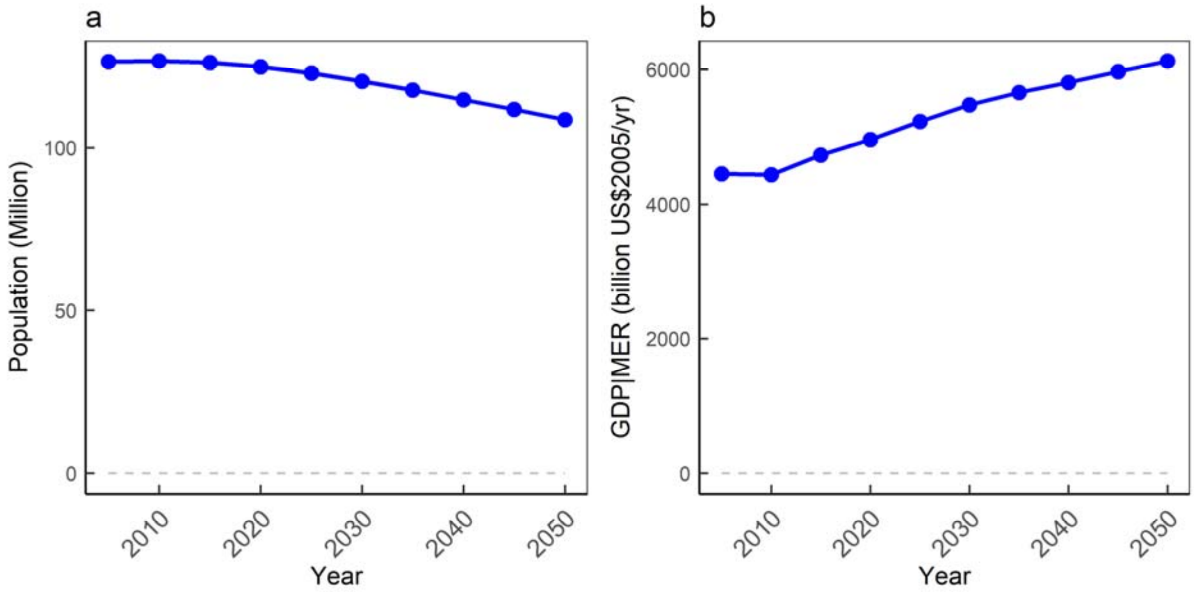
SUPPLEMENATRY INFORMATION for

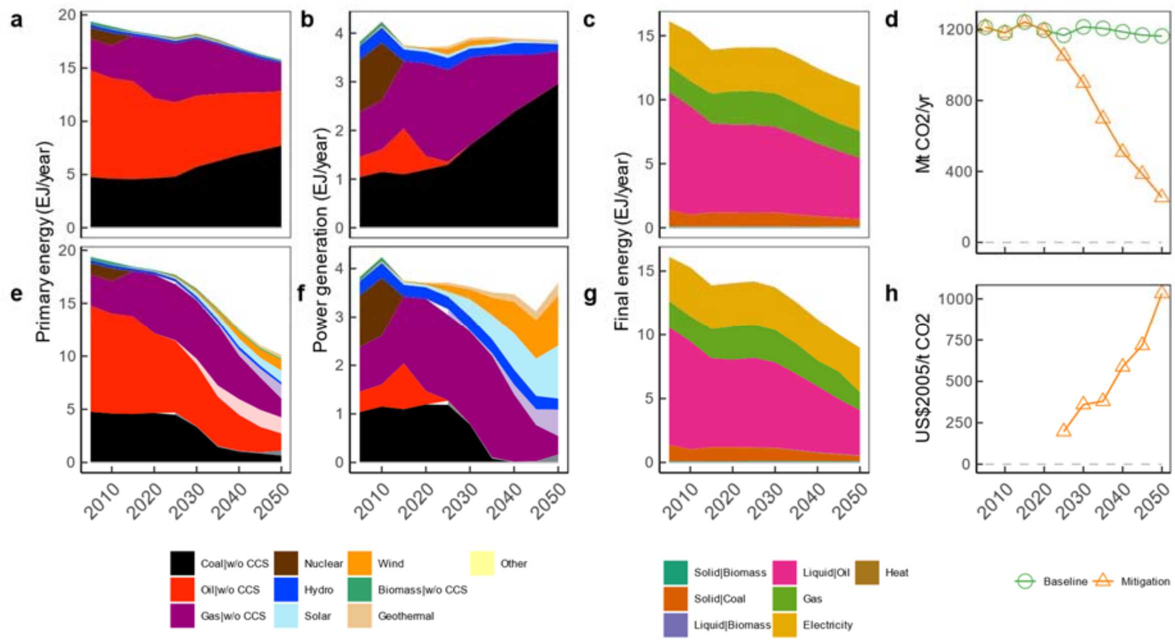
# *Energy Transformation Cost for the Japanese Mid-century Strategy*

Fujimori et al.

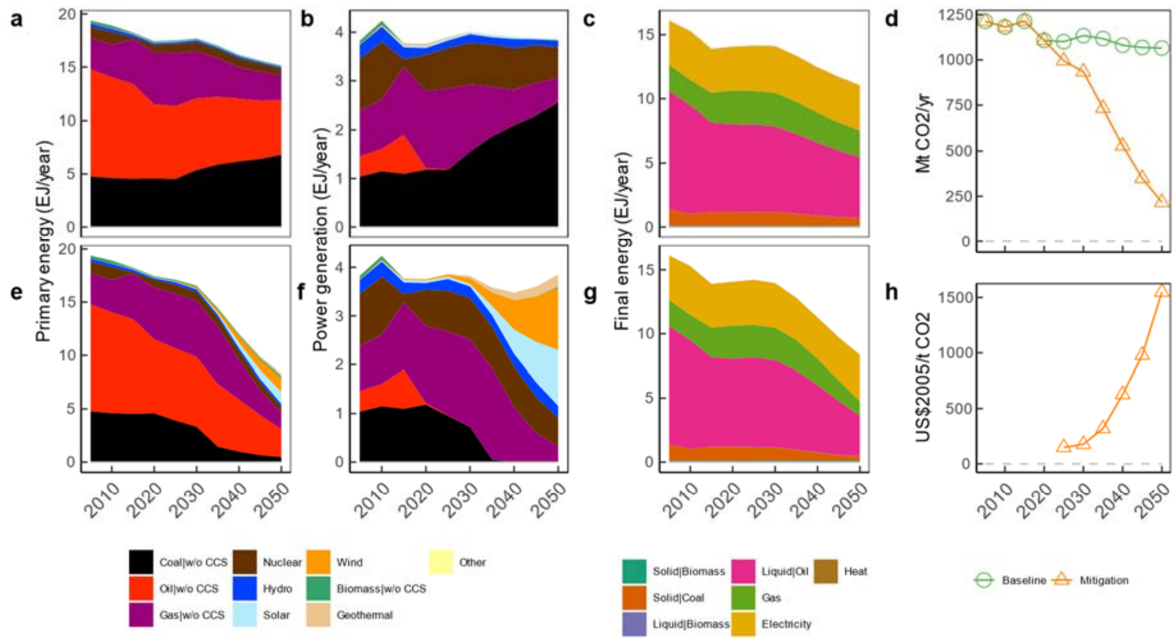
## 1. Supplementary figures



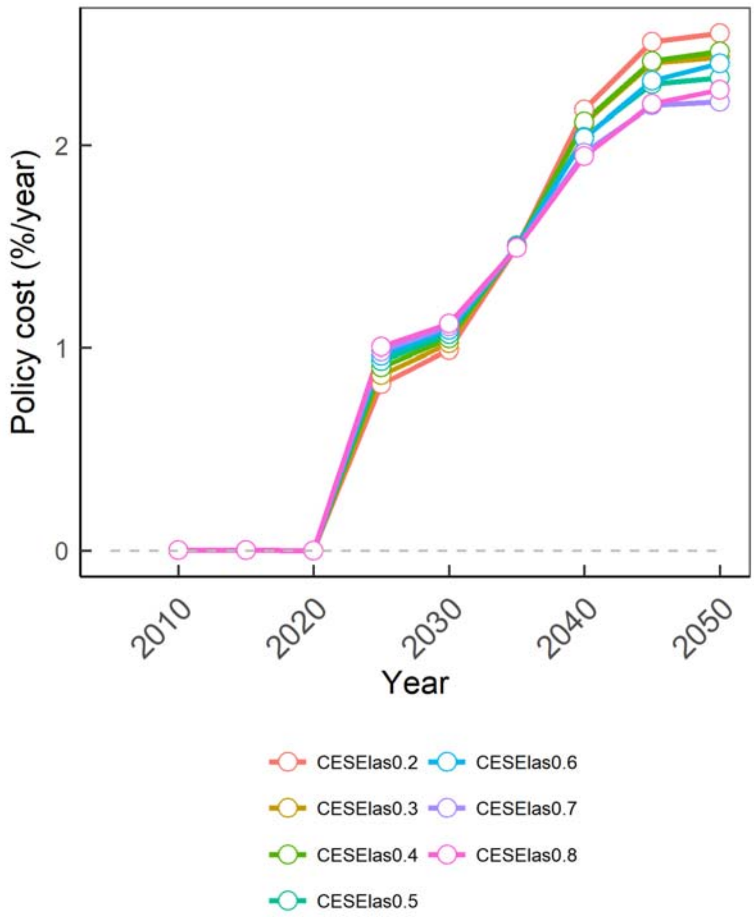

*Supplementary Figure 1. Population (a) and GDP MER (Market Exchange Rates) (b) assumptions.*



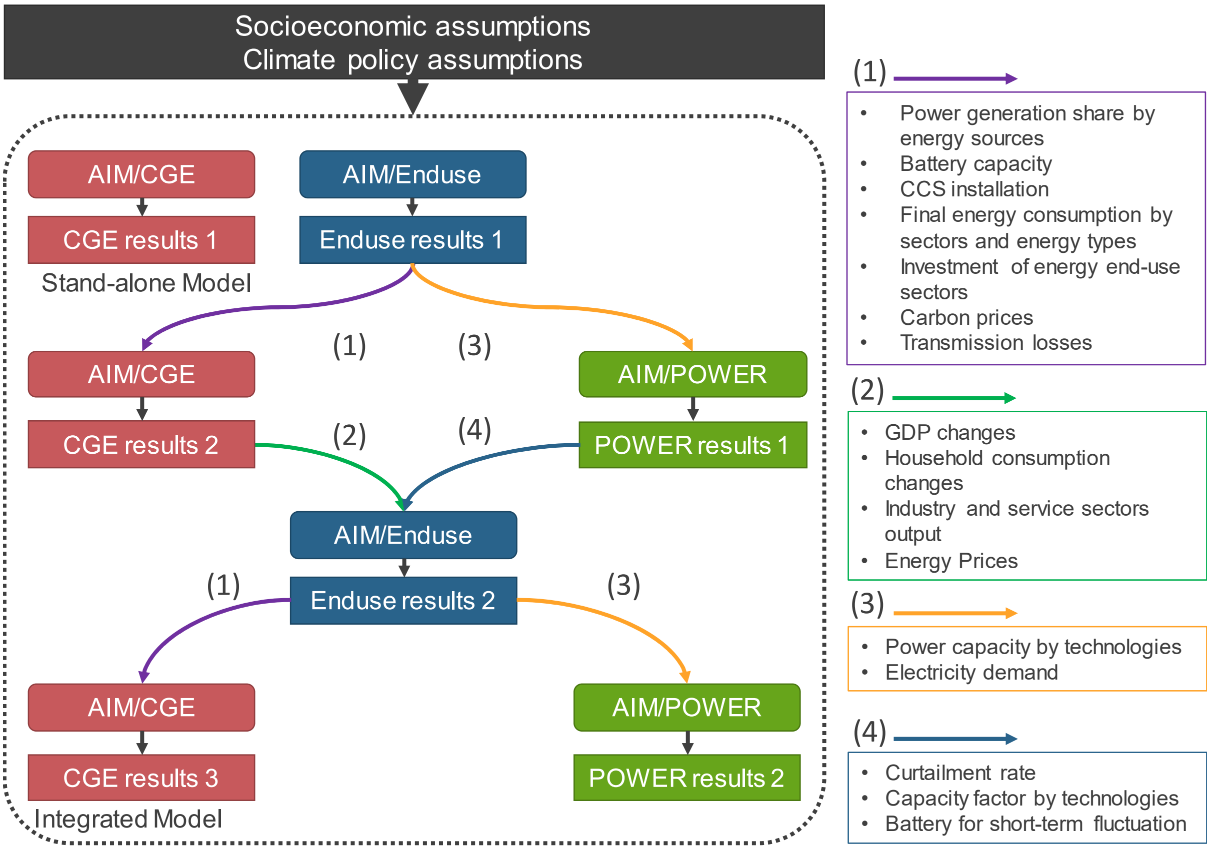

*Supplementary Figure 2. Primary energy (panels **a** and **e**), power generation (panels **b** and **f**), final energy demand (panels **c** and **g**), $CO_2$ emissions (panel **d**), and carbon price (panel **h**) projections for no-nuclear scenarios. Panels **a**, **b**, and **c** are baseline scenarios, whereas panels **e**, **f**, and **g** are mitigation scenarios. The other in panel **a** and **e** includes secondary energy net imports.*



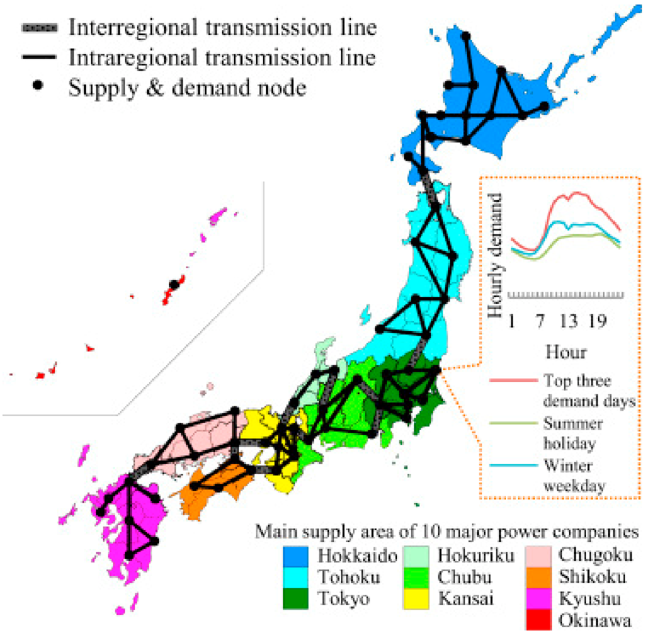

*Supplementary Figure 3. Primary energy (panels **a** and **e**), power generation (panels **b** and **f**), final energy demand (panels **c** and **g**), $CO_2$ emissions (panel **d**), and carbon price (panel **h**) projections for no-CCS scenarios. Panels **a**, **b**, and **c** are baseline scenarios, whereas panels **e**, **f**, and **g** are mitigation scenarios. The other in panel **a** and **e** includes secondary energy net imports.*



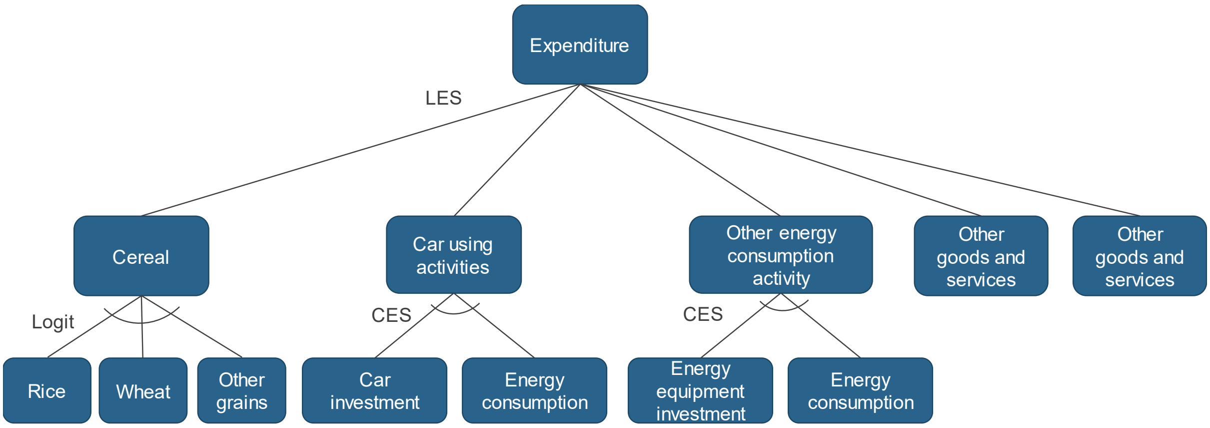

*Supplementary Figure 4. The GDP loss rates associated with variation in the substitution elasticity between energy and value-added in the stand-alone model*



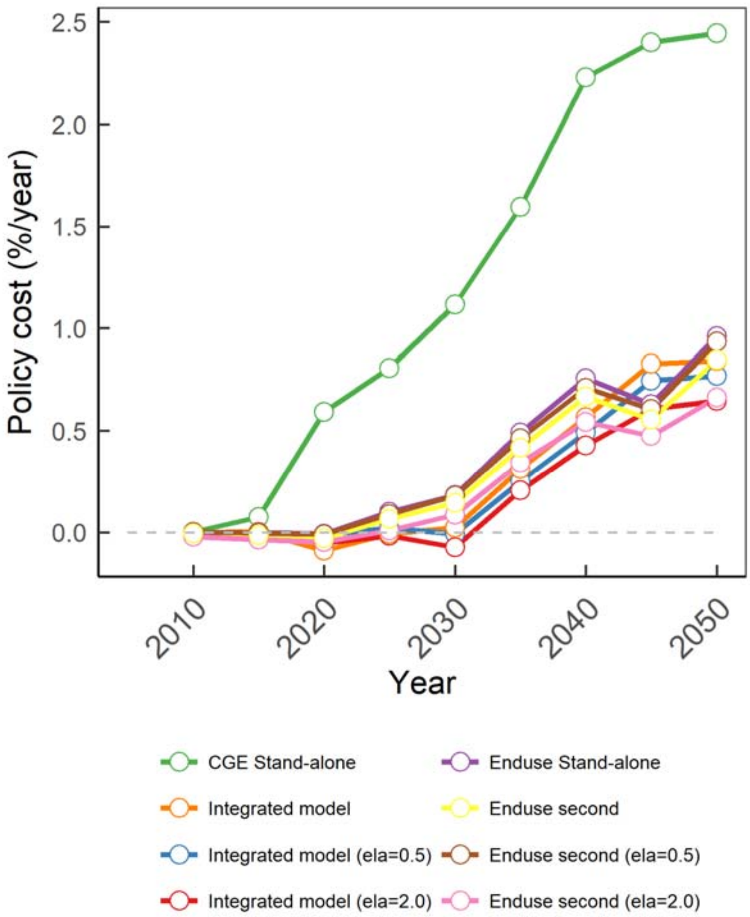

*Supplementary Figure 5. Model integration strategy.*



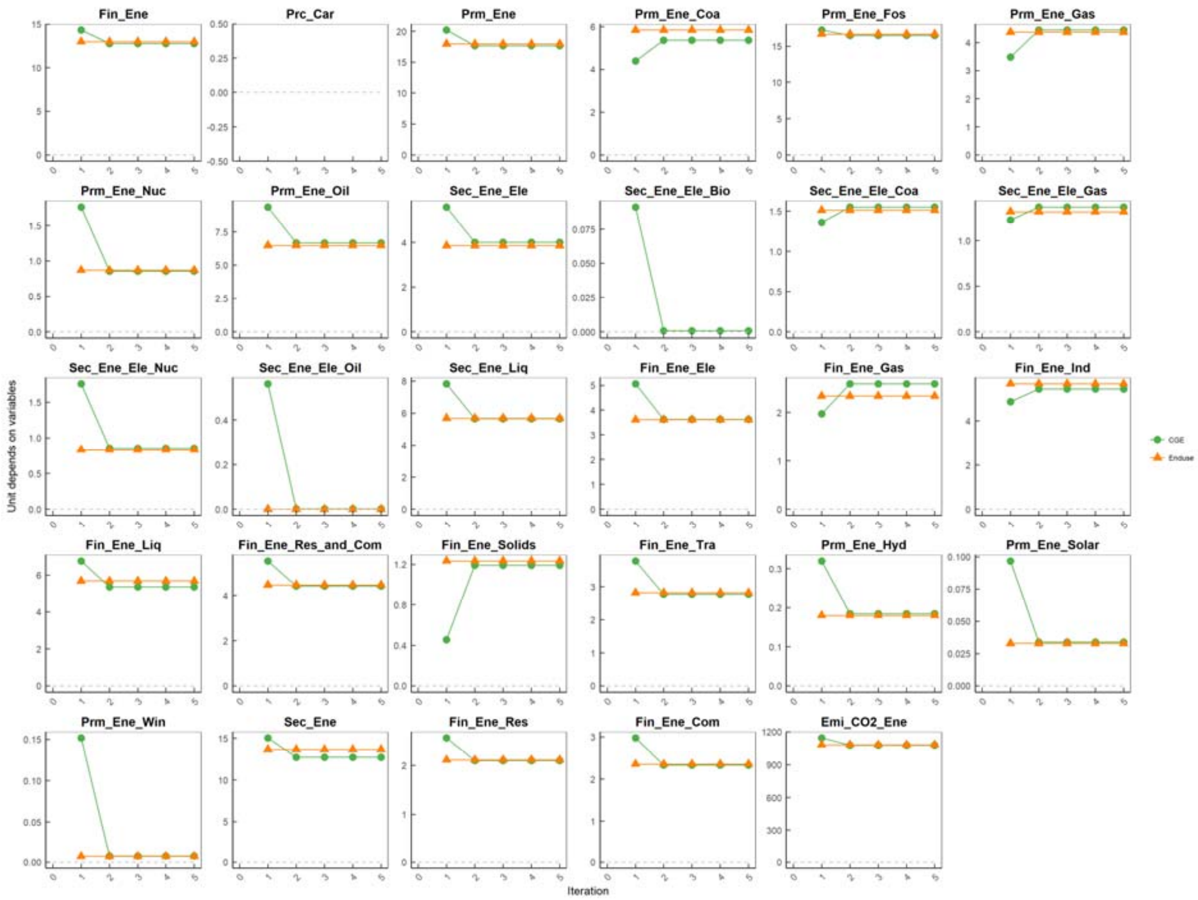

*Supplementary Figure 6. Regional classification of AIM/Enduse, AIM/Power, and the power grid system (Source: Shiraki et al. 2016[1]). For AIM/Power, since a version of the model that classifies Japan into 10 regions is used in this study, intraregional transmission lines were not considered.*



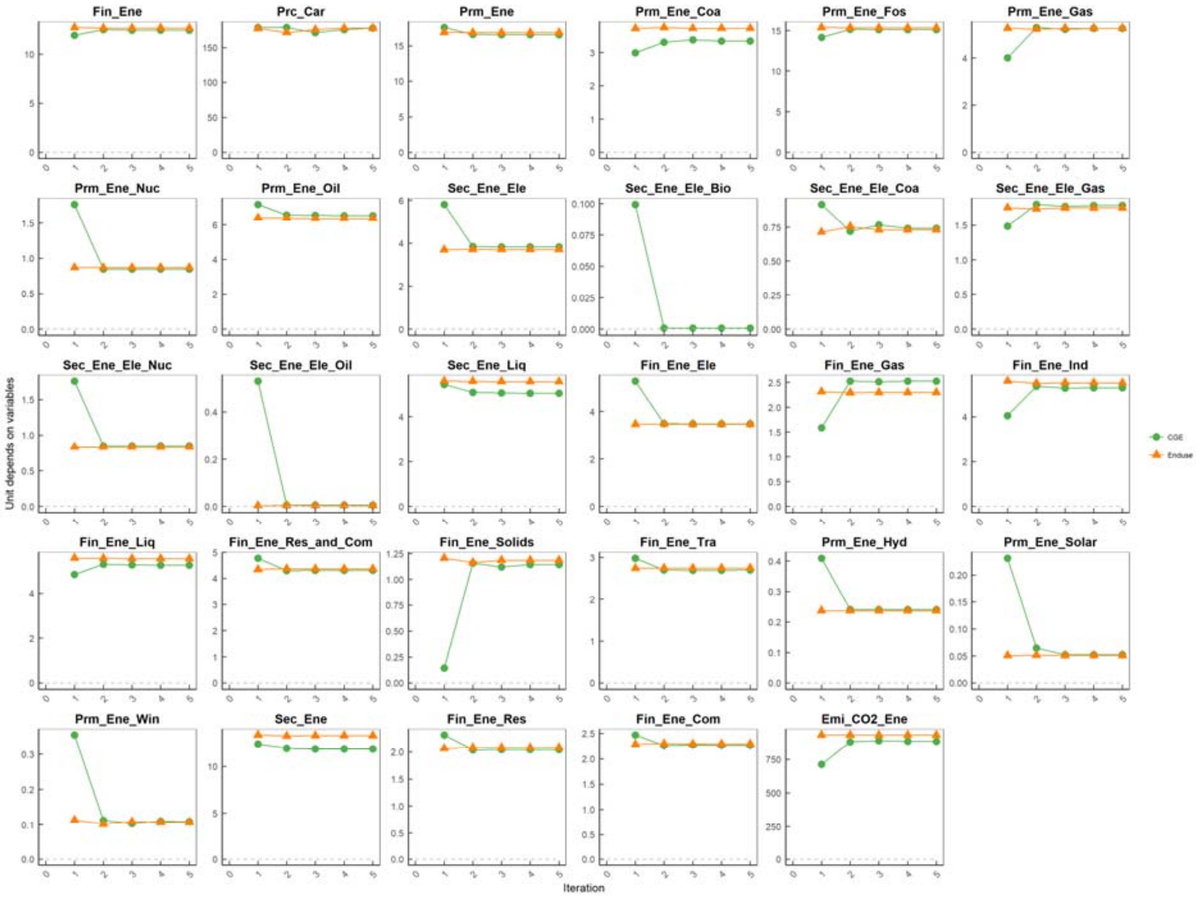

*Supplementary Figure 7. Household expenditure structure.*



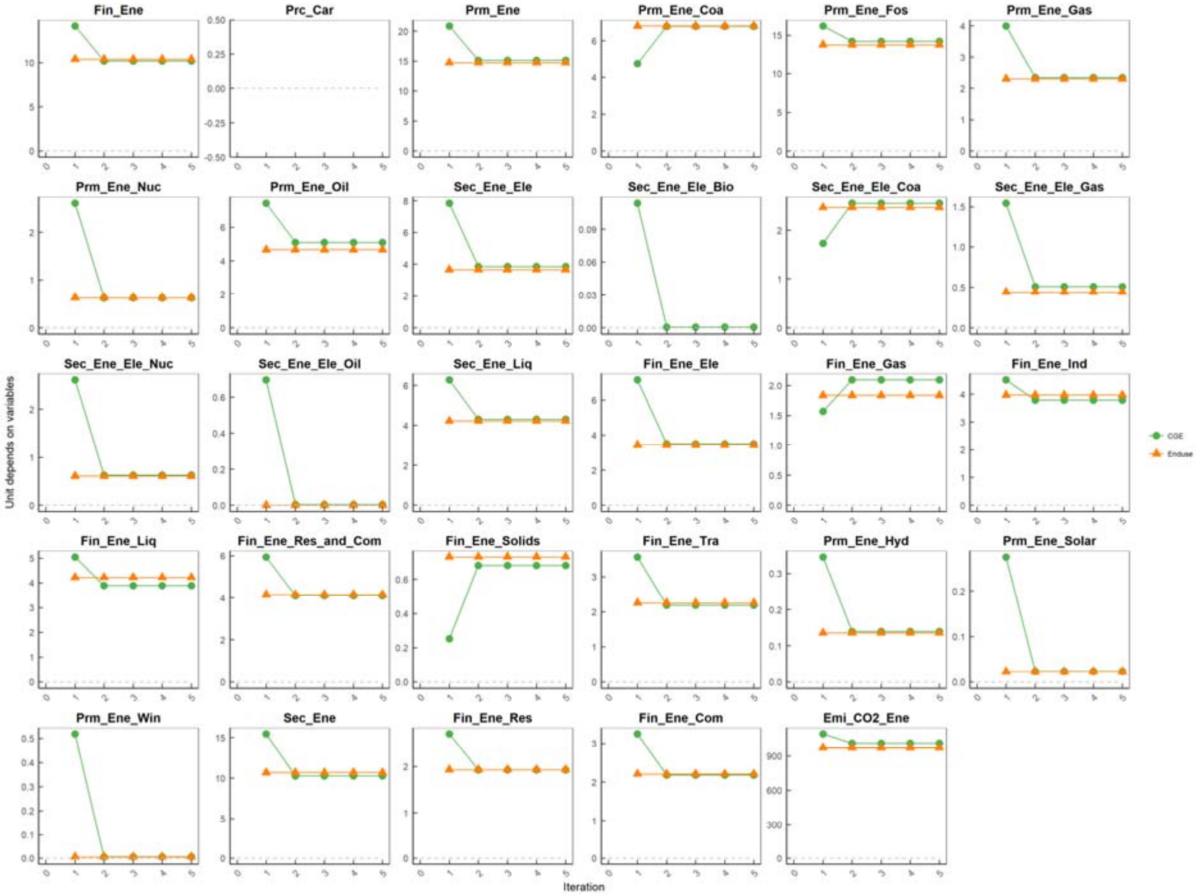

*Supplementary Figure 8. Climate mitigation policy costs associated with variations in the elasticity of monetary outputs and physical energy service demand.*



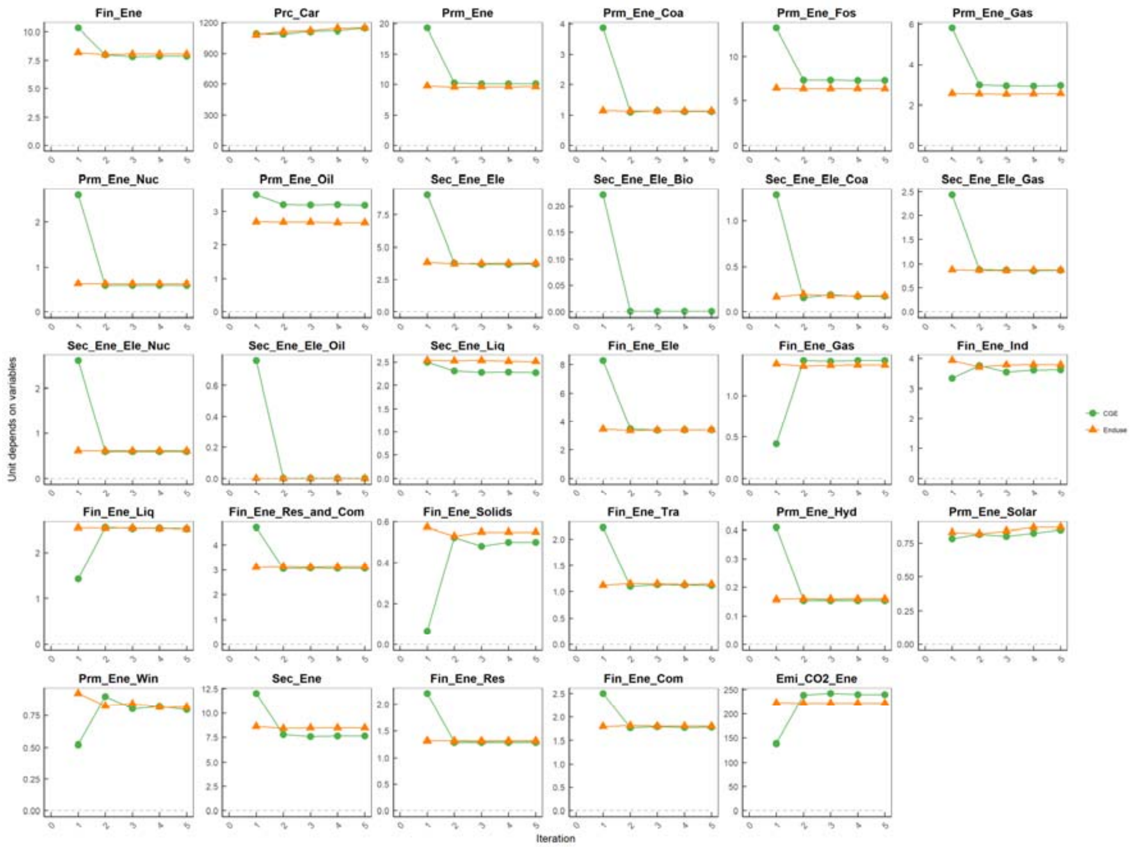

*Supplementary Figure 9. Main energy, emissions and economic indicators of the baseline scenario in 2030 by iteration. Each panel illustrates an individual variable, the codes and units of which are listed in*



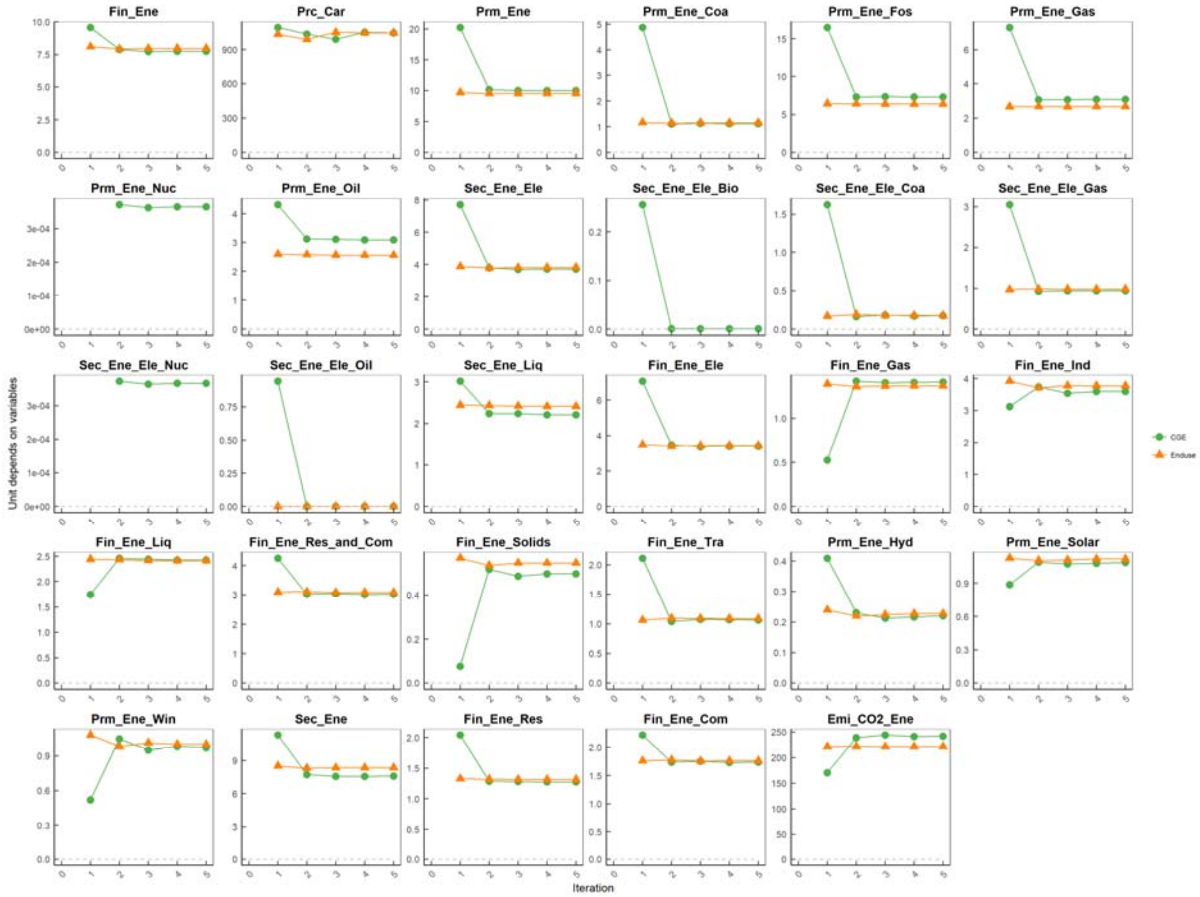

*Supplementary Figure 10. Main energy, emissions and economic indicators of the mitigation scenario in 2030 by iteration. Each panel illustrates an individual variable, the codes and units of which are listed in .*



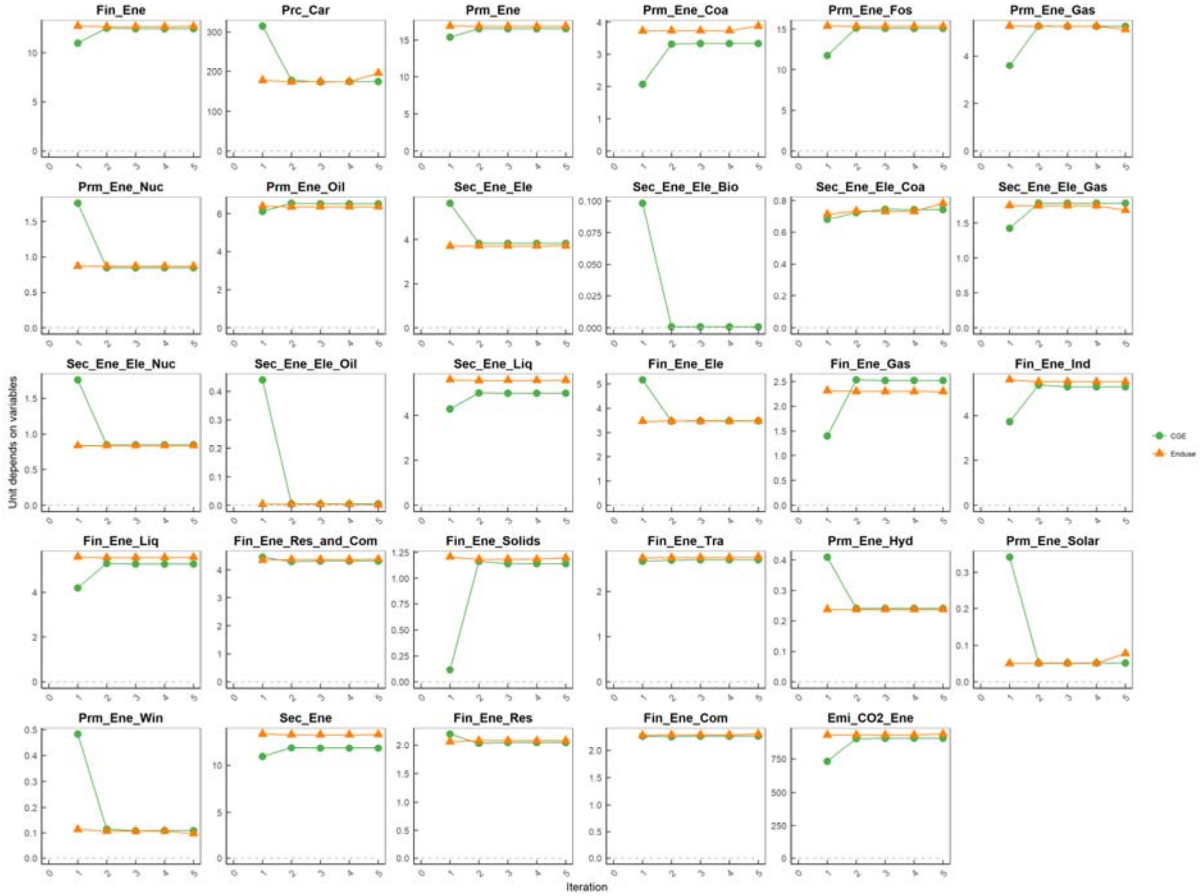

*Supplementary Figure 11. Main energy, emissions and economic indicators of the baseline scenario in 2050 by iteration. Each panel illustrates an individual variable, the codes and units of which are listed in .*



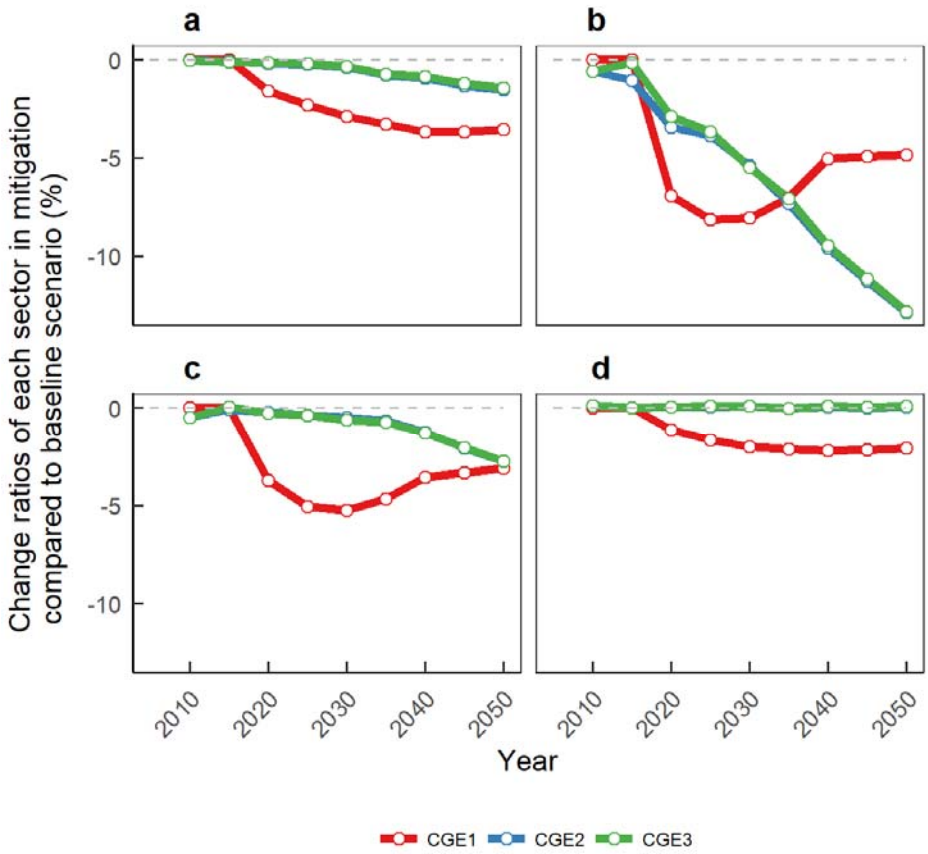

*Supplementary Figure 12. Main energy, emissions and economic indicators of the mitigation scenario in 2050 by iteration. Each panel illustrates an individual variable, the codes and units of which are listed in .*



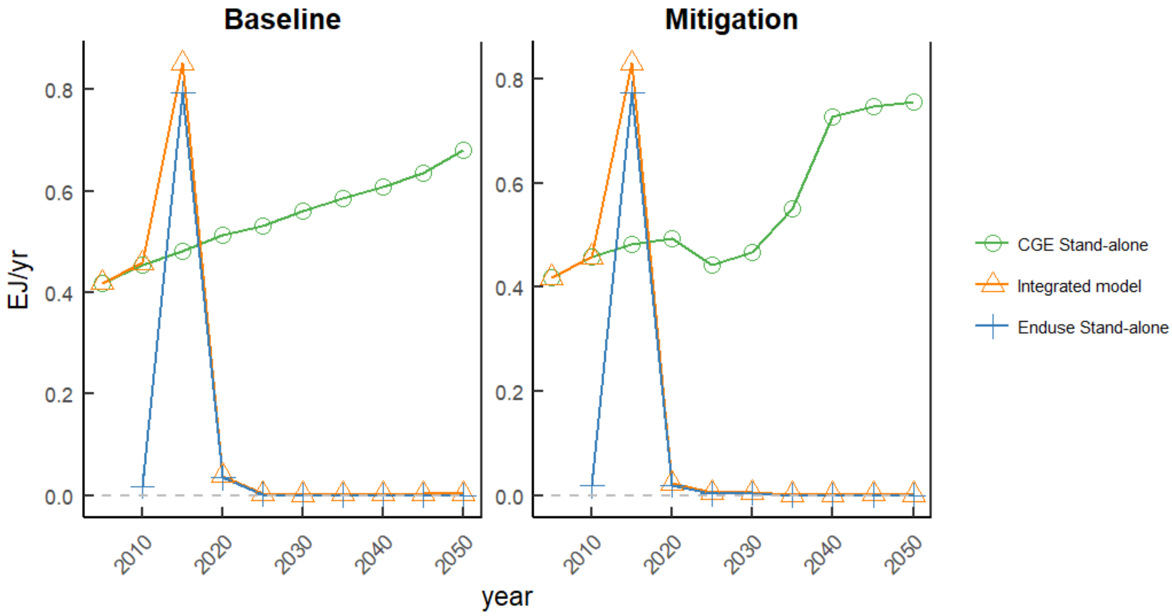

*Supplementary Figure 13. Main energy, emissions and economic indicators of the mitigation scenario without nuclear in 2030 by iteration. Each panel illustrates an individual variable, the codes and units of which are listed in .*



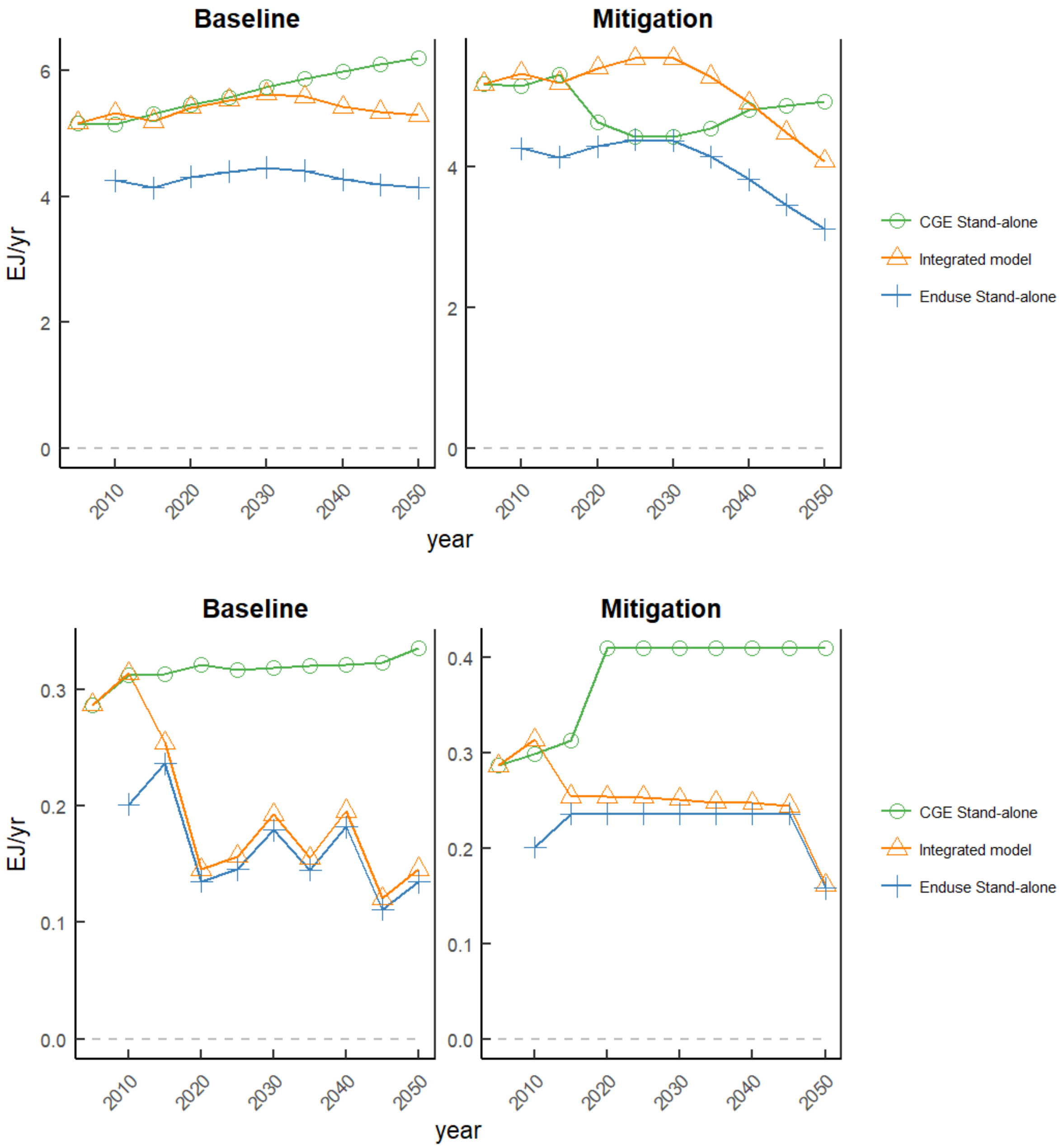

*Supplementary Figure 14. Main energy, emissions and economic indicators of the mitigation scenario without CCS in 2030 by iteration. Each panel illustrates an individual variable, the codes and units of which are listed in .*



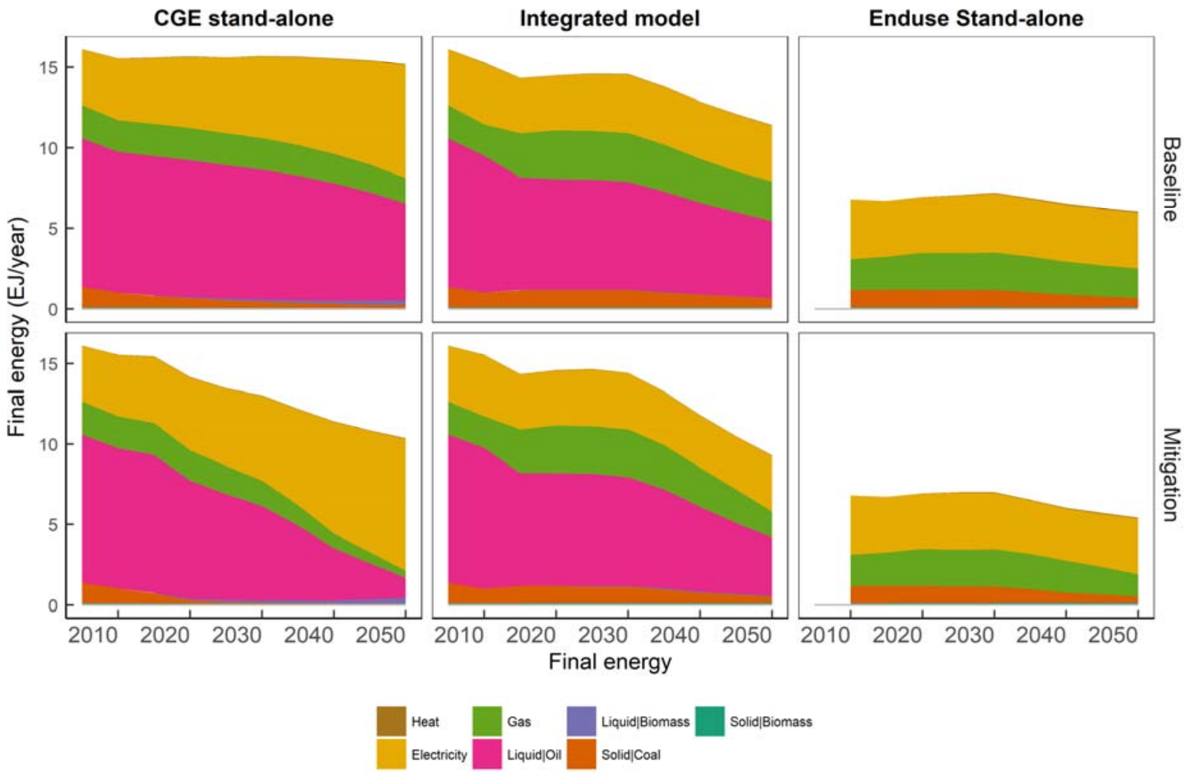

*Supplementary Figure 15. Change ratios of industrial outputs or household consumption in mitigation scenarios relative to the baseline scenario. Panels **a**, **b**, **c**, and **d** illustrate household, iron and steel, and other manufacturing and service sectors, respectively.*



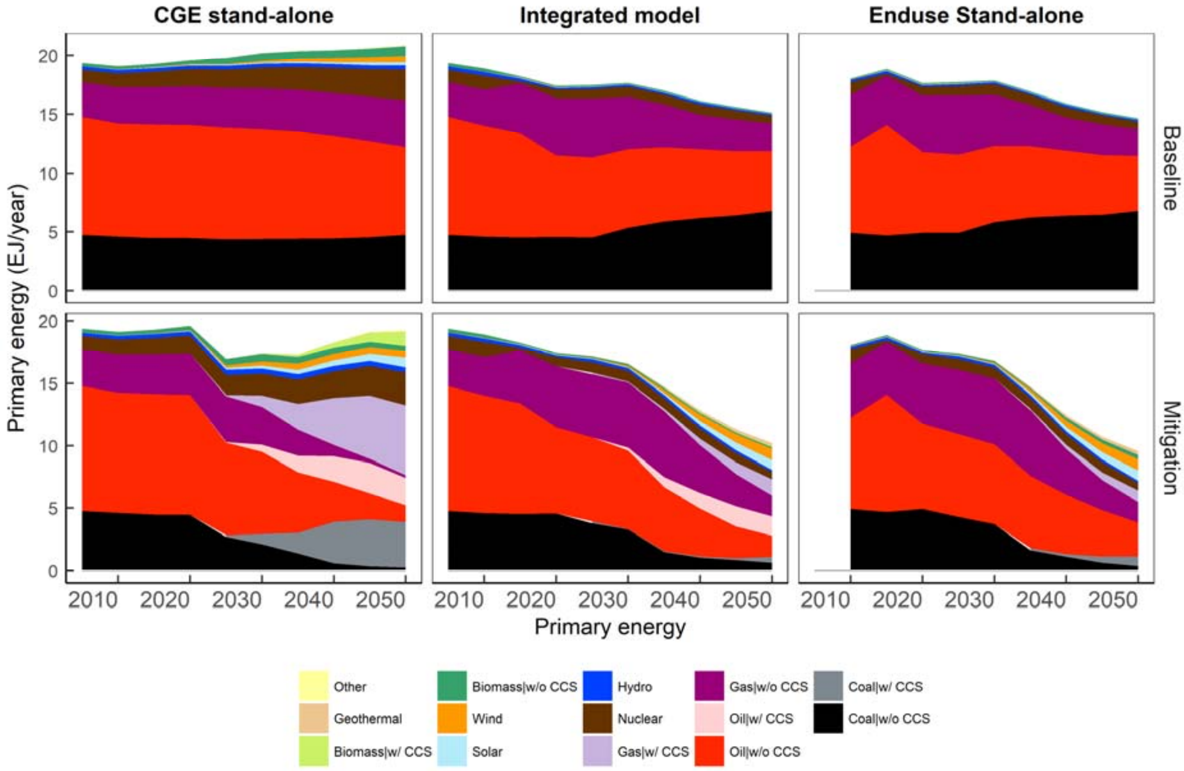

*Supplementary Figure 16. Evolution of oil-fired power generation. Left and right panels show the baseline and mitigation cases.*



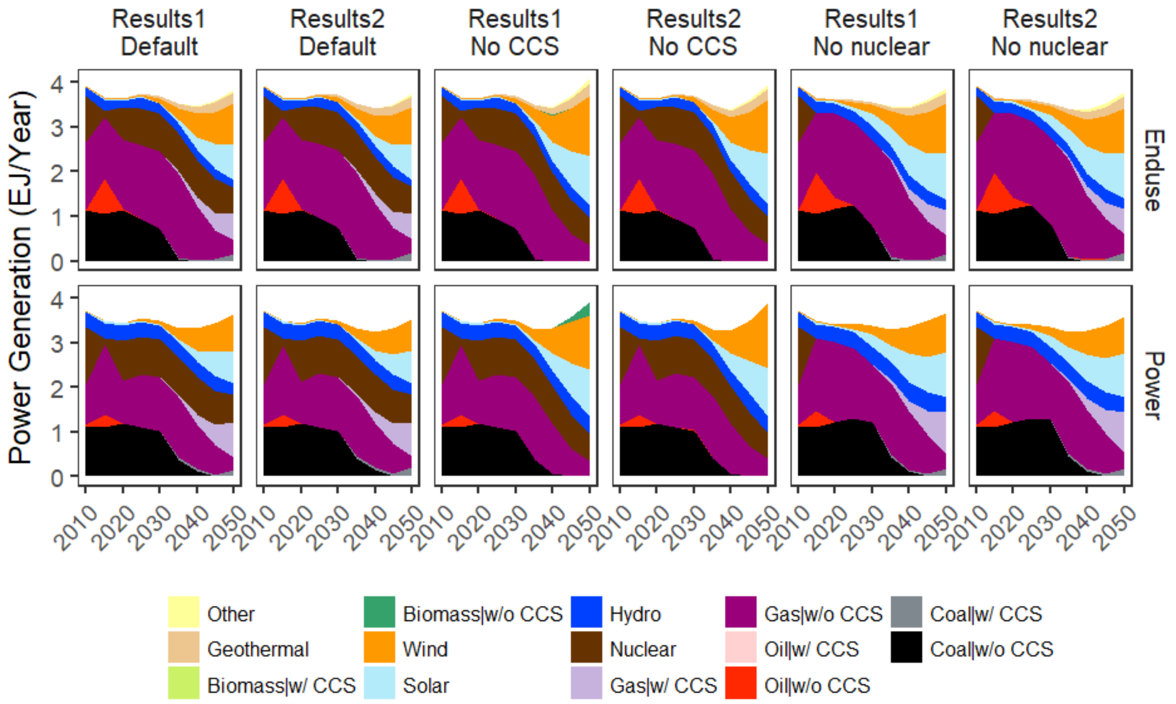

*Supplementary Figure 17. Evolution of residential and commercial final energy consumption and hydropower generation. Left and right panels show the baseline and mitigation cases. Top and bottom panels show residential and commercial final energy consumption and hydropower generation, respectively.*




*Supplementary Figure 18. Final energy consumption by energy carriers. Top and bottom panels show the baseline and mitigation cases, respectively. From left to right, CGE stand-alone, integrated model (CGE second run), and Enduse stand-alone simulation results are shown.*




*Supplementary Figure 19. Primary energy supply by energy source. Top and bottom panels show the baseline and mitigation cases, respectively. From left to right, CGE stand-alone, integrated model (CGE second run), and Enduse stand-alone simulation results are shown.*




*Supplementary Figure 20. Power generation by energy source generated by AIM/Enduse and AIM/Power. Top and bottom panels show AIM/Enduse and AIM/Power results, respectively. From left to right, results 1 and 2 correspond to the results of each iteration. 'Default', 'No CCS', and 'No nuclear' represent the scenario variations in technological availability.*

## 2. Supplementary tables

*Supplementary Table 1. Regression results of mitigation costs in the IPCC AR5 database[2].*

| | Estimate | Std. Error | t value | Pr(>\|t\|) | |
|---|---|---|---|---|---|
| (Intercept) | -73.791 | 7.594 | -9.717 | < 2e-16 | *** |
| 550ppm | -1.238 | 0.217 | -5.717 | 1.E-08 | *** |
| Year | 0.037 | 0.004 | 10.076 | < 2e-16 | *** |
| Asia | 0.352 | 0.347 | 1.014 | 0.311 | |
| Latin America | -1.527 | 0.356 | -4.287 | 2.E-05 | *** |
| Middle East and Africa | 0.293 | 0.355 | 0.825 | 0.410 | |
| OECD | -1.368 | 0.346 | -3.950 | 8.E-05 | *** |
| Reforming regions | 0.546 | 0.383 | 1.425 | 0.154 | |
| CGE | 4.120 | 0.386 | 10.677 | < 2e-16 | *** |

1130 degrees of freedom and adjusted R-squared: 0.199

*Supplementary Table 2. Literature review of CGE and energy system integration studies*

| Literature | Region | Integration method | Top-down model | Bottom-up model | Sector coverage of energy integration | Convergence confirmation | Electricity intermittency representation |
|---|---|---|---|---|---|---|---|
| Abrell and Rausch, 2016[3] | Europe | Soft-linking with iterative procedure | Static CGE | Electricity | Electricity | Electricity price and quantity | LDC |
| Andersen et al. 2019[4] | Denmark | Soft-linking with iterative procedure | Static CGE | Energy system model (TIMES) | All energy | Energy price and quantity | LDC (32 time slices per annual) |
| Arndt et al. 2016[5] | South Africa | Soft-linking with iterative procedure | Static CGE (SAGE) | Energy system model (TIMES) | Electricity | Electricity price and quantity | No |
| Boeringer et al. 2008[6] | Global | Hard-linking | Static and dynamic CGE | Electricity | Electricity | - | No |
| Fortes et al. 2014[7] | Portugal | Soft-linking with iterative procedure | Static CGE (GEM-E3) | Energy system model (TIMES) | All energy | Energy service demand differences | No |
| Helgesen et al. 2018[8] | Norway | Soft-linking with iterative procedure | Static CGE (REMES) | Energy system model (TIMES) | All energy | Commodity price and sectoral output | LDC (260 time slices per annual) |
| Hwang and Lee, 2015[9] | Korea | Soft-linking with iterative procedure | Static CGE | Electricity | Electricity | Electricity price and quantity | LDC (12 time slices per annual) |
| Krook-Riekkola et al. 2017[10] | Sweden | Soft-linking with iterative procedure | Static CGE (EMEC) | Energy system model (TIMES) | All energy | Energy consumption | LDC (12 time slices per annual) |
| Lanzi et al. 2012[11] | Global | Parameter calibration | Recursive dynamic CGE | World Energy Outlook | All energy | None | No |
| Laurent et al. 2004[12] | Switzerland | Soft-linking with iterative procedure | Static CGE | Energy system model (MARKAL) | Houshold | Carbon price | No |
| Sue Wing et al. 2008[13] | The US | Hard-linking | Static CGE | Electricity disaggregation | Electricity | - | No |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Tapia-Ahumada et al. 2015[14] | Global | Soft-linking | Recursive dynamic CGE | Electricity | Electricity | - | Hourly |
| Tuladhar et al. 2009[15] | US | Soft-linking with iterative procedure | Dynamic CGE | Electricity | Electricity | Energy price and quantity | LDC (20 time slices per annual) |
| Vandyck et al. 2016[16] | Global | One-way Soft-linking | Recursive dynamic CGE | Energy system model (POLES) | All energy | None | No |
| Waisman et al. 2012[17] | Global | Recursive soft-linking | Recursive dynamic CGE | Energy system model (POLES) | All energy | None | No |

*Supplementary Table 3. Additional annual investment of energy end-use sector in the mitigation scenario relative to the baseline scenario computed by AIM/Enduse (unit is billion 2010US$). Negative values indicate that investment in mitigation scenario is lower than baseline scenario due to energy service demand changes and cross-sectoral effects generated by total system cost optimization.*

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Industry | -0.01 | -0.01 | -0.07 | 0.06 | 0.02 | 0.16 | 0.02 | 0.28 | -0.26 |
| Commercial | 0.01 | 0 | 0.01 | 0.21 | 0.42 | 0.5 | 0.53 | 0.83 | 0.92 |
| Residential | 0 | 0 | 0 | 0.11 | 0.26 | 0.82 | 1.26 | 1.27 | 1.71 |
| Transport | 0 | 0 | 0.01 | 0.29 | 0.57 | 1.97 | 2.8 | 3.18 | 6.12 |

*Supplementary Table 4. Full list of diagnostic scenarios and their GDP loss rates in 2050. Column names are sectors, and 'on' and 'off' refer to whether AIM/Enduse information is incorporated. The red and blue rows indicate the stand-alone and integrated models, respectively. Yellow and green rows indicate scenarios that include and exclude information from a single sector given by AIM/Enduse, respectively. Uncoloured rows do not appear in Table1.*

| | Energy Supply | Industry | Service | Transport | Residential | GDP loss rate (%) | |
|---|---|---|---|---|---|---|---|
| | | | | | | 2030 | 2050 |
| scenario 1 | off | off | off | off | off | 1.1 | 2.4 |
| scenario 2 | off | off | off | off | on | 0.9 | 2.3 |
| scenario 3 | off | off | off | on | off | 1.1 | 2.4 |
| scenario 4 | off | off | off | on | on | 1.0 | 2.3 |
| scenario 5 | off | off | on | off | off | 0.6 | 1.7 |
| scenario 6 | off | off | on | off | on | 0.5 | 1.5 |
| scenario 7 | off | off | on | on | off | 0.7 | 1.6 |
| scenario 8 | off | off | on | on | on | 0.6 | 1.5 |
| scenario 9 | off | on | off | off | off | 0.4 | 0.8 |
| scenario 10 | off | on | off | off | on | 0.3 | 0.6 |
| scenario 11 | off | on | off | on | off | 0.5 | 0.7 |
| scenario 12 | off | on | off | on | on | 0.4 | 0.6 |
| scenario 13 | off | on | on | off | off | 0.1 | 0.4 |
| scenario 14 | off | on | on | off | on | 0.0 | 0.3 |
| scenario 15 | off | on | on | on | off | 0.2 | 0.3 |
| scenario 16 | off | on | on | on | on | 0.1 | 0.2 |
| scenario 17 | On | off | off | off | off | 0.9 | 2.2 |
| scenario 18 | on | off | off | off | on | 0.9 | 2.3 |
| scenario 19 | on | off | off | on | off | 1.1 | 2.4 |
| scenario 20 | on | off | off | on | on | 0.9 | 2.5 |
| scenario 21 | on | off | on | off | off | 0.5 | 2.0 |
| scenario 22 | on | off | on | off | on | 0.4 | 1.8 |
| scenario 23 | on | off | on | on | off | 0.7 | 2.3 |
| scenario 24 | on | off | on | on | on | 0.5 | 2.2 |
| scenario 25 | on | on | off | off | off | 0.4 | 1.2 |
| scenario 26 | on | on | off | off | on | 0.3 | 1.0 |
| scenario 27 | on | on | off | on | off | 0.6 | 1.3 |
| scenario 28 | on | on | off | on | on | 0.4 | 1.2 |
| scenario 29 | on | on | on | off | off | 0.0 | 0.8 |
| scenario 30 | on | on | on | off | on | -0.1 | 0.6 |
| scenario 31 | on | on | on | on | off | 0.1 | 0.8 |
| scenario 32 | on | on | on | on | on | 0.0 | 0.8 |

*Supplementary Table 5. List of production sectors in AIM/CGE*

| Classification | Sectors | ISIC rev3 code |
|---|---|---|
| Energy supply (transformation) sectors | Coal mining | 101, 102 |
| | Oil mining | 111, 112 (related to oil extraction), 103 |
| | Gas mining | 111, 112 (related to gas extraction) |
| | Petroleum refinery | 231, 232, 233 |
| | Coal transformation | |
| | Biomass transformation (1st generation) | - |
| | Biomass transformation (2nd generation with energy crop) | - |
| | Biomass transformation (2nd generation with residue) | - |
| | Gas manufacture distribution | 402, 403 |
| | Coal-fired power | 401 |
| | Oil-fired power | |
| | Gas-fired power | |
| | Nuclear power | |
| | Hydroelectric power | |
| | Geothermal power | |
| | Photovoltaic power | |
| | Wind power | |
| | Waste biomass power | |
| | Other renewable energy power generation | |
| | Advanced biomass-power generation | |
| | Hydrogen production by gas | - |
| | Hydrogen production by biomass | - |

*Supplementary Table 6 List of production sectors in AIM/CGE*

| Classification | Sectors | ISIC rev3 code |
| --- | --- | --- |
| Agricultural sectors (Energy end-use sectors) | Rice | 01 |
| | Wheat | |
| | Other grains | |
| | Oil seed crops | |
| | Sugar crops | |
| | Other crops | |
| | Ruminant livestock | 05 |
| | Raw milk | |
| | Other livestock and fishery | |
| | Forestry | 02 |
| Other production sectors (Energy end-use sectors) | Mineral mining and Other quarrying | 12, 13, 14 |
| | Food products | 15, 16 |
| | Textiles and Apparel and Leather, and Wood products | 17, 18, 19, 243, 20 |
| | Paper, Paper products and Pulp | 21, 2211, 2212, 2213, 2219, 222, 223 |
| | Chemical, Plastic and Rubber products | 241, 242, 25 |
| | Mineral products nec | 26 |
| | Iron and Steel | 271, 2731 |
| | Non-Ferrous products | 272, 2732 |
| | Other Manufacturing | 28, 29, 31, 33, 30, 32, 34, 35, 36, 37 |
| | Construction | 45 |
| | Transport and communications | 60, 61, 62, 63, 64 |
| | Other service sectors | 41, 50,51,52,55, 65, 66, 67, 70, 71, 72, 73, 74, 75, 80, 85, 90, 91, 92, 93, 94, 95, 99 |
| | CCS service | - |

*Supplementary Table 7. List of technologies in AIM/Enduse adopted from Oshiro et al. (2015)* [18]

| Sector | Technology option |
|---|---|
| Industrial sector | High performance pulp washing device, High efficient black liquid boiler, Next generation coke oven, CCS for steel/cement production, DC electric furnace, Naphtha catalytic cracker, High efficient industrial boiler, Industrial heat pump, High efficient motor, High efficient agricultural device |
| Residential and Commercial sector | High efficient air conditioner, High efficient water heater (e.g. Heat pump water heater), Electric heat pump water heater, SOFC, High efficient lighting, High efficient appliance, High performance building envelope, Building energy management system |
| Transport sector | High efficient passenger vehicle, Hybrid vehicle, Plug-in hybrid electric vehicle, Battery electric vehicle (BEV), Fuel-cell electric vehicle (FCEV), CNG vehicle, Biofuel, High efficient train, High efficient ship, High efficient aircraft, Eco driving |
| Power generation sector | IGCC w/CCS, IGCC wo/CCS, IGFC w/CCS, IGFC wo/CCS, Advanced gas combined cycle (ACC) w/CCS, ACC wo/CCS, Fuel cell gas combined cycle w/ or wo/CCS, Nuclear, Onshore wind power, Offshore wind power, Solar PV, Geothermal, Bioenergy, Hydropower, Pumped hydro, Reinforcing electricity interconnection capacity, Hydrogen generation by electrolysis |
| Other sectors | Reduced fertilization, HFCs leakage reduction and recovery, Reduced municipal solid waste |

*Supplementary Table 8. List of technoeconomic information of power sector in AIM./Enduse.*

| Variable | Unit | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital Cost\|Biomass\|w/ CCS | US$2010/kW | 7540 | 8063 | 8063 | 8063 | 8063 | 8063 | 8063 | 8063 | 8063 |
| Capital Cost\|Biomass\|w/o CCS | US$2010/kW | 3813 | 4336 | 4336 | 4336 | 4336 | 4336 | 4336 | 4336 | 4336 |
| Capital Cost\|Coal\|w/ CCS | US$2010/kW | 4338 | 4338 | 4338 | 4338 | 4338 | 4338 | 4338 | 4338 | 4338 |
| Capital Cost\|Coal\|w/o CCS | US$2010/kW | 2704 | 2704 | 2704 | 2704 | 2704 | 2704 | 2704 | 2704 | 2704 |
| Capital Cost\|Gas\|w/ CCS | US$2010/kW | 2174 | 2174 | 2174 | 2174 | 2174 | 2174 | 2174 | 2174 | 2174 |
| Capital Cost\|Gas\|w/o CCS | US$2010/kW | 1122 | 1122 | 1122 | 1122 | 1122 | 1122 | 1122 | 1122 | 1122 |
| Capital Cost\|Geothermal | US$2010/kW | 8716 | 8607 | 8607 | 8607 | 8607 | 8607 | 8607 | 8607 | 8607 |
| Capital Cost\|Hydro | US$2010/kW | 8716 | 8716 | 8716 | 8716 | 8716 | 8716 | 8716 | 8716 | 8716 |
| Capital Cost\|Nuclear | US$2010/kW | 4506 | 4721 | 4721 | 4721 | 4721 | 4721 | 4721 | 4721 | 4721 |
| Capital Cost\|Solar\|PV | US$2010/kW | 5704 | 4031 | 3035 | 2588 | 2141 | 2065 | 1990 | 1914 | 1838 |
| Capital Cost\|Wind\|Offshore | US$2010/kW | 5443 | 5704 | 5449 | 5194 | 4940 | 4797 | 4655 | 4513 | 4370 |
| Capital Cost\|Wind\|Onshore | US$2010/kW | 3046 | 3145 | 2918 | 2725 | 2531 | 2531 | 2531 | 2490 | 2449 |
| Lifetime\|Biomass\|w/ CCS | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Biomass\|w/o CCS | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Coal\|w/ CCS | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Coal\|w/o CCS | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Gas\|w/ CCS | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Gas\|w/o CCS | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Geothermal | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Hydro | years | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 80 |
| Lifetime\|Nuclear | years | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| Lifetime\|Solar\|PV | years | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Lifetime\|Wind\|Offshore | years | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Lifetime\|Wind\|Onshore | years | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| OM Cost\|Fixed\|Biomass\|w/ CCS | US$2010/kW/yr | 982 | 982 | 982 | 982 | 982 | 982 | 982 | 982 | 982 |
| OM Cost\|Fixed\|Biomass\|w/o CCS | US$2010/kW/yr | 290 | 290 | 290 | 290 | 290 | 290 | 290 | 290 | 290 |
| OM Cost\|Fixed\|Coal\|w/ CCS | US$2010/kW/yr | 303 | 303 | 303 | 303 | 303 | 303 | 303 | 303 | 303 |
| OM Cost\|Fixed\|Coal\|w/o CCS | US$2010/kW/yr | 106 | 106 | 106 | 106 | 106 | 106 | 106 | 106 | 106 |
| OM Cost\|Fixed\|Gas\|w/ CCS | US$2010/kW/yr | 159 | 159 | 159 | 159 | 159 | 159 | 159 | 159 | 159 |
| OM Cost\|Fixed\|Gas\|w/o CCS | US$2010/kW/yr | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 | 34 |
| OM Cost\|Fixed\|Geothermal | US$2010/kW/yr | 354 | 354 | 354 | 354 | 354 | 354 | 354 | 354 | 354 |
| OM Cost\|Fixed\|Hydro | US$2010/kW/yr | 379 | 379 | 379 | 379 | 379 | 379 | 379 | 379 | 379 |
| OM Cost\|Fixed\|Nuclear | US$2010/kW/yr | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| OM Cost\|Fixed\|Solar\|PV | US$2010/kW/yr | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 |
| OM Cost\|Fixed\|Wind\|Offshore | US$2010/kW/yr | 241 | 241 | 241 | 241 | 241 | 241 | 241 | 241 | 241 |
| OM Cost\|Fixed\|Wind\|Onshore | US$2010/kW/yr | 64 | 64 | 64 | 64 | 64 | 64 | 64 | 64 | 64 |

*Supplementary Table 9. Assumed power plant capacity by construction year (Unit is GW)*

| Construction year | -1970 | 1971 -75 | 1976 -80 | 1981 -85 | 1986 -90 | 1991 -95 | 1996 -00 | 2001 -05 | 2006 -10 |
|---|---|---|---|---|---|---|---|---|---|
| Coal\|w/o CCS | 0.2 | 4.4 | 2.5 | 4.1 | 4.1 | 8.3 | 10.1 | 10.7 | 2.8 |
| Gas\|w/o CCS | 0.6 | 14.5 | 9.0 | 6.7 | 7.9 | 4.5 | 12.9 | 4.3 | 9.6 |
| Oil\|w/o CCS | 12.8 | 15.0 | 7.8 | 8.1 | 3.3 | 2.3 | 3.4 | 2.3 | 1.5 |
| Hydro | 16.1 | 1.0 | 1.0 | 1.1 | 0.6 | 0.4 | 0.2 | 0.2 | 0.1 |
| Nuclear | | 12.1 | 5.7 | 3.4 | 6.5 | 11.1 | 4.7 | 2.2 | 3.2 |
| Biomass\|w/o CCS | | | | | | | | | 0.2 |
| Geothermal | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.1 | | 0.0 |
| Solar\|PV | | | | | | 0.0 | 0.2 | 0.9 | 1.9 |
| Wind\|Onshore | | | | | 0.0 | 0.0 | 0.1 | 0.9 | 1.4 |

*Supplementary Table 10. Assumptions on fuel prices*

| Variable | Unit | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Price\|Coal | US$2010/GJ | 4.1 | 3.9 | 3.8 | 3.4 | 3.3 |
| Price\|Gas | US$2010/GJ | 9.9 | 9.3 | 11.2 | 11.3 | 11.4 |
| Price\|Oil | US$2010/GJ | 12.8 | 14.9 | 17.3 | 15.9 | 14.7 |

*Supplementary Table 11. Mapping of household consumption goods and general goods categories*

| Household consumption goods category | General goods category |
|---|---|
| Car related consumption | Petroleum products<br>Electricity<br>Biofuel<br>Other Manufacturing |
| Non-car related energy | Coal<br>Oil<br>Gas<br>Petroleum products<br>Coal products<br>Biofuel<br>Town gas<br>Electricity<br>Hydrogen<br>Other Manufacturing |
| Cereal | Rice<br>Wheat<br>Other grains |
| Oil seed crops | Oil seed crops |
| Sugar crops | Sugar crops |
| Other crops | Other crops |
| Ruminant livestock | Ruminant livestock |
| Raw milk | Raw milk |
| Other livestock and fishery | Other livestock and fishery |
| Forestry | Forestry |
| Mineral mining and Other quarrying | Mineral mining and Other quarrying |
| Food products | Food products |
| Textiles and Apparel and Leather | Textiles and Apparel and Leather |
| Wood products | Wood products |
| Paper, Paper products and Pulp | Paper, Paper products and Pulp |
| Chemical, Plastic and Rubber products | Chemical, Plastic and Rubber products |
| Iron and Steel | Iron and Steel |
| Non-Ferrous products | Non-Ferrous products |
| Construction | Construction |
| Transport and communications | Transport and communications |
| Other services | Other services |

*Supplementary Table 12. Error rates (%) between AIM/CGE and AIM/Enduse models. CGE1, CGE2, CGE3, End1, and End2 correspond to the results shown in Supplementary Figure 5 results for each model output. For example, CGE_results1 and Enduse results1 are CGE1 and End1 respectively.*

| | Baseline | | | Mitigation | | |
|---|---|---|---|---|---|---|
| | End1_CGE1 | End1_CGE2 | End2_CGE3 | End1_CGE1 | End1_CGE2 | End2_CGE3 |
| Final Energy (EJ/yr) | 7% | 1% | 1% | 4% | 1% | 1% |
| Primary Energy (EJ/yr) | 8% | 1% | 1% | 13% | 1% | 1% |
| Primary Energy\|Coal (EJ/yr) | 11% | 2% | 2% | 26% | 6% | 4% |
| Primary Energy\|Fossil Fuel (EJ/yr) | 4% | 1% | 1% | 11% | 2% | 2% |
| Primary Energy\|Gas (EJ/yr) | 13% | 1% | 1% | 15% | 2% | 2% |
| Primary Energy\|Nuclear (EJ/yr) | 34% | 1% | 1% | 34% | 1% | 1% |
| Primary Energy\|Oil (EJ/yr) | 15% | 2% | 2% | 6% | 2% | 2% |
| Secondary Energy\|Electricity (EJ/yr) | 20% | 2% | 2% | 25% | 1% | 1% |
| Secondary Energy\|Electricity\|Coal (EJ/yr) | 11% | 1% | 1% | 43% | 5% | 1% |
| Secondary Energy\|Electricity\|Gas (EJ/yr) | 21% | 2% | 2% | 18% | 1% | 1% |
| Secondary Energy\|Electricity\|Non-Biomass Renewables (EJ/yr) | 0% | 0% | 0% | 0% | 0% | 0% |
| Secondary Energy\|Electricity\|Nuclear (EJ/yr) | 35% | 1% | 1% | 35% | 1% | 1% |
| Secondary Energy\|Electricity\|Oil (EJ/yr) | 75% | 15% | 15% | 75% | 37% | 11% |
| Secondary Energy\|Liquids (EJ/yr) | 13% | 0% | 0% | 3% | 4% | 4% |
| Final Energy\|Electricity (EJ/yr) | 19% | 0% | 0% | 25% | 0% | 0% |
| Final Energy\|Gases (EJ/yr) | 5% | 4% | 4% | 20% | 3% | 4% |
| Final Energy\|Industry (EJ/yr) | 4% | 2% | 2% | 10% | 2% | 2% |
| Final Energy\|Liquids (EJ/yr) | 7% | 2% | 2% | 9% | 2% | 2% |
| Final Energy\|Residential and Commercial (EJ/yr) | 10% | 0% | 0% | 8% | 1% | 1% |
| Final Energy\|Solids (EJ/yr) | 32% | 2% | 2% | 58% | 2% | 2% |
| Final Energy\|Transportation (EJ/yr) | 13% | 1% | 1% | 9% | 1% | 1% |
| Primary Energy\|Hydro (EJ/yr) | 29% | 1% | 1% | 25% | 7% | 1% |
| Primary Energy\|Solar (EJ/yr) | 57% | 1% | 1% | 13% | 1% | 1% |
| Primary Energy\|Wind (EJ/yr) | 86% | 1% | 1% | 22% | 1% | 1% |
| Secondary Energy (EJ/yr) | 8% | 2% | 2% | 6% | 4% | 4% |
| Final Energy\|Residential (EJ/yr) | 9% | 0% | 0% | 10% | 1% | 1% |
| Final Energy\|Commercial (EJ/yr) | 11% | 0% | 0% | 7% | 0% | 0% |
| Emissions\|CO2\|Energy and Industrial Processes (Mt CO2/yr) | 4% | 1% | 1% | 10% | 2% | 1% |

*Supplementary Table 13. Variable code and unit list*

| Code | Variable | Unit |
|---|---|---|
| Fin_Ene | Final Energy | EJ/yr |
| Prc_Car | Price\|Carbon | US$2005/t CO2 |
| Prm_Ene | Primary Energy | EJ/yr |
| Prm_Ene_Coa | Primary Energy\|Coal | EJ/yr |
| Prm_Ene_Fos | Primary Energy\|Fossil Fuel | EJ/yr |
| Prm_Ene_Gas | Primary Energy\|Gas | EJ/yr |
| Prm_Ene_Nuc | Primary Energy\|Nuclear | EJ/yr |
| Prm_Ene_Oil | Primary Energy\|Oil | EJ/yr |
| Sec_Ene_Ele | Secondary Energy\|Electricity | EJ/yr |
| Sec_Ene_Ele_Bio | Secondary Energy\|Electricity\|Biomass | EJ/yr |
| Sec_Ene_Ele_Coa | Secondary Energy\|Electricity\|Coal | EJ/yr |
| Sec_Ene_Ele_Gas | Secondary Energy\|Electricity\|Gas | EJ/yr |
| Sec_Ene_Ele_Nuc | Secondary Energy\|Electricity\|Nuclear | EJ/yr |
| Sec_Ene_Ele_Oil | Secondary Energy\|Electricity\|Oil | EJ/yr |
| Sec_Ene_Liq | Secondary Energy\|Liquids | EJ/yr |
| Fin_Ene_Ele | Final Energy\|Electricity | EJ/yr |
| Fin_Ene_Gas | Final Energy\|Gases | EJ/yr |
| Fin_Ene_Ind | Final Energy\|Industry | EJ/yr |
| Fin_Ene_Liq | Final Energy\|Liquids | EJ/yr |
| Fin_Ene_Res_and_Com | Final Energy\|Residential and Commercial | EJ/yr |
| Fin_Ene_Solids | Final Energy\|Solids | EJ/yr |
| Fin_Ene_Tra | Final Energy\|Transportation | EJ/yr |
| Prm_Ene_Hyd | Primary Energy\|Hydro | EJ/yr |
| Prm_Ene_Solar | Primary Energy\|Solar | EJ/yr |
| Prm_Ene_Win | Primary Energy\|Wind | EJ/yr |
| Sec_Ene | Secondary Energy | EJ/yr |
| Fin_Ene_Res | Final Energy\|Residential | EJ/yr |
| Fin_Ene_Com | Final Energy\|Commercial | EJ/yr |
| Emi_CO2_Ene | Emissions\|CO2\|Energy | Mt CO2/yr |

## 3. Supplementary notes

### Supplementary Note 1. Climate mitigation costs in the IPCC AR5 database

We investigated the IPCC AR5 database to determine whether climate mitigation costs in multi-sector CGE models are higher than those in other types of models. The AR5 database includes various scenarios that cannot be dealt with equally. For example, the scenarios developed under EMF27 (Energy Modeling Forum) include assumptions about technological variations. Climate targets also differ among scenarios. Therefore, we first selected scenarios that do not have any restrictions on technological availability from EMF27. Then, the climate targets were classified into two categories equivalent to 450 and 550 ppm $CO_2$ at the end of this century. We then applied simple regression analysis, as follows:

$$MCR_s = \sum_{(s,l)\in SL} b_l Y_l + e_s$$

where $MCR_s$ is the climate mitigation cost (%) for scenario $s$; $b_l$ is a dummy parameter representing a set of model classifications (multi-sector CGE or not), years, regions (five regions, Asia, Latin America, Middle East-Africa, OECD, and Reforming region + global), and climate targets (450 or 550ppm); $Y_l$ is an estimated variable; and $e_s$ is an error term. Here, we take climate mitigation cost to represent GDP losses as a standard metric, but for models that do not include GDP losses, additional energy system costs or area under MAC (marginal abatement cost) are used. The regression results show that the CGE model is a positive factor with a statistically significant *t*-value.

### Supplementary Note 2. Mathematical formula of CGE model

In this section, we describe the mathematical formulas in the AIM/CGE model, which is particularly relevant to energy consumption and power generation. We use different production functions between energy end-use and power generation sectors and they are described as below.

#### 1) Energy end-use sectors other than household sector in CGE model

We begin with the representation of the energy end-use sectors (Supplementary Table 5). As many of other CGE models, AIM/CGE assumes KL-E type multi-nested CES production function[19]. The value-added and energy composite inputs are determined by multiplying a coefficient by the output from the energy end-use sectors (Equation 1) that is calibrated. Then, value-added and energy composite are combined with the CES function (Equation 2). Labour and capital inputs are further nested in the CES function, as shown in Equation 3.

$$QVAE_a^B = ivae_a \cdot QA_a^B \tag{1}$$

$$QVAE_a^B = \alpha ae_a \left(\beta ae_a \cdot {QVA_a^B}^{-\rho ae_a} + (1-\beta ae_a) \cdot (at_a \cdot QENE_a^B)^{-\rho ae_a}\right)^{\frac{1}{-\rho ae_a}} \tag{2}$$

$$QVA_a^B = tfp \cdot \alpha f_a \left(\beta f_a \cdot {QF^B_{"capital",a}}^{-\rho ae_a} + (1-\beta f_a) \cdot {QF^B_{"labor",a}}^{-\rho f_a}\right)^{\frac{1}{-\rho f_a}} \tag{3}$$

where

$a \in A$ is a set of production activities,

$QA_a^B$ is an output of sector $a$ in the baseline scenarios (monetary unit),

$QVAE_a^B$ is the composite of value-added and energy of sector $a$ in the baseline scenarios (monetary unit),

$QVA_a^B$ is value-added of sector $a$ in baseline scenarios (monetary unit),

$QENE_a^B$ is the total energy inputs including any energy carriers (e.g. gas, liquids, and electricity) of sector $a$ in baseline scenarios (physical unit),

$QF_{f,a}^B$ is the primary factor inputs of factor $f$ and sector $a$ in baseline scenarios ($f$ = capital or labor) (monetary unit),

$ivae_a$ is an input coefficient of the output of sector $a$,

$\alpha ae_a$ is the scale parameter of the CES function for value-added and energy aggregates,

$\beta ae_a$ is the share parameter of the CES function for value-added and energy aggregates,

$\rho ae_a$ is the exponent parameter of the CES function for value-added and energy aggregates,

$\alpha f_a$ is the scale parameter of the CES function for primary factor aggregates,

$\beta f_a$ is the share parameter of the CES function for primary factor aggregates,

$\rho f_a$ is the exponent parameter of the CES function for primary factor aggregates,
$at_a$ is an autonomous energy efficiency improvement parameter, and
$tfp$ is a parameter that represents the economy wide total factor productivity that is calibrated in the baseline scenarios by hitting the target GDP and the calibrated values are adopted in the mitigation scenarios.

The energy carriers shares in the energy end-use sectors are calculated by using McFadden's (1981)[20] logit share equation. The concept underlying the logit is that the decision makers determine the share of each element under a certain probability distribution function. This function form is applied in some other IAMs (GCAM[21] and IMAGE[22]). For further theoretical discussion of the logit sharing mechanism, see Clarke and Edmonds (1993)[23]. $QENE$ shown above is the sum of the individual energy carriers determined by this equation.

$$SHENE_{c,a} = \frac{ae_c \cdot \delta_{c,a}^{en} \cdot PQ_{c,a}^{-\beta^{el}}}{\sum_{cp \in CENE} ae_{cp} \cdot \delta_{cp,a}^{en} \cdot PQ_{cp,a}^{-\beta^{el}}} \quad c \in CENE, a \in AEnd \tag{5}$$

Where
$a \in AEnd$ is energy end-use production activities and a subset of the production activities (e.g. industry, transport and so on),
$c \in CENE$ is set of energy commodities (coal, petroleum products and so on), which is a subset of all commodities,
$SHENE_{c,a}$ is the energy consumption share of energy commodity $c$ in production activity $a$,
$PQ_{c,a}$ is the price of commodity $c$ in production activity $a$ (monetary/physical unit),
$\delta_{c,a}^{en}$ and $\beta^{el}$ are parameters for logit selection, and
$ae_c$ is the fuel-wise energy preference change parameter of commodity $c$.

For the stand-alone model, $\beta ae_a^B$ and $\delta_{c,a}$ are calibrated by base year information. Autonomous Energy Efficiency Improvement (AEEI) in the stand-alone model $at_a$ is one of the critical parameters determining energy consumption. We adopted a uniform AEEI across energy end-use sectors for each year, which is associated with GDP growth. For the years that assumes more than 1% of GDP annual growth, AEEI change rate is 1%, and half of the annual GDP growth rates is assumed for the other years. The fuel-wise energy preference change parameter $ae_c$ is set annually to 1%, 0.5% and -0.5% for electricity, gas and coal respectively, which represent fuel shift from conventional solid and liquids to gas and electricity. They are arbitrarily assumed and their validity should be interpreted within the baseline scenario's perspective.

With respect to the integrated model, the $SHENE_{c,a}$ and $QENE_a^B$ are fixed based on the AIM/Enduse model results and endogenise $\delta_{c,a}^{en}$ and $at_a$.

Then, we can derive the input coefficients of capital in the baseline scenarios after obtaining the simulation results of the baseline scenarios as shown in Equation (6). For the mitigation scenarios, the derived input coefficients of the primary factors shown above are used to estimate primary factor inputs. For the capital inputs of the energy end-use sector, additional investment costs (associated with mitigation scenarios) relative to baseline scenarios, which are given by the AIM/Enduse model, have been added to the baseline inputs, as shown in Equation (7).

$$ifa_{f,a}^B = QF_{f,a}^B / QA_a^B \quad f \in Fcap \tag{6}$$

$$QF_{f,a}^M = ifa_{f,a}^B * QA_a^M + AddInv_{f,a} \quad f \in Fcap \tag{7}$$

where
$f \in Fcap$ is a set of capital and a subset of primary factors
$ifa_a^B$ is an input coefficient of primary factor $f$ and sector $a$ in the baseline scenarios.
$AddInv_{f,a}$ is the additional investment cost associated with mitigation costs provided by AIM/Enduse,
$QF_{f,a}^M$ is the primary factor input of factor $f$ and sector $a$ in the mitigation scenarios ($f$ = capital or labour) (monetary unit), and
$QA_a^M$ is an output of sector $a$ in the mitigation scenarios (monetary unit).

### 2) Power generation in CGE model

The total consumption of electricity is determined by the demand side representation shown in the previous subsection (*QENE* and *SHEHE*, and the latter for household). Then, the power generation is determined based on logit sharing which has already been mentioned above, as below.

$$SHAC_{c,a} = \frac{\delta^{el}_{c,ap} \cdot PXAC_{c,a}{}^{-\beta^{el}}}{\sum_{ap \in AEly} \delta^{el}_{c,ap} \cdot PXAC_{c,ap}{}^{-\beta^{el}}} \quad c \in CEly, a \in AEly \tag{8}$$

where $a \in AEly$ is a subset of production activity and electricity production activity (e.g. coal, solar PV and so on),
$c \in CEly$ is a subset of commodity and electricity,
$SHAC_{c,a}$ is the electricity generation share of production activity $a$,
$PXAC_{c,a}$ is the price of commodity *c* produced by production activity $a$ (monetary/physical unit),
$\delta^{el}_{c,a}$ and $\beta^{el}$ are parameters for the logit selection of power general technologies.

For the stand-alone model, $\delta^{el}_{c,a}$ is calibrated using base year information. The integrated model fixes the $SHAC_{c,a}$ as the AIM/Enduse model results and endogenises $\delta^{el}_{c,a}$ . This treatment is the same between the baseline and the mitigation scenarios. As the absolute amount of power generation is determined by the demand side, here we specify only the share. The transmission losses are also considered. Battery capacity is input as an absolute amount.

### 3) Household consumption in CGE model

Household consumption is formulated using a LES function and further nested in a CES for energy and other manufacturing goods. The function is derived from a function originally defining how spending on individual commodities has a linear relation with total consumption spending, based on the assumption that each household maximises a Stone–Geary utility function subject to consumption expenditure constraints. The parameters of the LES function other than food were calibrated based on income elasticity values (Nganou, 2005)[24]. The income elasticity of food demand for each region and commodity was from Bruinsma (2010)[25].

Then, total energy consumption is finally split out into fuel-wise consumption using a logit function

$$QCH_{ch} = \mu_{ch} + \theta_{ch} \cdot \left( \frac{EH}{PCH_{ch}} - \sum_{chp \in CH} \mu_{chp} \right) \quad ch \in CH \tag{9}$$

$$QCH_{ch} = \alpha h_{ch} \left( \beta h_{ch} \cdot QHE_{ch}{}^{-\rho h_{ch}} + (1 - \beta h_{ch}) \cdot QHM_{ch}{}^{-\rho h_{cp}} \right)^{\frac{1}{-\rho h_{ch}}} \tag{10}$$

$$SHHENE_{c,ch} = \frac{ae_c \cdot \delta^h_{c,ch} \cdot PQ_{c,h}{}^{-\beta^h}}{\sum_{cp \in CENE} ae_{cp} \cdot \delta^h_{cp,ch} \cdot PQ_{cp,h}{}^{-\beta^h}} \quad c \in CENE, ch \in CHE \tag{11}$$

$$QH_c = \begin{cases} \sum_{ch \in CHE} SHHENE_{c,ch} \cdot QHE_{ch} & c \in CENE \\ \sum_{(c,ch) \in mapCCH} QCH_{ch} & c \in CNENE \\ \sum_{(c,ch) \in mapCCH} QHM_{ch} & c \in COMF \end{cases} \tag{12}$$

where
$ch \in CH$ is a set of household consumption goods of which mappings with goods *c* are shown in Supplementary Table 11
$ch \in CHE$ is a set of energy related household consumption goods (car usage and other energy related consumption)
$(c, ch) \in mapCCH$ is a mapping from household consumption goods *ch* to general goods *c*. shown in Supplementary Table 11,
$PCH_{ch}$ are the quantity and price of household consumption goods $ch$ (relative ratio to base year),
$QCH_{ch}$ are the quantity and price of household consumption goods $ch$ (monetary unit but energy is accounted as physical unit),
$SHHENE_{c,ch}$ is the share of energy fuel c of household consumption goods *ch*,
$QHE_{ch}$ and $QHM_{ch}$ are the quantity of energy and other manufacturing goods, respectively, for household consumption goods *ch* (car usage and other energy related consumption; physical unit),
$\theta_{ch}$ and $\mu_{ch}$are LES function parameters which are calibrated recursively,
$\alpha h_{ch}$ is the scale parameter of the CES function for energy and other manufacturing goods aggregates,
$\beta h_{ch}$ is the share parameter of the CES function for energy and other manufacturing goods aggregates,
$\rho h_{ch}$ is the exponent parameter of the CES function for energy and other manufacturing goods aggregates,
$\delta^h_{c,ch}$ and $\beta^h$ are parameters for logit selection of household energy fuel.

Household LES function parameters are updated recursively based on income elasticity. Electricity and biofuel used in transport, are not accounted in the base year social accounting matrix and, thus, we introduce the initial parameters for $\delta_{c,ch}^{h}$ and $\delta_{c,a}^{en}$ by calibrating 0.1% of the share in each energy consumption in 2015 and 2020. They are then updated afterwards to one third of the value of petroleum products in 40 years. They are same as used in the SSPs quantification. For the integrated model, the parameters $\beta h_{ch}$ and $\rho h_{ch}$ were determined endogenously based on the energy consumption and investment needs for other manufacturing goods computed by AIM/Enduse.

## Supplementary Note 3. Consistency check across models

We confirm how the outputs of two models change over iterations and reach convergence. Supplementary Table 12 shows the degree of coincidence for each pair of AIM/Enduse and AIM/CGE datasets. An indicator shown below is adopted as the indicator. i, t and s are sets of variables of model (e.g. energy demand), years and scenarios respectively. $X_{i,t,s}$ and $Y_{i,t,s}$ are AIM/CGE and AIM/Enduse outputs respectively.

$$ErrI_{i,s} = \sqrt{\frac{\sum_t \left(X_{t,i,s} - Y_{t,i,s}\right)^2}{\left[\sum_t \left(\frac{X_{t,i,s} + Y_{t,i,s}}{2}\right)\right]^2}}$$

CGE results drastically changed from the standalone version to the coupled version, and the discrepancy with AIM/Enduse falls substantially (End1_CGE1 to End1_CGE2 in Supplementary Figure 5). The differences in these improvements are nearly stable in the second iteration run, wherein AIM/Enduse incorporated energy service demand changes given by AIM/CGE and AIM/CGE further input revised AIM/Enduse data (End1_CGE2 to End2_CGE3 in Supplementary Figure 5). We run five iterations and the results indicate that the second iteration sufficiently converges the variables (see Supplementary Figure 9 to Supplementary Figure 14). This result may be due to energy service demand changes produced by AIM/CGE, which fed into AIM/Enduse, being small in the second and third iterations. Here, we can estimate the value-added and household consumption changes (differences between CGE2 and CGE3 in Supplementary Figure 5). Consequently, the third CGE run showed few changes from the second run.

Overall, the errors are less than 20%, but there are some exceptions. Final energy in the residential and service sectors and electricity generation from oil and hydropower in the baseline scenarios exhibit relatively high discrepancies, which show relatively small improvements in the third iteration. Therefore, we classified two types of errors. First, some years have very small values in one or both models, causing the error rates of these two models to be large in some years. Oil-fired power generation is one such example, as shown in Supplementary Figure 16. The second type of error is mainly due to discrepancies in the base year information between the two models. The residential and service sectors' final energy consumption and hydropower explain the cause of these differences, as shown in Supplementary Figure 17. As indicated in the Methods section, we incorporated the change ratios from AIM/Enduse into AIM/CGE relative to the base year for final energy consumption, and thus trends after the base year for AIM/Enduse, which is 2010, are quite similar in the second AIM/CGE run. We further provide figures comparing energy-related data, Supplementary Figure 18 and Supplementary Figure 19, to explore the future evolution of energy systems.

Regarding the consistency of the AIM/Power and AIM/Enduse models, power generation appears to be almost the same at the end of the run (Supplementary Figure 20). Caution is still required, as other indicators such as capacity factor, may play a role here. That possibility is not necessarily true for the detailed technological contributions, but would hardly affect the overall trend because the main differences affect tiny power generation sources (e.g. the coal power capacity factor in mitigation scenarios).

## 4. Supplementary references


1. Shiraki H, Ashina S, Kameyama Y, Hashimoto S, Fujita T. Analysis of optimal locations for power stations and their impact on industrial symbiosis planning under transition toward low-carbon power sector in Japan. *Journal of Cleaner Production* 2016, **114:** 81-94.

2. International Institute for Applied Systems Analysis, (IIASA). IAMC AR5 scenario database. 2015 [cited]Available from: https://secure.iiasa.ac.at/web-apps/ene/AR5DB/dsd?Action=htmlpage&page=about#intro

3. Abrell J, Rausch S. Cross-country electricity trade, renewable energy and European transmission infrastructure policy. *Journal of Environmental Economics and Management* 2016, **79:** 87-113.

4. Andersen KS, Termansen LB, Gargiulo M, Ó Gallachóirc BP. Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models. *Energy* 2019, **169:** 277-293.

5. Arndt C, Davies R, Gabriel S, Makrelov K, Merven B, Hartley F*, et al.* A sequential approach to integrated energy modeling in South Africa. *Applied Energy* 2016, **161:** 591-599.

6. Böhringer C, Rutherford TF. Combining bottom-up and top-down. *Energy Economics* 2008, **30**(2)**:** 574-596.

7. Simões S, Seixas J, Van Regemorter D, Ferreira F. Top-down and bottom-up modelling to support low-carbon scenarios: climate policy implications AU - Fortes, Patricia. *Climate Policy* 2013, **13**(3)**:** 285-304.

8. Helgesen PI, Tomasgard A. From linking to integration of energy system models and computational general equilibrium models – Effects on equilibria and convergence. *Energy* 2018, **159:** 1218-1233.

9. Hwang W-S, Lee J-D. A CGE analysis for quantitative evaluation of electricity market changes. *Energy Policy* 2015, **83:** 69-81.

10. Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. *Energy* 2017, **141:** 803-817.

11. Lanzi E, Chateau J, Dellink R. Alternative approaches for levelling carbon prices in a world with fragmented carbon markets. *Energy Economics* 2012, **34:** S240-S250.

12. Drouet L, Haurie A, Labriet M, Thalmann P, Vielle M, Viguier L. A Coupled Bottom-Up/Top-Down Model for GHG Abatement Scenarios in the Swiss Housing Sector. In: Loulou R, Waaub J-P, Zaccour G (eds). *Energy and Environment*. Springer US, 2005, pp 27-61.

13. Sue Wing I. The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technology detail in a social accounting framework. *Energy Economics* 2008, **30**(2)**:** 547-573.

14. Tapia-Ahumada K, Octaviano C, Rausch S, Pérez-Arriaga I. Modeling intermittent renewable electricity technologies in general equilibrium models. *Economic Modelling* 2015, **51:** 242-262.

15. Tuladhar SD, Yuan M, Bernstein P, Montgomery WD, Smith A. A top–down bottom–up modeling approach to climate change policy analysis. *Energy Economics* 2009, **31:** S223-S234.

16. Vandyck T, Keramidas K, Saveyn B, Kitous A, Vrontisi Z. A global stocktake of the Paris pledges: Implications for energy systems and economy. *Global Environmental Change* 2016, **41**(Supplement C)**:** 46-63.

17. Waisman H, Guivarch C, Grazi F, Hourcade JC. The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change* 2012, **114**(1)**:** 101-120.

18. Oshiro K, Masui T. Diffusion of low emission vehicles and their impact on CO2 emission reduction in Japan. *Energy Policy* 2015, **81:** 215-225.

19. van der Werf E. Production functions for climate policy modeling: An empirical analysis. *Energy Economics* 2008, **30**(6)**:** 2964-2979.

20. McFadden D. Econometric models of probabilistic choice. *Structural analysis of discrete data with econometric applications* 1981, **198272**.

21. Brenkert AL, Smith SJ, Kim SH, Pitcher HM. Model Documentation for the MiniCAM. PNNL; 2003.

22. de Vries BJM, van Vuuren DP, den Elzen MGJ, Janssen MA. The Targets IMage Energy Regional (TIMER) model Technical Documentation. Department of International Environmental Assessment
National Institute of Public Health and the Environment (RIVM); 2001.

23. Clarke JF, Edmonds JA. Modelling energy technologies in a competitive market. *Energy Economics* 1993, **15**(2)**:** 123-129.

24. Nganou J-P. Estimation of the parameters of a linear expenditure system (LES) demand; 2005.

25. Bruinsma J. The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050?, Expert meeting on how to feed the world in 2050; 2010.