hydrogen	1563	1.98

Transport cost

		Facility cost	Variable cost*1
		Electricity: $/kW Other energy: US$/(toe/yr) CO_2 : US$/(t$CO_2$/yr)	Energy: US$/toe CO_2: US$/tCO_2
Electricity*2		283.3+1066.7L	-
Hydrogen	Pipeline*3	210.0L	5.0L
	Tanker	69.5L	7.26+0.60L
CO_2	Pipeline*3	99.4L	2.35L
	Tanker	47.5L	1.77L
Natural gas (The same applies to synthetic methane.)	Pipeline*2	128.3L	3.5L
	Tanker	35.1L	8.09+0.39L

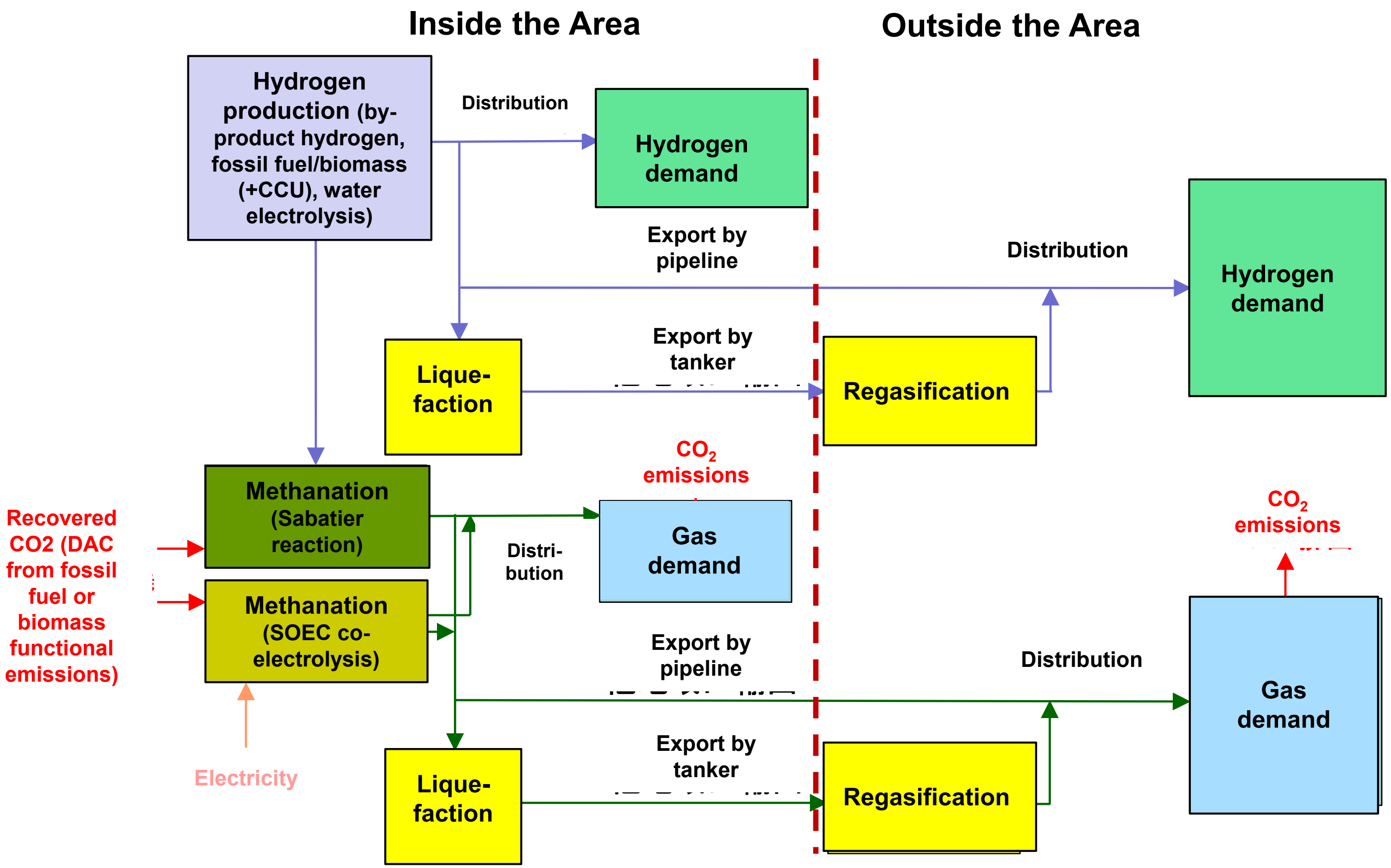
L: Distance between regions (1000km)

*1 For ships, the distance-independent term assumes fuel costs. For pipelines, the distance-dependent terms assume fuel costs and compression power costs, respectively.

*2 For submarine transmission lines, fixed costs are assumed to be 10 times higher than the above.

*3 For submarine pipelines, fixed costs are assumed to be three times higher than above.

Modeling of e-methane (methanation)



- ✓ Hydrogen is not limited to renewable-based hydrogen (green hydrogen). The most economical one is selected according to the assumed scenarios.
- ✓ Recovered CO2 can be obtained from fossil fuel / biomass combustion emissions or by DAC. The most economical one is selected according the assumed scenarios.

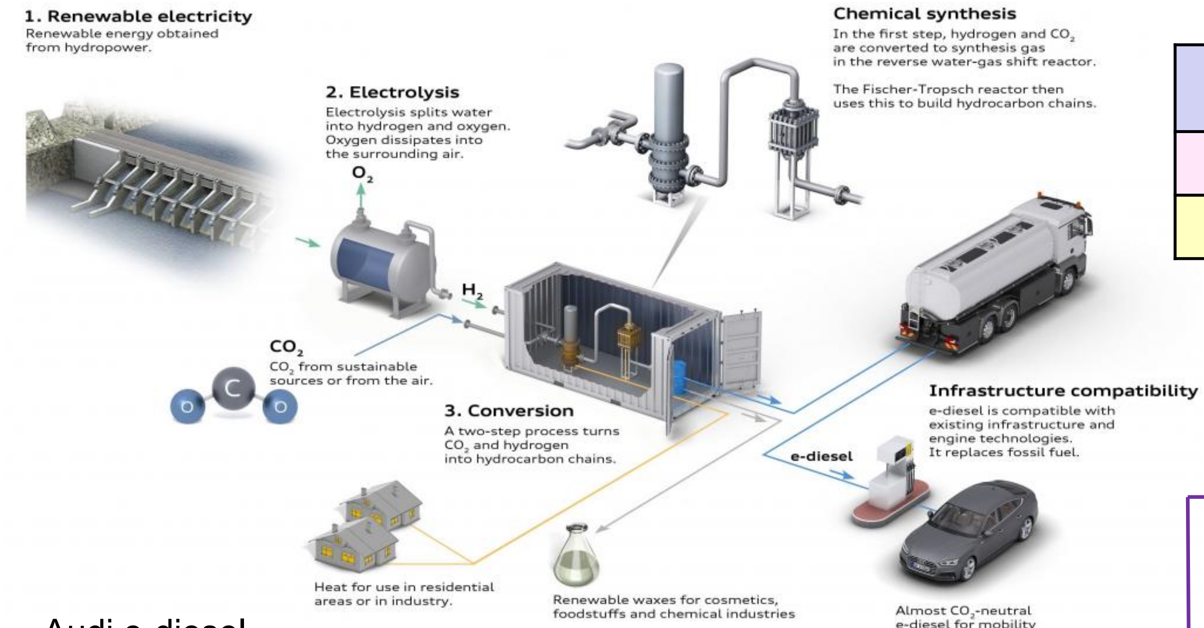
Note) In this analysis in order to provide incentives to use of synthetic fuels for the countries that use the fuels, CO2 emissions are not recorded in the countries that use them, but in the countries that produce them.

Balance in Methanation（Assumption in 2050）

Sabatier reaction	Hydrogen	1.22 toe	⇒	**Methane**	1 toe
	CO_2	2.33 tCO2			
SOEC co-electrolysis	Electricity	15.7 MWh (=1.35 toe)	⇒		
	CO_2	2.33 tCO2			

Modeling of e-fuels (synthetic oil)

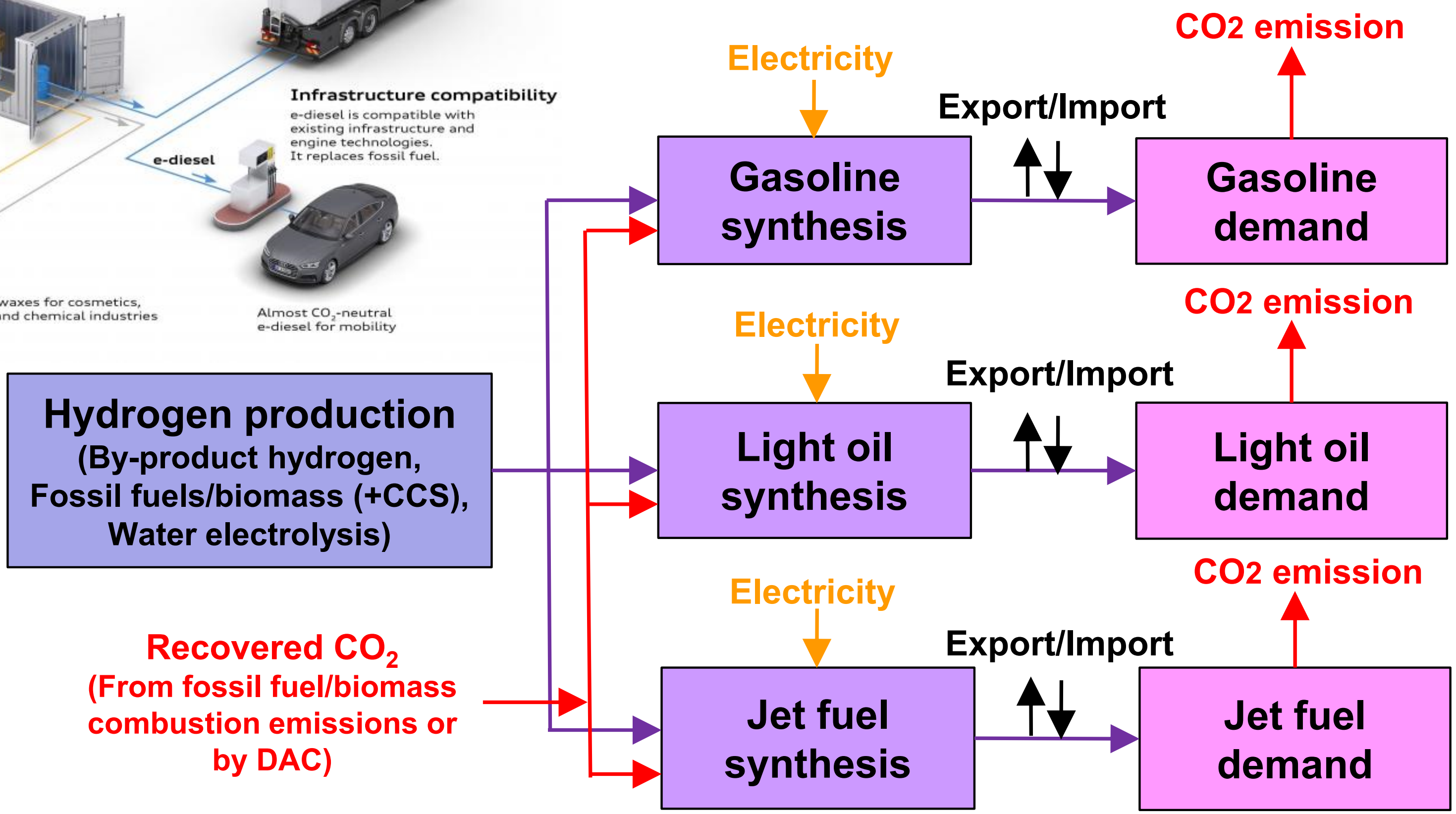
- ✓ **Hydrogen is not limited to renewable-based hydrogen (green hydrogen). The most economical one is selected according to the assumed scenarios.**
- ✓ **Recovered CO_2 can be obtained from fossil fuel / biomass combustion emissions or by DAC. The most economical one is selected according the assumed scenarios.**



Audi e-diesel

Balance in synthetic oil generation in 2050

Hydrogen	1.25 toe	⇒	Synthetic oil	1 toe (Available energy: 0.71 toe)
CO_2	3.02 tCO2			
Electricity	0.02 toe			

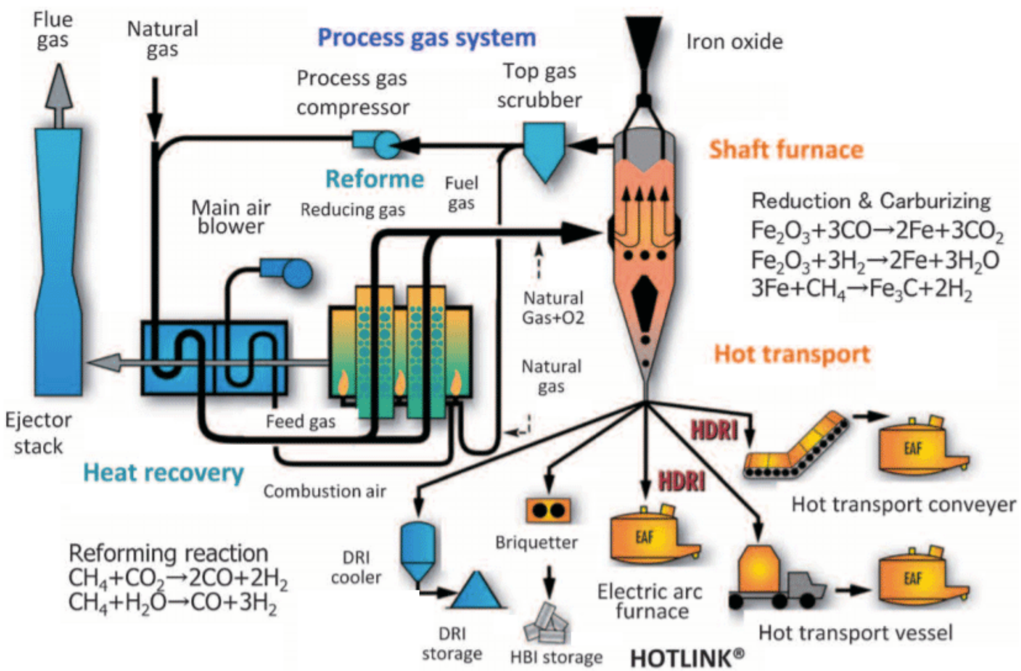


Note) In this analysis in order to provide incentives to use of synthetic fuels for the countries that use the fuels, CO2 emissions are not recorded in the countries that use them, but in the countries that produce them.

Modeling and assumption of H2-based DRI process

- ✓ The fuel used for existing direct reduced iron (DRI) production is natural gas, etc. (see left Fig).
- ✓ H_2-based DRI is a process that replaces fuel with hydrogen (see right Fig).
- ✓ DNE21+ assumes a set of integrated processes up to EAF and hot rolling in addition to the H_2-based DRI process [capital cost: 438.1$/(t-cs/yr), H_2 consumption: 12.1GJ/t-cs, power consumption: 695kWh/t-cs]
- ✓ In the H_2-based DRI acceleration scenario, it is assumed that new construction will be possible from 2041.

Example of gas-based DRI making process



J. Kopfle et al. Millenium Steel 2007, p.19

Demonstration plant for H_2-based DRI

https://www.midrex.com/
https://www.kobelco.co.jp/releases/1201993_15541.html

Assumptions for vehicle: compact cars

Standard technology scenarios

	2015	2020	2030	2050
Conventional internal combustion engine	1700	1700	1800	1850
Hybrid (gasoline)	2100	2090	2020	2010
Plug-in hybrid (gasoline)	2700	2480	2190	2100
Pure electric (BEV)	3110	3050	2650	2250
Fuel cell (FCEV)	5980	5140	3880	2440

Unit: thousand JPY per vehicle

High cost reduction in EVs (rapid cost reductions in BEV and FCEV)
(Battery costs: 10,000 JPY/kWh in 2030, 5,000 JPY/kWh in 2050)

	2015	2020	2030	2050
Conventional internal combustion engine	1700	1700	1800	1850
Hybrid (gasoline)	2100	2080	2010	2010
Plug-in hybrid (gasoline)	2700	2440	2100	2050
Pure electric (BEV)	3110	2850	2100	2050
Fuel cell (FCEV)	5980	4120	2440	2050

Unit: thousand JPY per vehicle

Assumptions for vehicle: large cars

Standard technology scenarios

	2015	2020	2030	2050
Conventional internal combustion engine	3700	3700	3800	3850
Hybrid (gasoline)	4180	4150	4040	4020
Plug-in hybrid (gasoline)	5210	4820	4290	4140
Pure electric (BEV)	6220	5500	4900	4300
Fuel cell (FCEV)	10460	9020	6820	4670

Unit: thousand JPY per vehicle

High cost reduction in EVs (rapid cost reductions in BEV and FCEV)
(Battery costs: 10,000 JPY/kWh in 2030, 5,000 JPY/kWh in 2050)

	2015	2020	2030	2050
Conventional internal combustion engine	3700	3700	3800	3850
Hybrid (gasoline)	4180	4150	3920	3910
Plug-in hybrid (gasoline)	5210	4710	4040	3970
Pure electric (BEV)	6220	5200	4070	4000
Fuel cell (FCEV)	10460	7480	4670	4020

Unit: thousand JPY per vehicle

Appendix 2:
Transition roadmap by sector provided by the Government of Japan (FY 2021, 2022)

The roadmap by GoJ (2021 edition): Power

- This Roadmap is aligned with the Paris Agreement, referring to various Japanese policies and international scenarios aimed to achieve carbon neutrality in 2050.
- In addition to the steady use of renewable energy and nuclear power, which are already in practical use as decarbonized power sources, the suspension and decommission of thermal power plant, introduction and expansion of ammonia, hydrogen co-firing and exclusive firing technologies, and CCUS will contribute to achieving carbon neutrality in 2050 .

Reference/ Evidence

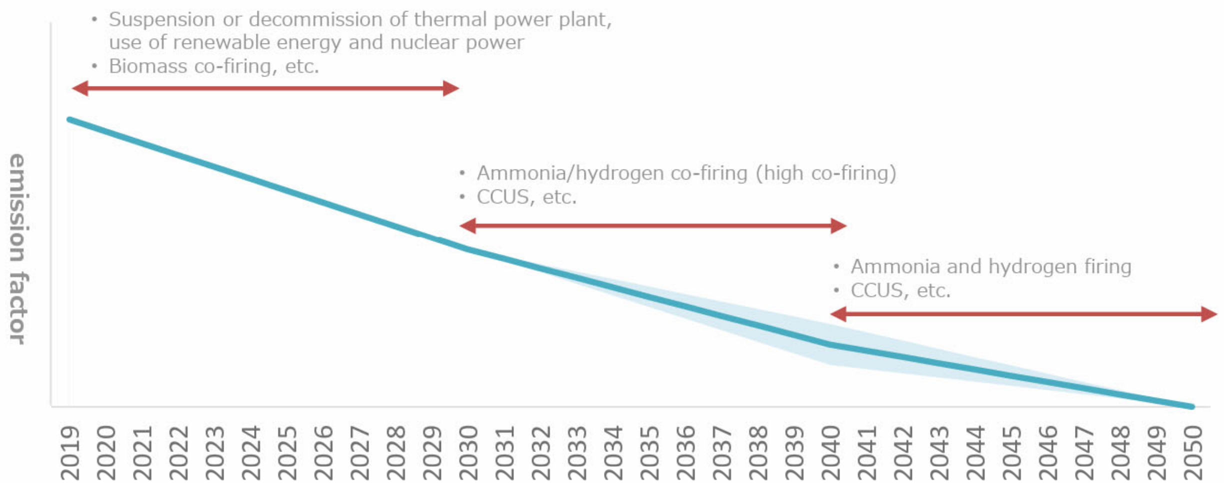
Government Policies

- ✓ The Basic Energy Plan and Strategic Policy Committee Materials
- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050
- ✓ R&D and Social Implementation Plan for the construction of a large-scale hydrogen supply chain project
- ✓ R&D and Social Implementation Plan for the construction of fuel ammonia supply chain project
- ✓ R&D and Social Implementation Plan for the development of technology for CO2 separation, capture, etc project

International Scenarios/ Roadmaps, etc. aligned with Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ World Energy Outlook 2021 (IEA)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway *



1 **2020~2030**
In addition to expanding the use of renewable energy and nuclear power, which are decarbonized power sources that have already been put into practical use, efforts will be made to reduce carbon emissions by co-firing biomass into thermal power generation and suspending or decommission thermal power. In parallel, ammonia/hydrogen co-firing technology and CCUS technology will be developed and demonstrated.

2 **2030~2040**
Expanding the introduction of the co-firing of ammonia/hydrogen and increasing the ratio of them to achieve higher co-firing.

3 **2040~2050**
Achieved carbon neutrality by significantly reducing emissions through the commercialization and expansion of ammonia/hydrogen exclusive firing.

* It should be noted that this only illustrates the assumption of the overall Japanese power sector's decarbonization pathway. In reality, decarbonization will be achieved based on each company's long-term strategy and hence, will not necessary be the reflection of this assumption.

The roadmap by GoJ (2021 edition): Gas

- The Technology Roadmap refers to Japanese policies and international scenarios that aim to achieve carbon neutrality in 2050, and it aligned with the Paris Agreement.
- It is focused on achieving 2050 carbon neutrality by energy conservation, advanced use of gas, improvement of supply network, conversion to synthetic methane/LP gas and hydrogen, and introduction of innovative technologies such as CCUS and DAC.

Main Reference/ Evidence

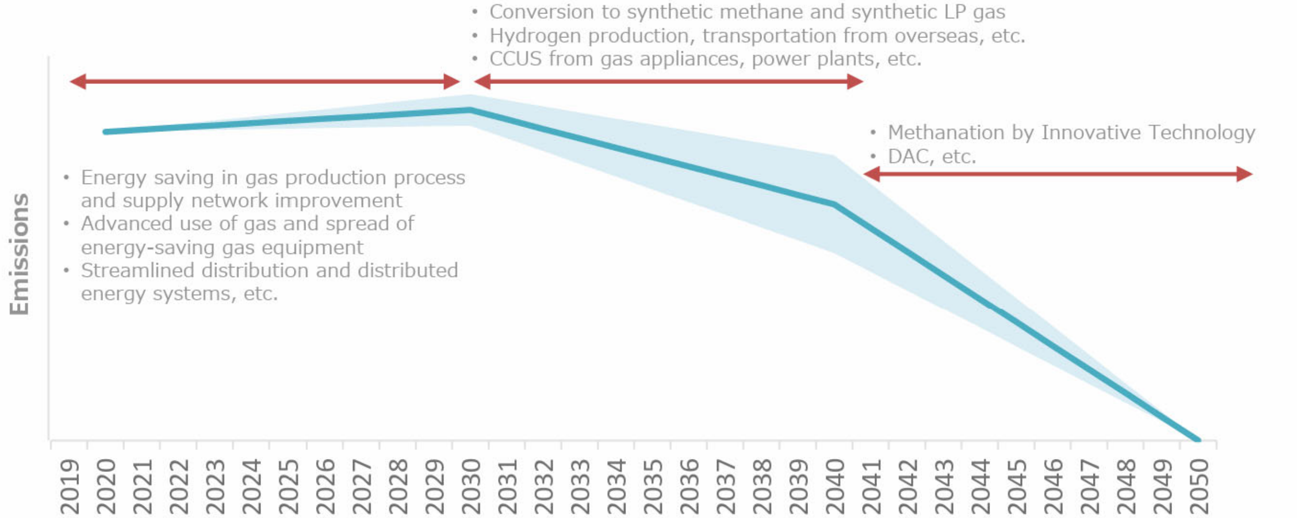
Government Policies

- ✓ Strategic Energy Plan and Strategic Policy Committee Materials
- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050
- ✓ R&D and Social Implementation Plan for the CO2 separation and recovery technology development project
- ✓ R&D and Social Implementation Plan for the fuel ammonia supply chain establishment project
- ✓ R&D and Social Implementation Plan for the hydrogen production through water electrolysis using electric power derived from renewable energy project
- ✓ R&D and Social Implementation Plan for the the large-scale hydrogen supply chain establishment project

International Scenarios/ Roadmaps, etc. aligned with Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ World Energy Outlook 2021 (IEA)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway *



1 2020~2030
It should be noted that, although there is a possibility of an increase in emissions in the gas sector by promoting fuel conversion to gas through the development of gas supply networks and advanced use of gas, the contribution (reduction contribution) to low-carbon emissions in other sectors is more significant than this increase (p. 33). In addition, while promoting energy conservation in the gas manufacturing process and reduction of emissions through the popularization of energy-saving gas equipment, technologies for synthetic methane and other products for the future will be developed.

2 2030~2040
Production technologies for synthetic methane and synthetic LP gas will be established, and decarbonization by converting fossil fuel-derived gas to carbon-neutral gas will be promoted. Hydrogen supply chains and CCUS will be practically applied and expanded.

3 2040~2050
Conversion to synthetic methane and synthetic LP gas will be further promoted and carbon neutrality will be realized through the practical application of innovative technologies such as DAC.

※This only illustrates the assumption of overall Japanese gas industry's decarbonization pathway as an area covered by this roadmap. In reality, decarbonization will be achieved based on each company's long-term strategy and hence, will not necessary be the reflection of this assumption.

The roadmap by GoJ (2021 edition): Oil

- The Technology Roadmap is aligned with the Paris Agreement, referring to various Japanese policies and international scenarios aimed at achieving carbon neutrality by 2050.
- With regard to crude oil treatment, in addition to steadily reducing CO2 emissions through various energy efficiency and fuel conversion measures, decarbonization by transforming refining processes and introducing innovative technologies such as CCS and CCU will be promoted. Furthermore, it is focused on achieving the 2050 carbon neutrality goal by shifting to a supply system of decarbonized fuels, including synthetic fuels.

Reference/Evidence

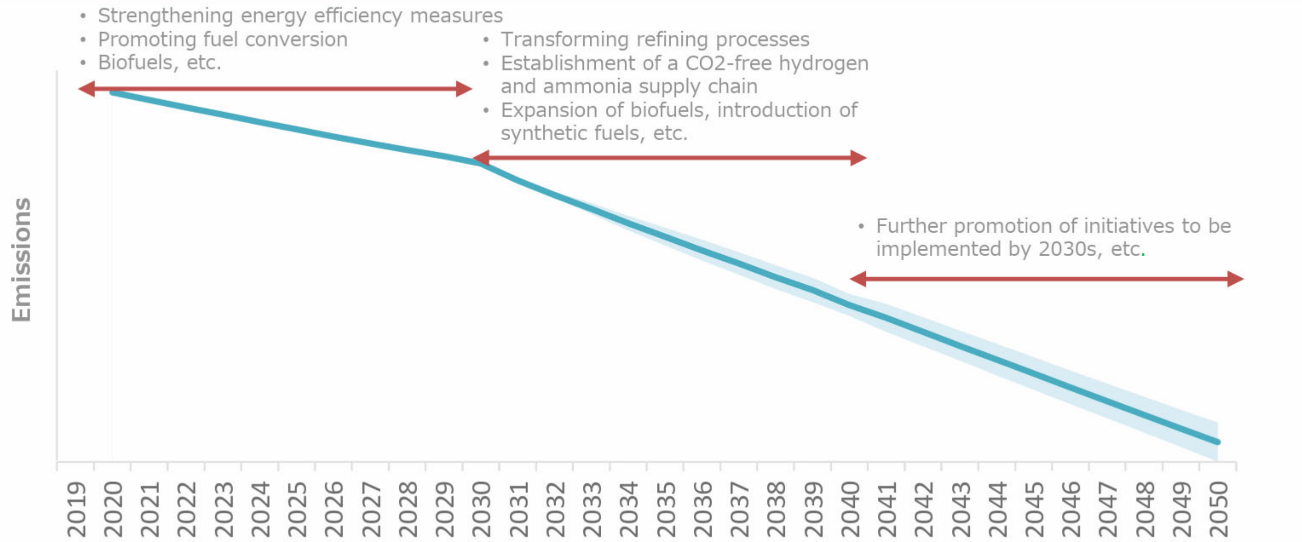
Government policies

- ✓ Basic Energy Plan and Strategic Policy Committee Materials
- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050
- ✓ R&D and Social Implementation Plan for the CO2 separation and recovery technology development project
- ✓ R&D and Social Implementation Plan for the fuel ammonia supply chain establishment project
- ✓ R&D and Social Implementation Plan for the hydrogen production through water electrolysis using electric power derived from renewable energy project
- ✓ R&D and Social Implementation Plan for the large-scale hydrogen supply chain establishment project
- ✓ R&D and Social Implementation Plan for the development of fuel manufacturing technology using CO2 project

International scenarios/roadmaps, etc. aligned with the Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ World Energy Outlook 2021 (IEA)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway[*1, 2]



1 **2020~2030**
Work toward steady CO2 reduction by strengthening measures on energy efficiency in petroleum refining, and promoting fuel conversion; make efforts to expand the use of decarbonized fuels such as biofuels (SAF, etc.), which are already at the practical application stage.

2 **2030~2040**
Accelerate efforts toward carbon neutrality by reforming the petroleum refining process and establishing technologies related to decarbonized fuels such as CO2-free hydrogen, ammonia, biofuels, and synthetic fuels.

3 **2040~2050**
Achieve carbon neutrality by significantly reducing emissions through expanded use of decarbonized fuels and CCUS.

*1 It should be noted that this only illustrates the assumption of the overall Japanese oil sector's decarbonization pathway. In reality, decarbonization will be achieved based on each company's long-term strategy and therefore may not necessarily reflect this assumption.
*2 Achieving carbon neutrality by 2050 is based on the premise that CCUS and its related infrastructure, including DAC (direct air capture), will be developed in cooperation with other industries, and that the entire supply chain will become net zero.

The roadmap by GoJ (2021 edition): Iron & Steel

- The Technology Roadmap is aligned with the Paris Agreement and Japanese policies aimed to achieve carbon neutrality.
- It is focused on achieving 2050 carbon neutrality by steady low-carbonization and implementing innovative technologies whilst sustaining and enhancing the Japanese iron and steel industry.

Reference/ Evidence

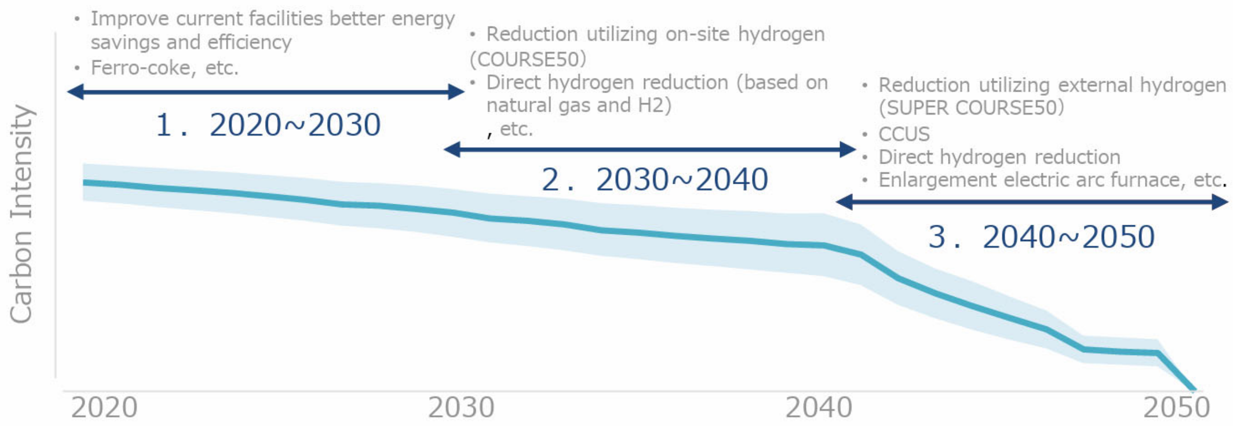
Government Policies

- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (Carbon recycling, materials)
- ✓ R&D and Social Implementation Plan about " Hydrogen utilization in iron and steelmaking processes " project
- ✓ Environment Innovation Strategy
- ✓ Strategic Energy Plan
- ✓ The Plan for Global Warming Countermeasures
- ✓ Roadmap for Carbon Recycling Technologies

International Scenarios/ Roadmaps, etc. aligned with Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ Energy Technology Perspective 2020 (IEA)
- ✓ Industrial Transformation 2050 (Material Economics)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway※



1 2020~2030

The Japanese iron and steel industry already meets the world's best standards on energy efficiency, though further efforts will be made for low-carbonization through energy efficiency in blast furnaces and other means. Moreover, high-quality steel such as eco products that are expected to grow in demand will be produced. This income will be the foundation of future R&D and demonstration for decarbonization technology.

2 2030~2040

Along with increased energy savings and efficiency, new technologies as COURSE50 will be introduced and establish innovative technologies for decarbonization through continuous R&D and demonstration.

3 2040~2050

Assuming hydrogen infrastructure and CCUS to be introduced, innovative technologies such as hydrogen reduction ironmaking will achieve immense reduction of CO2 by 2050 and hence reach carbon neutrality.

※This only illustrates the assumption of overall Japanese iron and steel industry's decarbonization pathway. In reality, decarbonization will be achieved based on each company's long-term strategy and hence, will not necessary be the reflection of this assumption.

The roadmap by GoJ (2021 edition): Cement

- The Technology Roadmap is based on Japan's various policies and international scenarios aimed at achieving carbon neutrality by 2050, and is aligned with the Paris Agreement.
- Specifically, carbon neutrality will be achieved by 2050 through the active introduction of innovative technologies such as CCUS, in addition to the steady achievement of low-carbon operations through various energy-saving and efficiency improvements, and fuel switching.

Main references/evidence

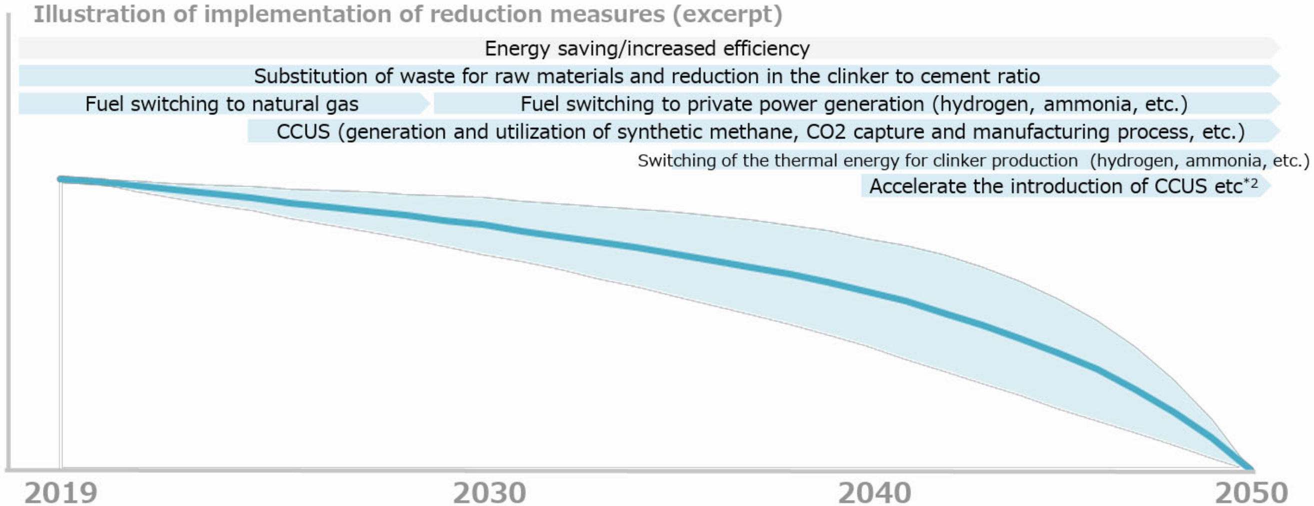
Government Policies

- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (Carbon recycling, materials industry)
- ✓ "Carbon recycling-related" project related R&D and Social Implementation Plan
- ✓ Environment Innovation Strategy
- ✓ Strategic Energy Plan
- ✓ Global Warming Prevention Plan
- ✓ Roadmap for Carbon Recycling Technologies

International scenarios, roadmaps, etc. aligned with Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ Energy Technology Perspective 2020 (IEA)
- ✓ Industrial Transformation 2050 (Material Economics)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway*[1, 2]



Main reduction methods	Overview
2020s	• Promote the introduction of energy-saving equipment and fuel switching to biomass, waste, etc. • Promote the development of technologies for CO2 capture, etc., reduction in the clinker ratio, the use of waste as raw material, etc.
2030 to 2040	• In addition to the initiatives in the 2020s, promote the implementation of technologies such as CO2 capture. • Promote switching to decarbonized fuels such as hydrogen for private power generation and kilns for clinker production.
After 2040	• Aim to decarbonize by implementing technologies such as CO2 capture, promoting fuel switching to decarbonized fuels for private power generation and kilns, developing new low-carbon binders, etc.

*1 This only illustrates the assumption of the overall cement sector's decarbonization pathway in Japan.
In reality, decarbonization will be achieved based on each company's long-term strategy and hence, will not necessary be a reflection of this assumption.

*2 Implementation of CCUS, hydrogen/ammonia etc. are of extreme importance to achieve 2050 carbon neutrality. On the condition of developing new societal such as promotion of energy-saving technologies, supply of affordable hydrogen/ammonia, development of related infrastructure, CCUS and circular economy through supply chain collaboration.

The roadmap by GoJ (2021 edition): Paper & Pulp

- The technology roadmap is based on Japan's various policies and international scenarios aimed at achieving carbon neutrality by 2050, and is aligned with the Paris Agreement.
- Carbon neutrality will be achieved by 2050 through the use of decarbonized fuel such as hydrogen/ammonia and the introduction of CCUS, in addition to the steady achievement of low-carbon operations through various energy-saving and efficiency improvements, and fuel switching.

Main references/evidence

Government Policies

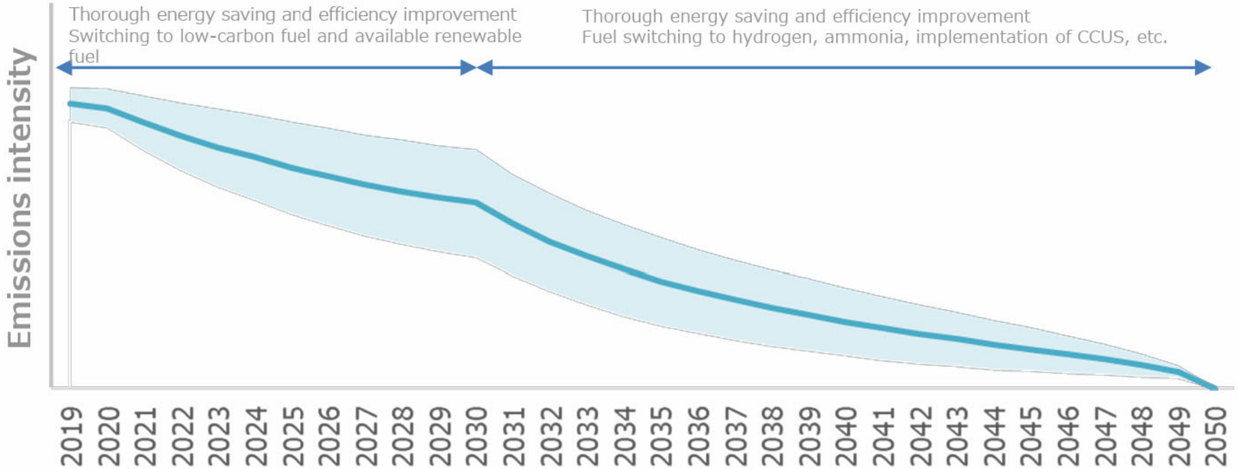
- ✓ Green Growth Strategy through Achieving Carbon Neutrality in 2050 (Carbon recycling, materials industry)
- ✓ "Carbon recycling-related" project related R&D and Social Implementation Plan
- ✓ Environment Innovation Strategy
- ✓ Strategic Energy Plan
- ✓ Global Warming Prevention Plan
- ✓ Roadmap for Carbon Recycling Technologies

International scenarios, roadmaps, etc. aligned with the Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ Energy Technology Perspective 2020 (IEA)
- ✓ Industrial Transformation 2050 (Material Economics)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway*[1, 2]

Illustration of implementation of reduction measures (excerpt)



2020s	• Shift fuel from coal and oil to natural gas and biomass while promoting energy saving and efficiency improvement
2030s 2040s	• Switch from coal, oil, and natural gas to decarbonized fuel such as hydrogen, ammonia, and biomass, while promoting energy saving and efficiency improvement. Also promote the introduction of the CCUS technology.

*1: Expected reduction in emissions in Japan's pulp and paper industry as the sector covered by this roadmap. To be precise, paper companies will all aim to achieve carbon neutrality under their own long-term strategies, so they are not required to be in accordance with the above path.

*2: Advances in energy-saving technologies, a stable and inexpensive supply of new fuels such as hydrogen and ammonia, CCUS and related infrastructure including direct air capture (DAC) and others in collaboration with other industries, and the establishment of new social systems such as a circular economy are assumed to be in place. Although CO2 absorption by plantation, etc. is not included in the above image, paper companies managing forests may include absorption as shown on pages 21 and 24 in their efforts to achieve net zero emissions in 2050.

The roadmap by GoJ (2021 edition): Chemical

- The Technology Roadmap, which is based on Japan's various policies and international scenarios aimed at achieving carbon neutrality by 2050, is aligned with the Paris Agreement.
- Carbon neutrality will be achieved by 2050 through the introduction of innovative technologies such as artificial photosynthesis, in addition to the steady achievement of low-carbon through various energy-saving and efficiency improvements, fuel switching, and increased recycling.

Main references/evidence

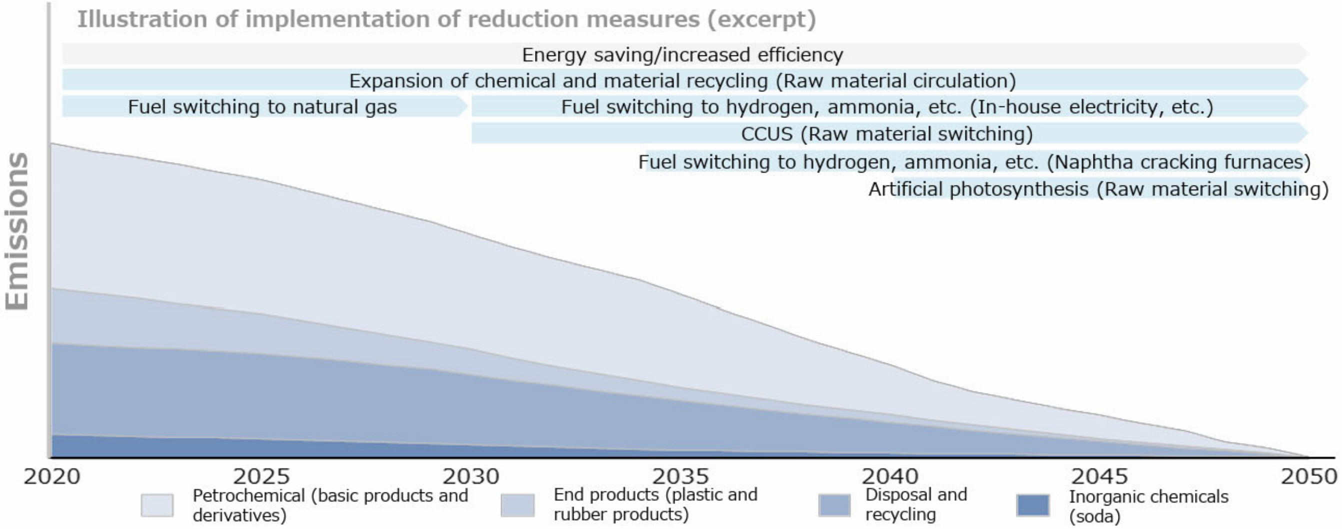
Government Policies

- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (Carbon recycling, materials industry)
- ✓ “Carbon recycling-related” project related R&D and Social Implementation Plan
- ✓ Environment Innovation Strategy
- ✓ Strategic Energy Plan
- ✓ Global Warming Prevention Plan
- ✓ Roadmap for Carbon Recycling Technologies

International scenarios, roadmaps, etc. aligned with Paris Agreement

- ✓ Clean Energy Technology Guide (IEA)
- ✓ Energy Technology Perspective 2020 (IEA)
- ✓ Industrial Transformation 2050 (Material Economics)
- ✓ Science Based Target initiative

Assumed CO2 Reduction Pathway*1, 2



Main reduction methods	Target	Overview
(1) Fuel switching	All sectors	• Fuel for naphtha cracking furnaces and in-house power generation will be switched to natural gas in the short term, and hydrogen, ammonia, etc. in the medium to long term.
(2) Raw material circulation (Recycling)	Disposal & recycling, petrochemicals	• Incineration and thermal recycling of waste plastics and waste rubber will be reduced, and chemical and material recycling will be expanded.
(3) Raw material switching	Petrochemicals End products	• Chemicals and products will be switched to those that use biomass and CO2-derived raw materials. Artificial photosynthesis technology will also be used.

*1: Expected reduction in emissions in Japan’s chemical industry as the sector covered by this Roadmap. In fact, chemical companies will all aim to achieve carbon neutrality under their own long-term strategies, so they are not required to conform with the above path.

*2: Advances in energy-saving technologies, a stable and inexpensive supply of new fuels such as hydrogen and ammonia, CCUS and related infrastructure including DAC and others in collaboration with other industries, and the establishment of new social systems such as a circular economy are assumed to be in place.

The roadmap by GoJ (2022 edition): Automobile

- The Technology Roadmap is based on Japan's various policies and international scenarios aimed at achieving carbon neutrality by 2050, and is aligned with the Paris Agreement.
- Carbon neutrality will be achieved by 2050 through various energy-saving and efficiency improvements, and fuel switching in manufacturing as well as increased introduction of electrified vehicles and decarbonized fuel.
  - ➢ In designing this technology roadmap, we referred to the composition of powertrains and fuels in one of the scenarios (CNF scenario) in "Transitioning to Carbon Neutrality by 2050: A Scenario-Based Analysis" of JAMA.
    https://www.jama.or.jp/operation/ecology/carbon_neutral_scenario/PDF/Transitioning_to_CN_by_2050A_Scenario_Based_Analysis_EN.pdf

Main references/evidence

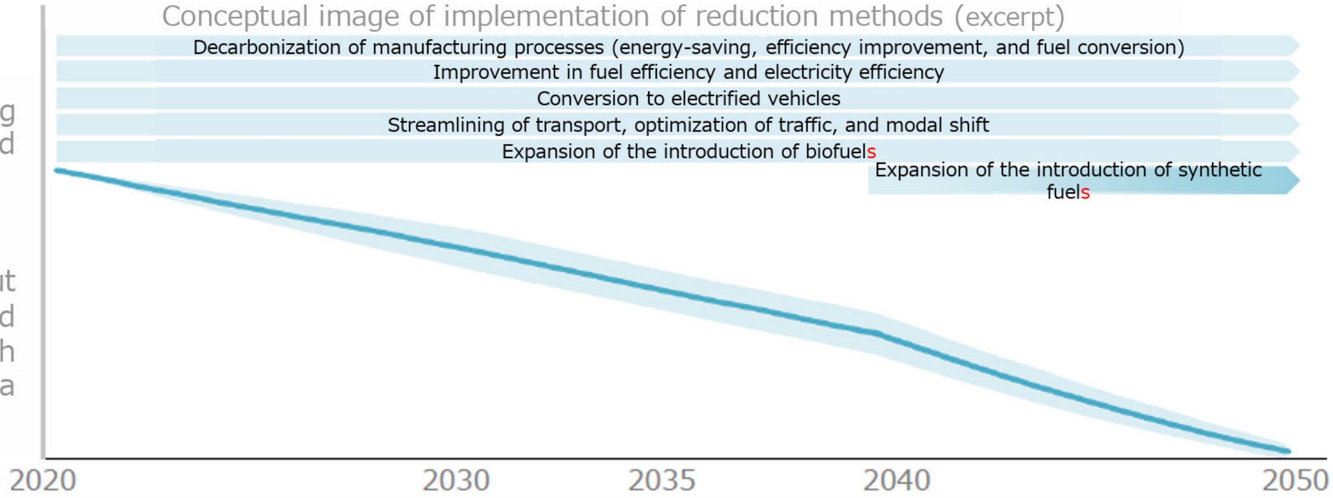
Main references/evidence

- ✓ Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (Automobile and battery industry)
- ✓ Strategic Energy Plan
- ✓ Global Warming Prevention Plan
- ✓ R&D and Social Implementation Plan about "Development of In-vehicle Computing and Simulation Technology for Energy Saving such as Electric Vehicles." and " Establishment of a Smart Mobility Society" project

International scenarios, roadmaps, etc. aligned with Paris Agreement

- ✓ IPCC AR6 WGIII
- ✓ Clean Energy Technology Guide (IEA)
- ✓ Energy Technology Perspective 2020 (IEA)
- ✓ Net Zero by 2050 (IEA)
- ✓ Science Based Target initiative
- ✓ Transitioning to Carbon Neutrality by 2050: A Scenario-Based Analysis (JAMA)

Assumed CO_2 Reduction Pathway*1, 2, 3



Main reduction methods	Overview
(1) Improvement in fuel efficiency and electricity efficiency	• Reduce consumption of fuel, electricity, etc. as a whole by continuously improving fuel efficiency and electricity efficiency and introducing vehicles with high energy efficiency such as HEV and PHEV.
(2) Introduction of electrification and decarbonized fuel	• Reduce the emissions from driving by proceeding with the introduction of BEV and FCV as well as expanding the use of synthetic fuel to HEV and PHEV.
(3) Decarbonization of manufacturing processes	• Reduce emissions from automobile manufacturing by expanding the use of renewable energy, converting to low-carbon and decarbonized fuel, etc.

*1 This shows a conceptual image of reduction as target sectors of the Roadmap in the Japanese automobile industry. Actually, each company will aim to realize decarbonization under their own long-term strategies, so they are not required to meet the pathway image shown above.
*2 The pathways shown above show emissions for the sources listed on p. 11 (product manufacturing, energy source manufacturing and supply, and vehicle use), and do not include emissions related to manufacturing, transport, etc. of hydrogen and synthetic fuels.
*3 It assumes, for example, the advancement of energy-saving technologies, stable and inexpensive supply of new fuel including hydrogen and ammonia, and the construction of new social systems such as CCUS, its related infrastructures, and circular economy including DAC in coordination with other industries, etc.