Sustainability Science Supplementary information

Stranded investment associated with rapid energy system changes under the mid-century strategy in Japan

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Supplementary text

Energy investment calculation in AIM/Enduse [Japan]

In AIM/Enduse [Japan], investment for energy technology is determined based on linear programming to minimize total annual energy system costs that include capital cost, energy cost, operation and management costs and emission cost. The capital costs of energy technologies are annualized using a discount rate in the range 5–33% (Oshiro et al., 2016). As shown in equation (1), objective function is expressed as minimization of total energy system costs which include initial, operation and management and emission costs.

$$TC = \sum_{i,l}\left(R_{i,l} \cdot c_{i,l} + X_{i,l} \cdot g^{o}_{i,l}\right) + \sum_{i,k}\left(E_{i,k} \cdot g^{e}_{i,k}\right)\sum_{i,m}\left(Q_{i,m} \cdot \zeta_{i,m}\right) \rightarrow min \quad (1)$$

where

i : sector

k : energy type

l : device

m : gas type

$E_{i,k}$: energy demand for energy type *k*.

$Q_{i,m}$: emission of gas type *m*.

$X_{i,l}$: operating quantity of device *l*.

$R_{i,m}$: new installation of device *l*.

TC : total energy system cost

$c_{i,l}$: annualized initial cost

$g^{e}_{i,l}$: variable operation and management cost

$g^{o}_{i,l}$: fixed operation and management cost

$\zeta_{i,m}$: emission tax for gas *m*.

Stranded investment calculation

As stranded asset indicators, stranded capacity and investment were calculated in this paper. The method of stranded investment calculation used here is similar to that of Johnson et al. (2015), where stranded investment is expressed as stranded capacity multiplied by its annualized cost based on a 5% discount rate. Stranded capacity and investment are calculated based on equations (2) and (3), respectively. Stranded capacity is estimated as the stock quantity that is never in operation in each time step. For power generation technologies, back-up capacities for VRE integration are estimated based on the peak demand and are not accounted as stranded capacity. In the figures included in this paper, stranded investment and capacity are presented as additional values relative to the baseline scenario (4). The full equation list of AIM/Enduse was reported by

Akashi et al. (2007); Kainuma et al. (2003). Detailed model descriptions of AIM/Enduse [Japan] can be found in Fujimori et al. (2019); Oshiro and Masui (2015).

$$S_{i,l} = X_{i,l} \cdot {\Lambda_{i,l}}^{-1} + \delta_{i,l} \tag{2}$$

$$V_{i,l} = c_{i,l} \cdot \delta_{i,l} \tag{3}$$

$$\Delta V_{i,l} = V_{i,l}^{mitigaion} - V_{i,l}^{baseline} \tag{4}$$

where

$S_{i,l}$: Total stock quantity

$X_{i,l}$: Operating stock quantity

$\delta_{i,l}$: Stranded capacity

$\Lambda_{i,l}$: Maximum operation rate

$V_{i,l}$: Stranded investment

$\Delta V_{i,l}$: Stranded investment relative to the baseline scenario

$c_{i,l}$: Annualized investment

i : Sector

l : Device

Supplementary figures

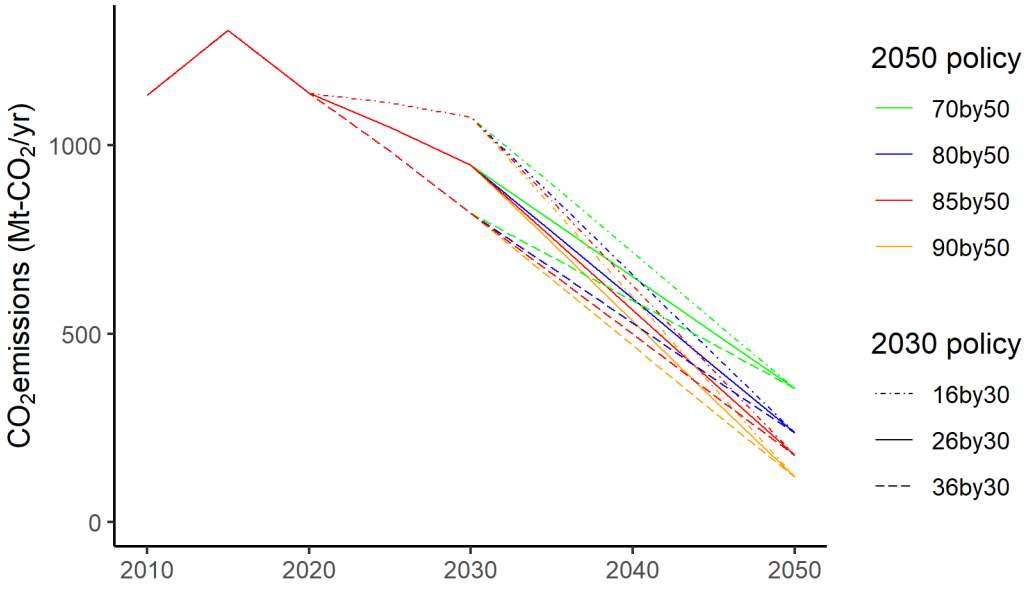

Fig. S 1 CO_2 emissions from energy and industrial processes

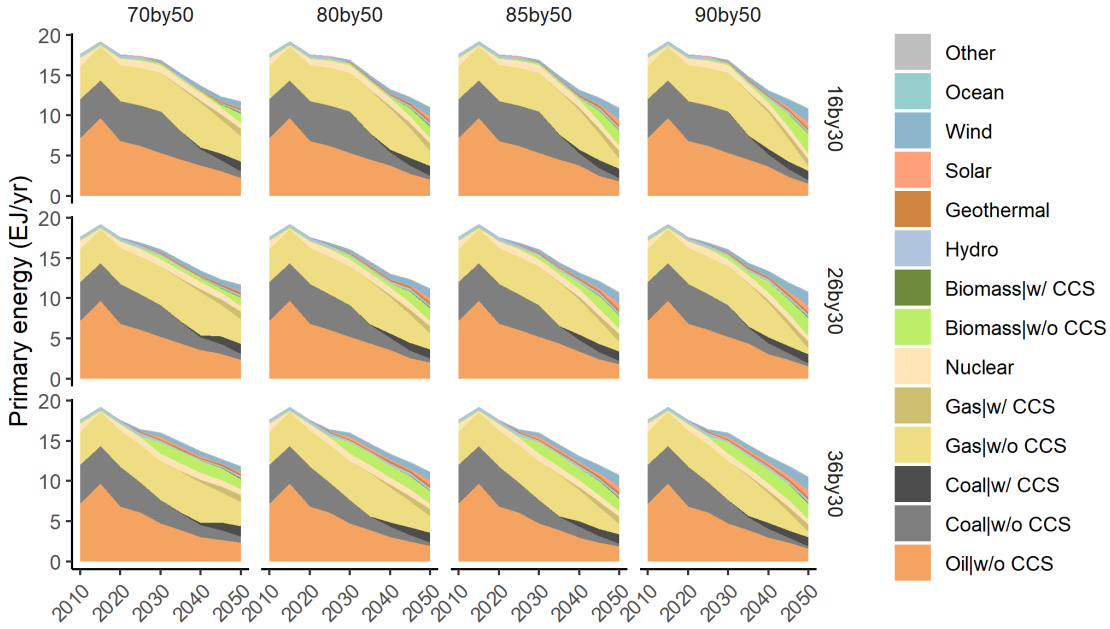

Fig. S 2 Primary energy supply. Primary energy accounting is based on the direct equivalent method (Krey et al., 2014).

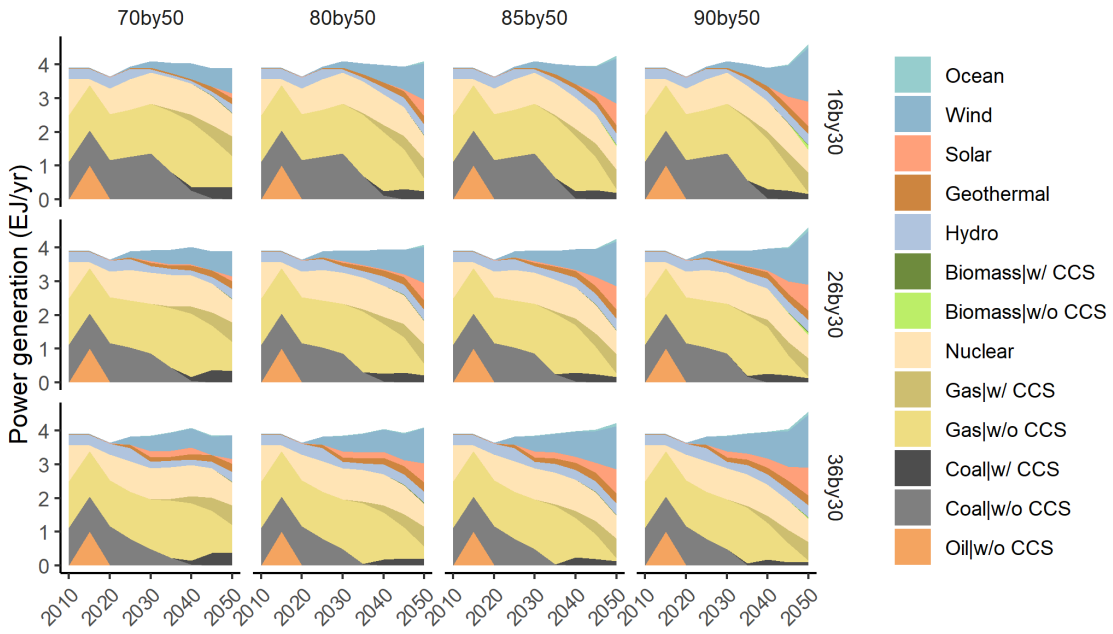

Fig. S 3 Power generation

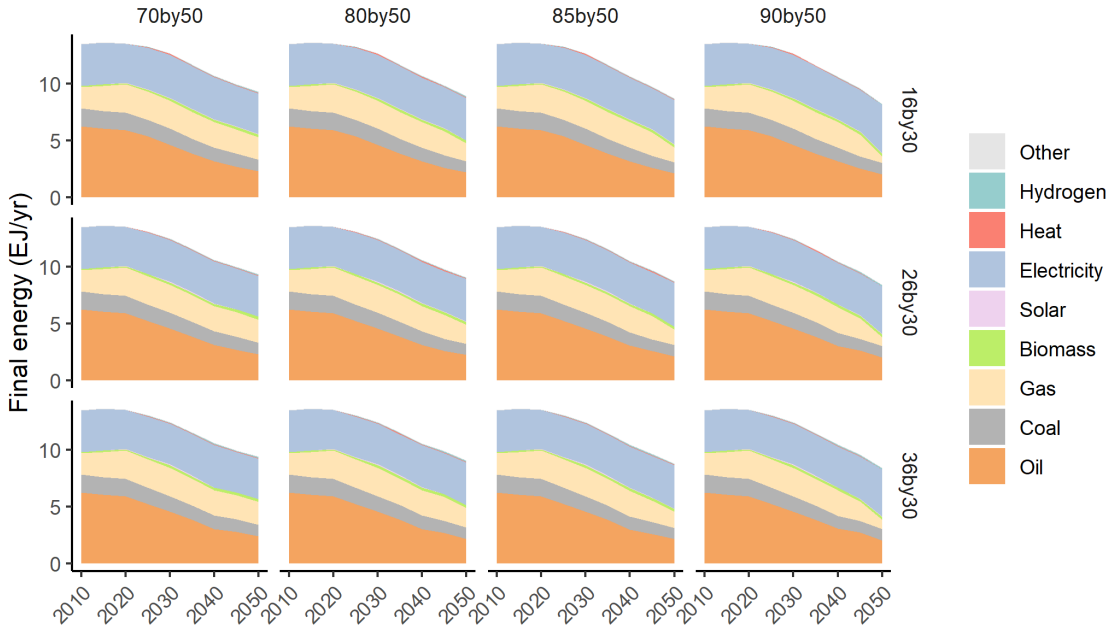

Fig. S 4 Final energy consumption

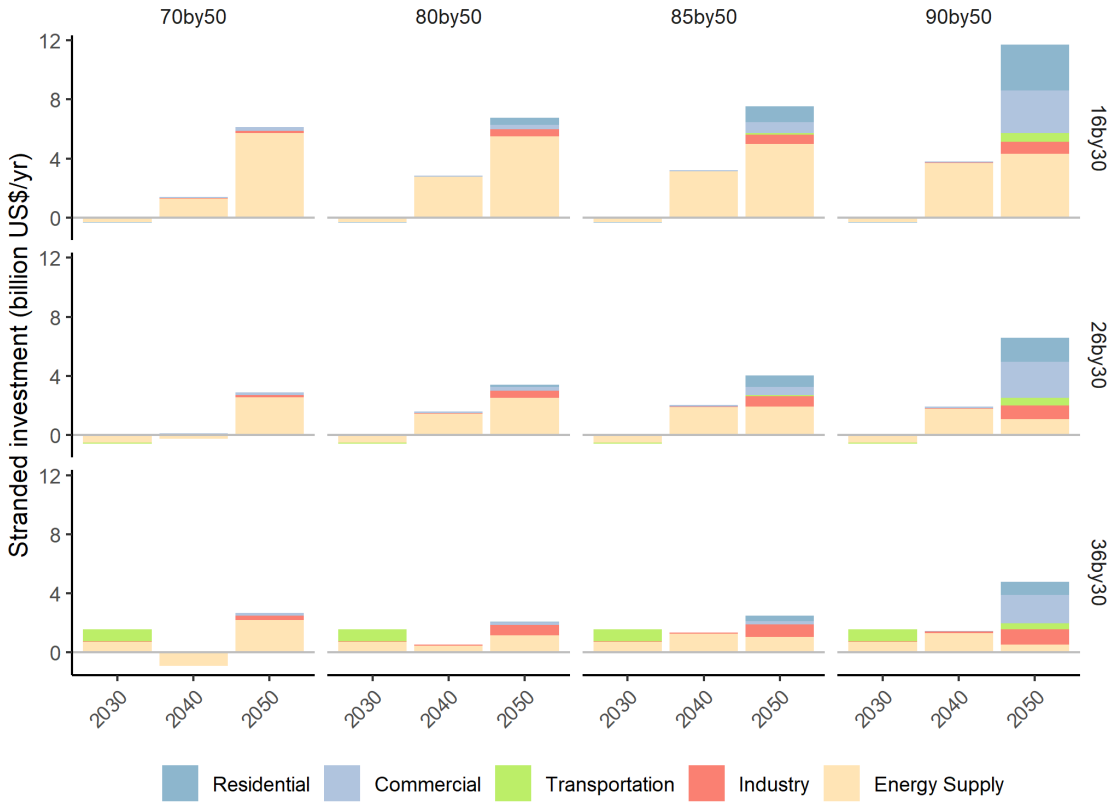

Fig. S 5 Stranded investment over time by different sector

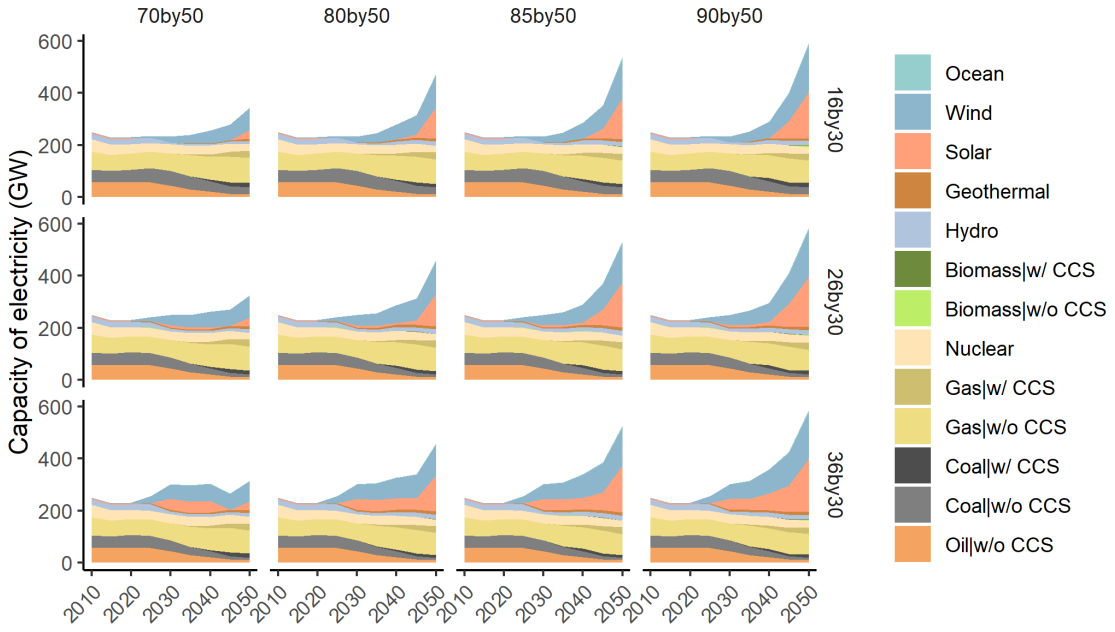

Fig. S 6 Capacity of electricity

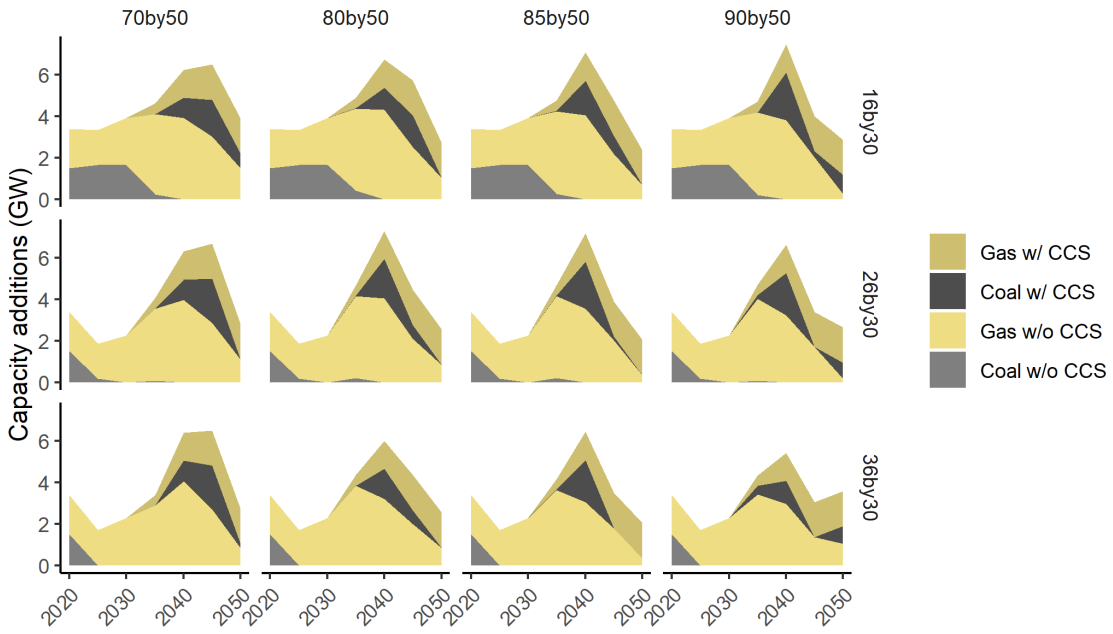

Fig. S 7 Capacity additions of coal and gas power plants

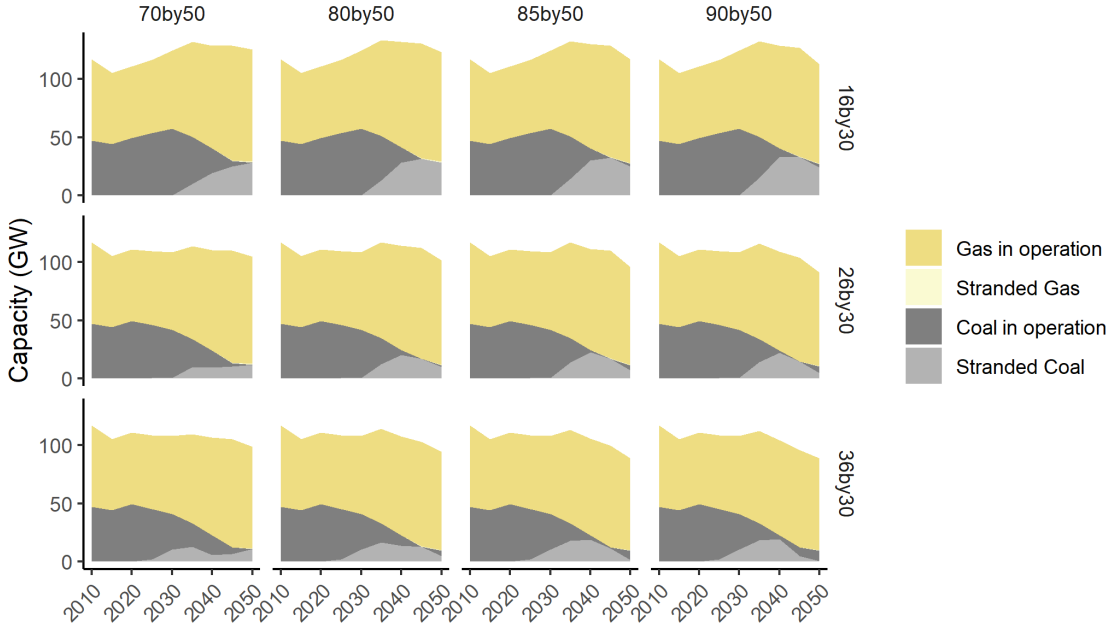

Fig. S 8 Coal and gas capacities without CCS

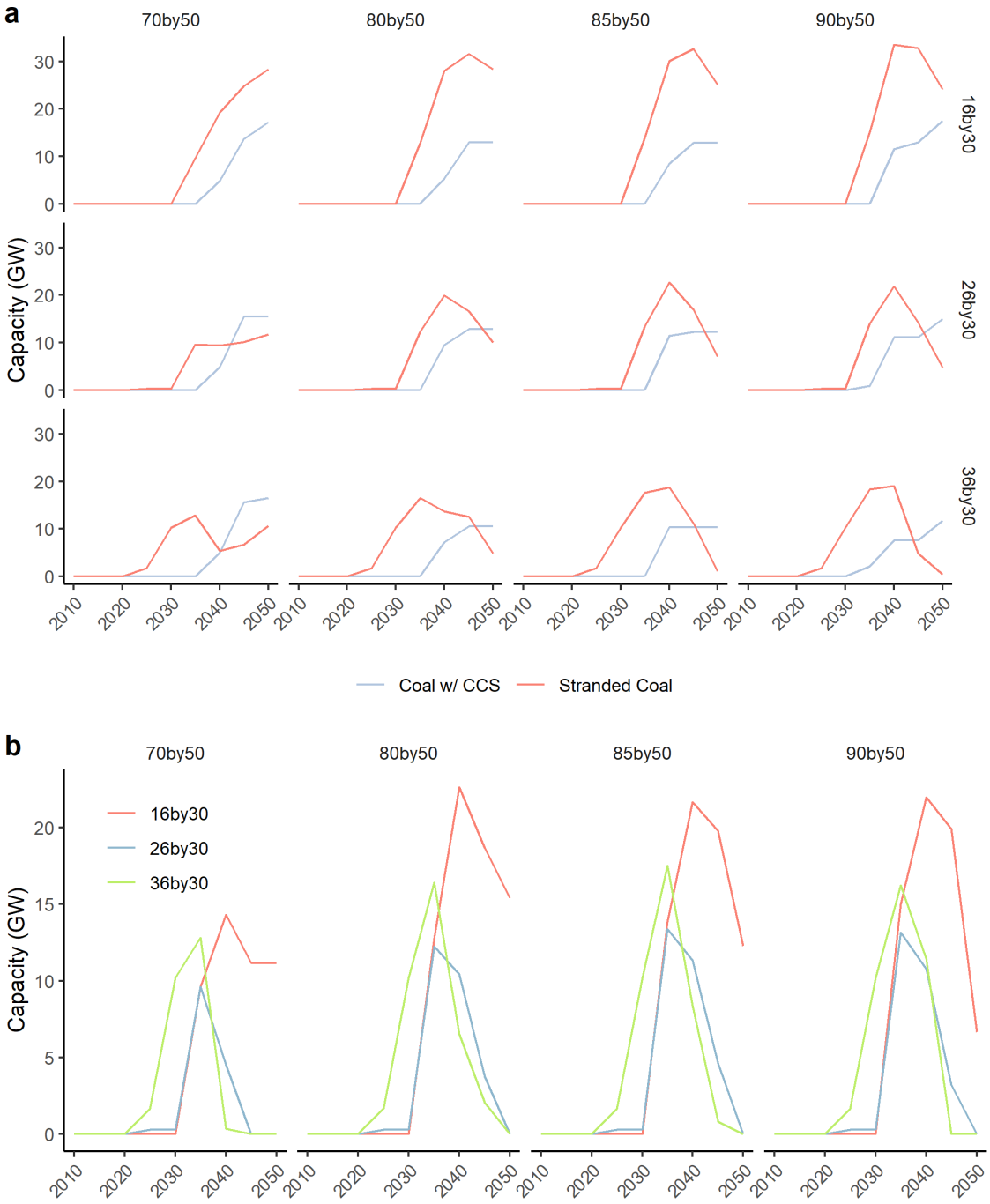

Fig. S 9 a) comparison of stranded coal capacity and coal with CCS in the different scenarios, b) capacity of stranded coal minus that of coal with CCS, which roughly equivalents to the stranded coal capacity assuming that CCS-ready and conversion to CCS-equipped plant are fully implemented.

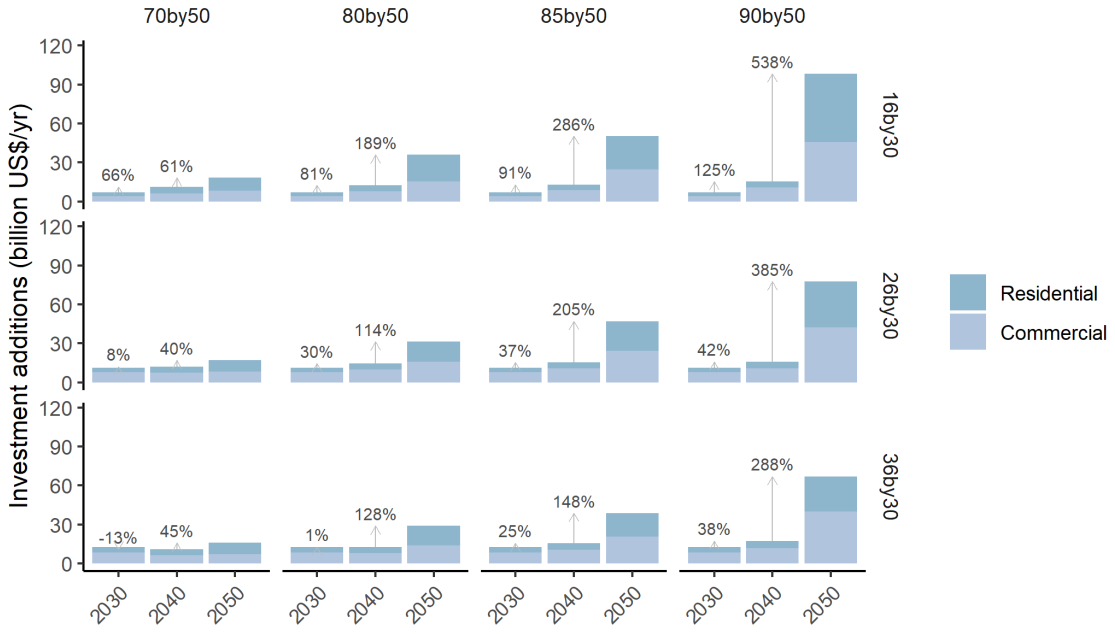

Fig. S 10 Investment for non-fossil infrastructures in the buildings sectors over time.

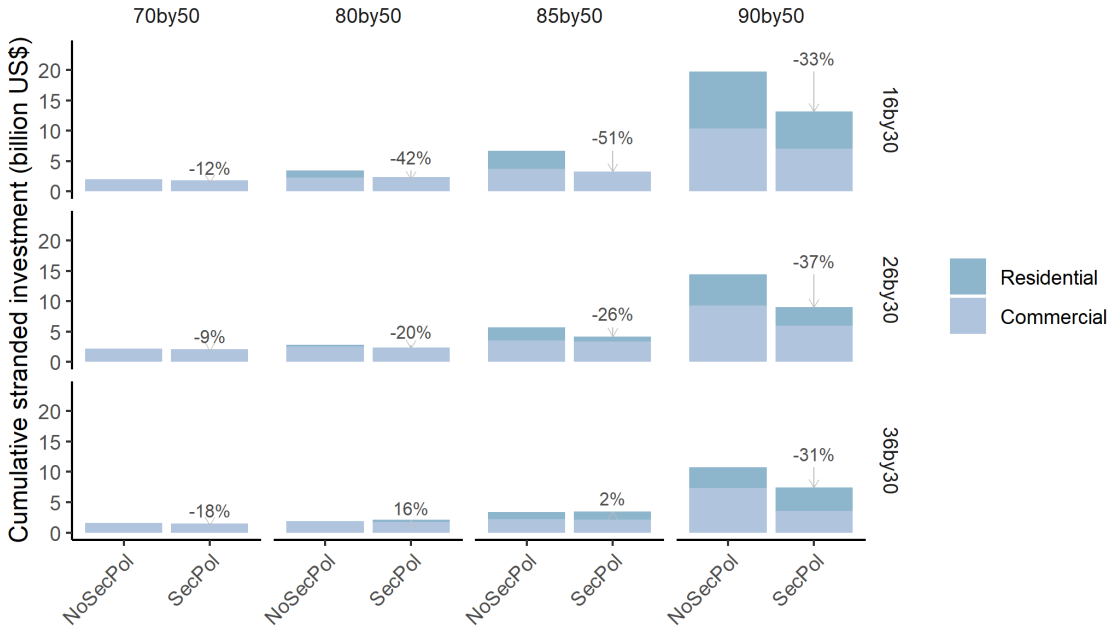

Fig. S 11 Cumulative stranded investment between 2021 and 2050 in the buildings sectors for all scenarios. NoSecPol indicates to the default scenarios without sectoral policy. SecPol indicates the scenarios with sectoral policy.

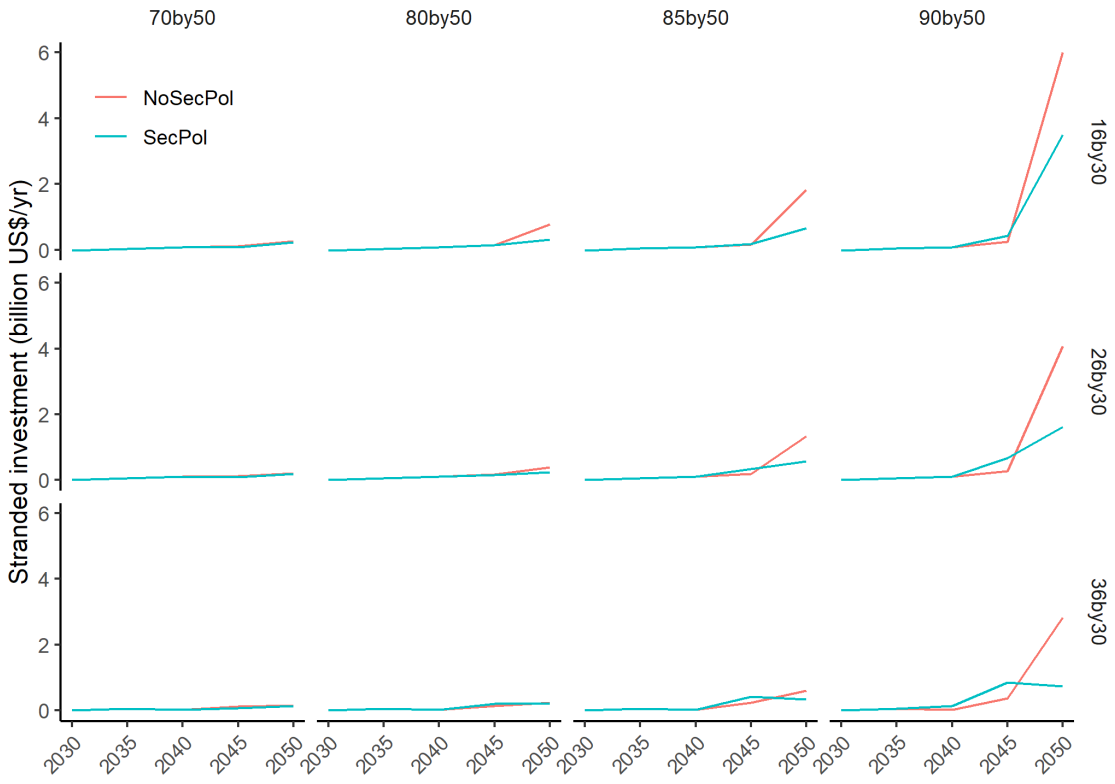

Fig. S 12 Stranded investment over time in the buildings sectors for all scenarios. NoSecPol indicates to the default scenarios without sectoral policy. SecPol indicates the scenarios with sectoral policy.

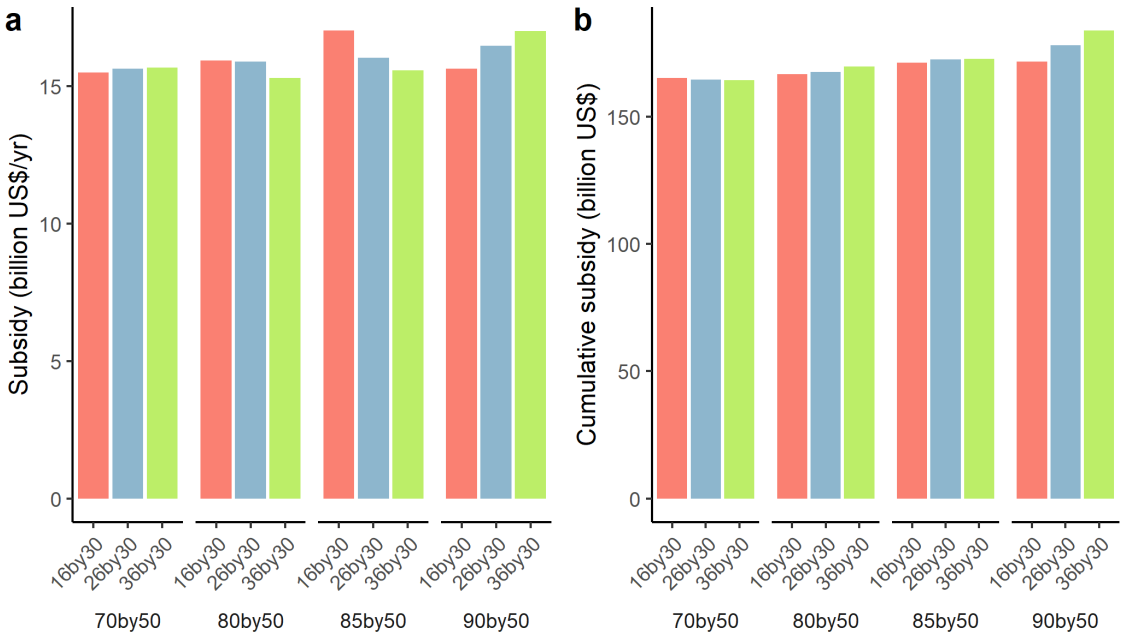

Fig. S 13 a) Subsidy in 2050 for sectoral policy implementation b) cumulative subsidy by 2050. Subsidy is not discounted here.

Supplementary tables

Table S 1 Assumption on the economic lifetime of infrastructure and devices in AIM/Enduse [Japan]

Sector	Technology	Lifetime (year)
Industrial	Sectoral specific energy efficiency technologies in steel, cement, paper and petrochemical sectors	20–30
	Industrial furnace, boiler, etc.	15
Buildings	Space and water heating/cooling systems	10–15
	Cooking devices	10
	Lighting and other home appliances	2-10
	Building envelope	30
Transport	Private car	10
	Bus, truck	10–12
	Train, ship and airplane	20
Power generation	Thermal power plants (Coal, oil, gas, biomass and geothermal)	40
	Nuclear	40–60
	Solar PV, wind	15
	Battery	10

Table S 2 Socio-economic assumptions

Variable	Unit	2010	2020	2030	2040	2050
GDP|MER	billion US$$_{2010}$/yr	5,499	6,407	7,583	8,037	8,466
Population	million	128	125	119	111	102
Floor Space|Commercial	million m^2	1,829	1,968	2,034	1,919	1,796
Floor Space|Residential	million m^2	5,023	5,192	5,053	4,739	4,390
Transportation|Freight	billion tkm/yr	451	450	469	442	420
Transportation|Passenger	billion pkm/yr	1,368	1,354	1,249	1,131	940
Production|Cement	Mt/yr	56	55	55	49	45
Production|Chemicals	Mt/yr	7	7	7	5	4
Production|Paper	Mt/yr	27	26	27	23	21
Production|Steel	Mt/yr	111	109	106	102	98

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