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SUPPLEMENTARY INFORMATION

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Keywords: coal exit, coal phase-out, sustainable development, co-benefits, life cycle assessment

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SI-1 Supporting Information

SI-1.1. Methods

Figure SI-1: |**Modelling framework.** Modelling framework of the cause effect chain of energy-economy-climate to monetized health and environmental impacts. The Integrated Assessment Energy-Economy Climate model REMIND is the starting point of the modelling chain. The policy cost are directly calculated from REMIND through climate policy induced consumption losses relative to the no policy Reference scenario. The right path represents the specific air pollution human health model chain, including the simplified Chemical Transport model and spatial population, urbanization and demography data. The middle path illustrates the Life Cycle Assessment model which covers non-air pollution human health impacts and ecosystem damages.

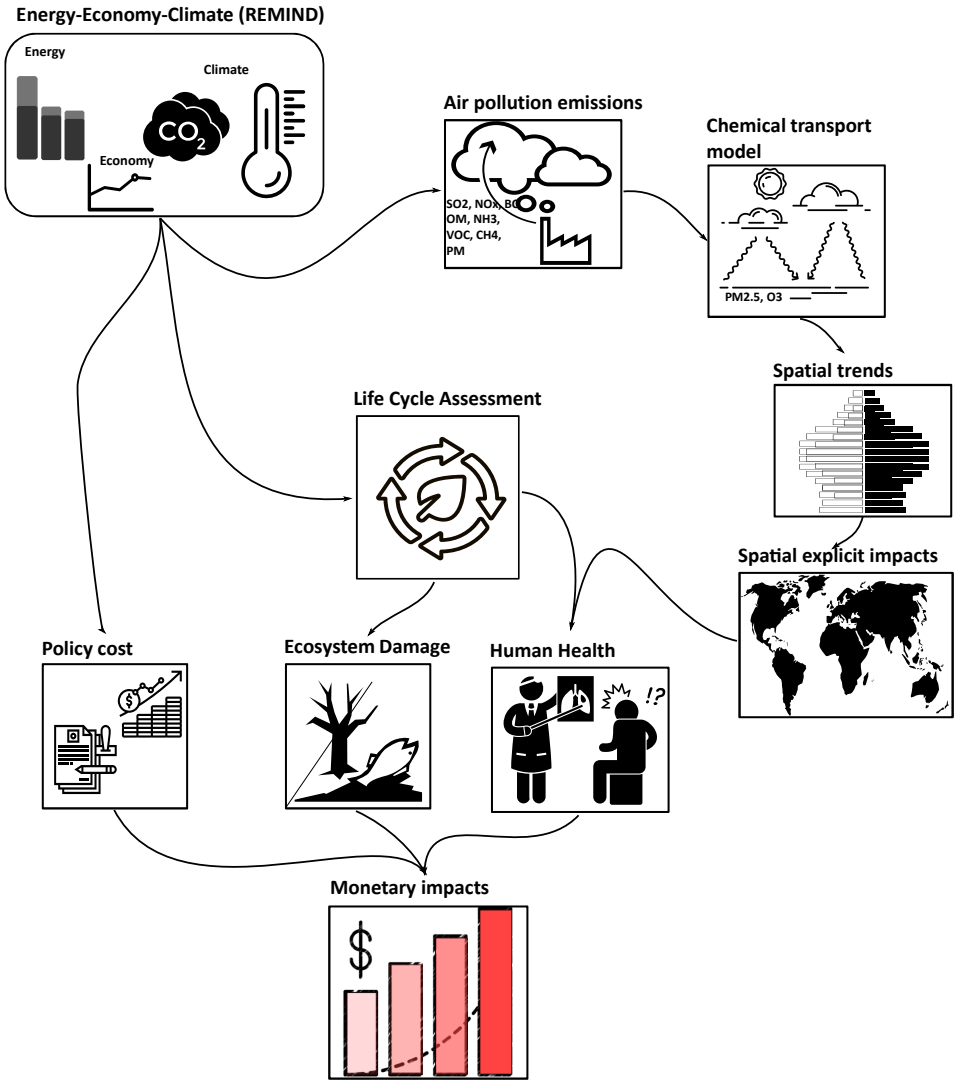
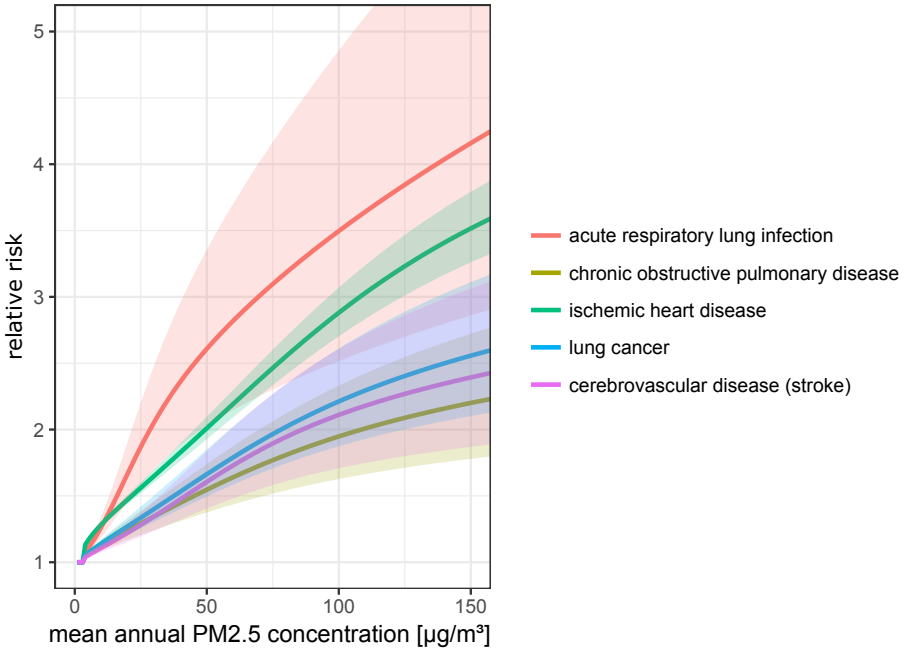


Table SI-1: |**Value transfer coefficients.** Value transfer coefficients of the Reference case for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) in 2015, 2020, 2030, 2040 and 2050. They are applied to the base value of human health 118421.1 US$ per VDALY and the ecosystem damages of 111,486,487.2 US$ per species.yr.

region	2015	2020	2030	2040	2050
LAM	0.500152	0.386202	0.513897	0.666233	0.858463
OAS	0.289746	0.343485	0.452139	0.580002	0.73834
AFR	0.104607	0.108863	0.155965	0.221625	0.320949
EUR	0.954087	1.025294	1.212767	1.429472	1.654259
ROW	1.084928	0.814886	0.962879	1.137768	1.333285
MEA	0.519368	0.575502	0.746901	0.925411	1.109441
CHN	1.275278	1.422803	1.669215	1.891424	2.090629
IND	0.106028	0.132382	0.230956	0.360532	0.527048
JPN	1.169837	1.216918	1.354231	1.474302	1.606203
USA	1.545993	1.652051	1.840732	1.976144	2.083858
RUS	0.55785	0.688134	1.015309	1.352588	1.6276

Figure SI-2: |**Global Exposure Mortality Model@Burnett2018.** Integrated exposure response functions describing the relationship between annual mean ambient $PM_{2.5}$ and relative risk of the five disease endpoints considered. Shading indicate the uncertainty ranges around the employed medium estimate.



SI-1.2. Energy-Economy-Climate Modeling

Table SI-2: |**Levelized cost of electricity (LCOE).** Global average generation LCOE in $/MWh for selected technologies of a new power plant build in the time step. LCOEs do not include a CO_2 price and other taxes but storage cost associated with renewable energy penetration.

Scenario	Power generation technology	2015	2030	2050
Reference	Coal|Pulverized Coal|w/o CCS	63.81	69.15	77.85
NDC	Coal|Pulverized Coal|w/o CCS	63.81	68.72	74.88
Coal exit	Coal|Pulverized Coal|w/o CCS	61.85	60.91	60.49
2°C	Coal|Pulverized Coal|w/o CCS	63.81	66.24	88.08
Reference	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	61.80	70.72
NDC	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	63.18	72.12
Coal exit	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	66.20	74.52
2°C	Gas|Natural Gas Combined Cycle|w/o CCS	53.99	64.88	73.63
Reference	Solar|PV	76.89	43.36	35.83
NDC	Solar|PV	76.89	41.74	35.69
Coal exit	Solar|PV	77.02	41.47	35.87
2°C	Solar|PV	76.89	41.77	36.36
Reference	Wind	64.58	56.93	54.82
NDC	Wind	64.58	56.25	54.66
Coal exit	Wind	64.58	56.05	54.58
2°C	Wind	64.58	54.52	54.13

Figure SI-3: |**Primary energy.** Primary energy mix for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

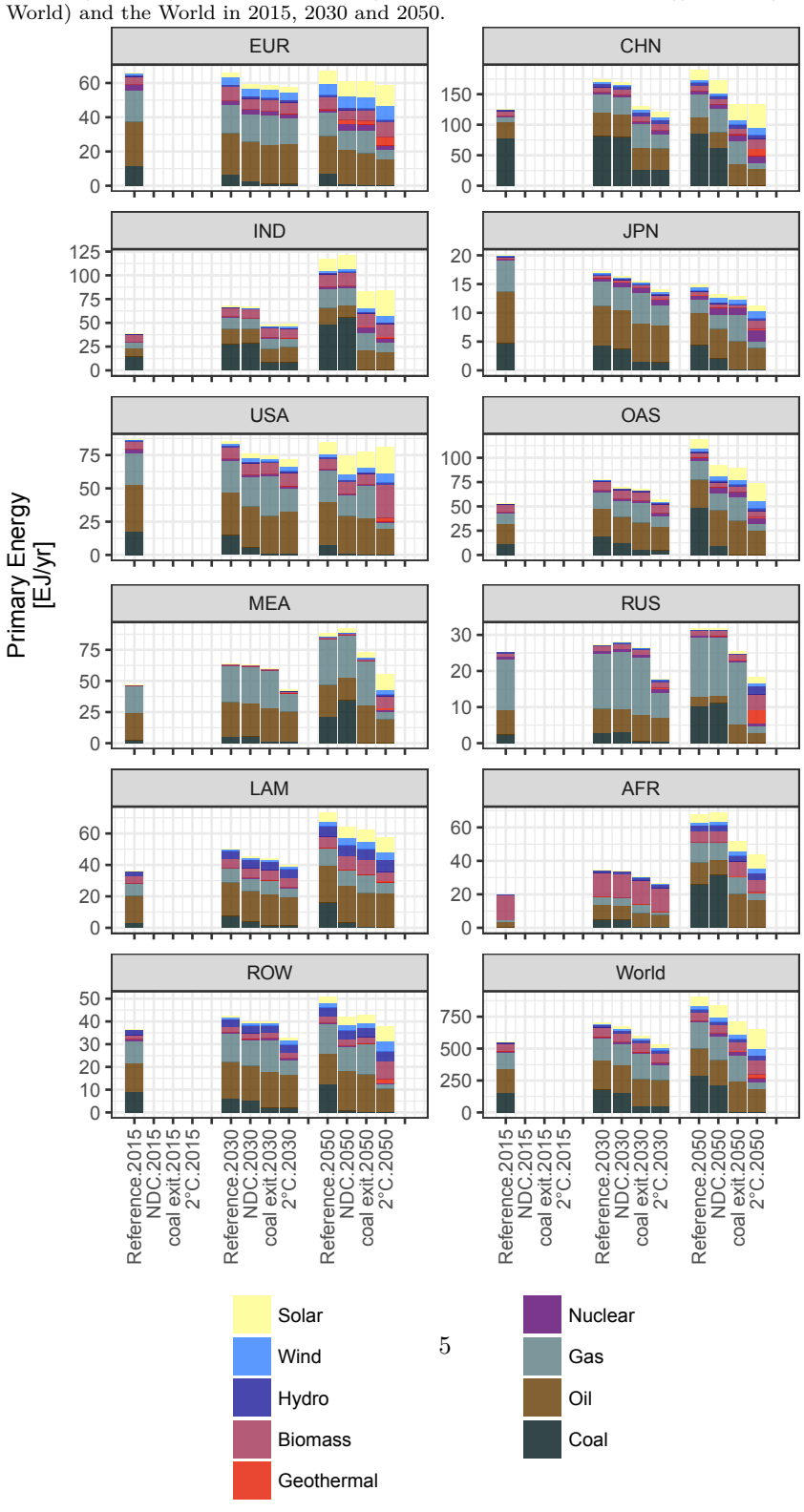


Figure SI-4: |**Secondary energy - electricity.** Secondary energy - electricity mix for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World in 2015, 2030 and 2050.

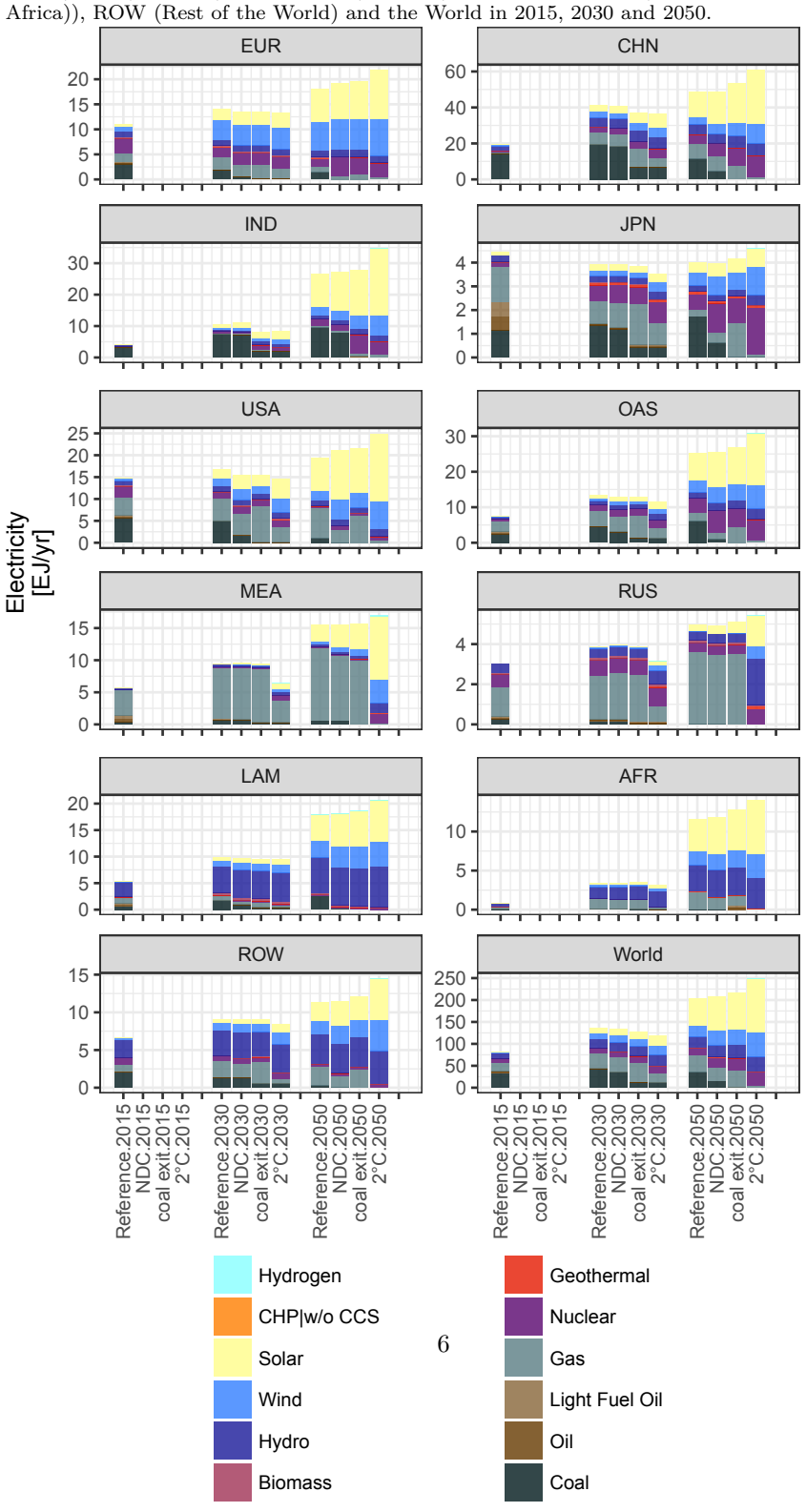


Figure SI-5: |**Carbon dioxide (CO_2) emissions.** CO_2 emissions for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World until 2050. The share of coal related emissions is indicated by the dashed line.

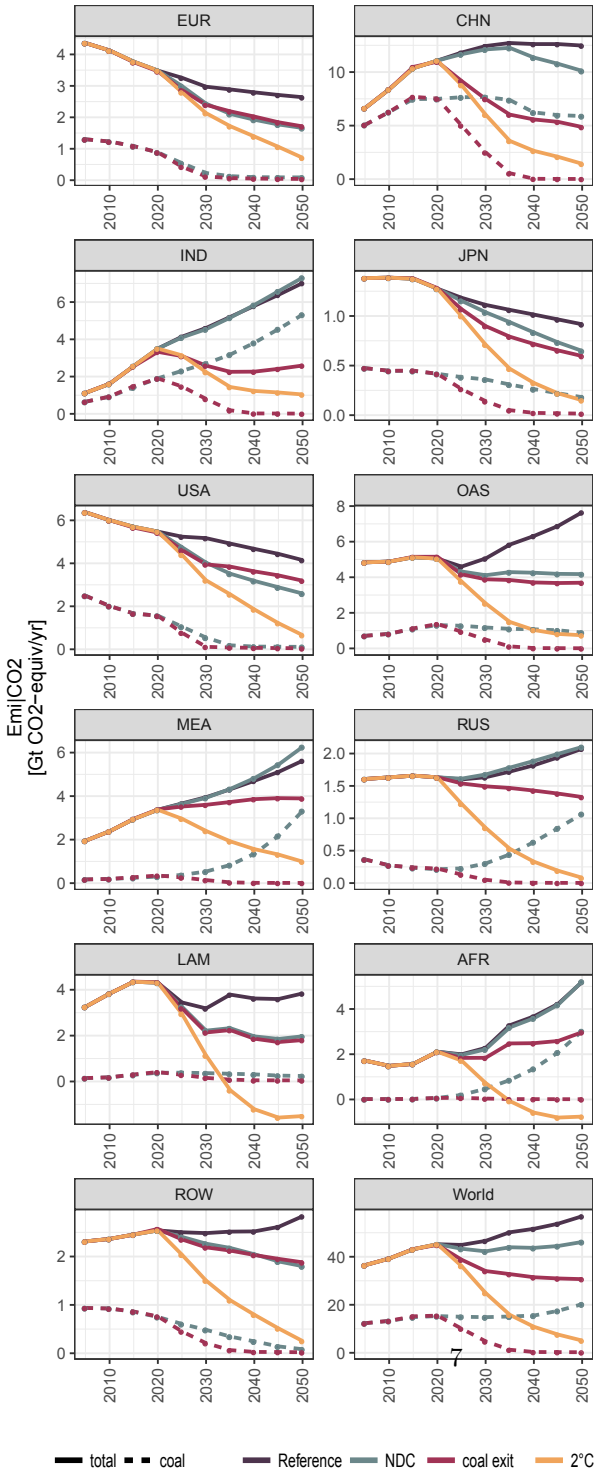


Figure SI-6: |**Carbon dioxide (CO_2) prices.** CO_2 prices for the Reference, NDC, 2°C and coal exit scenario for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World until 2050.

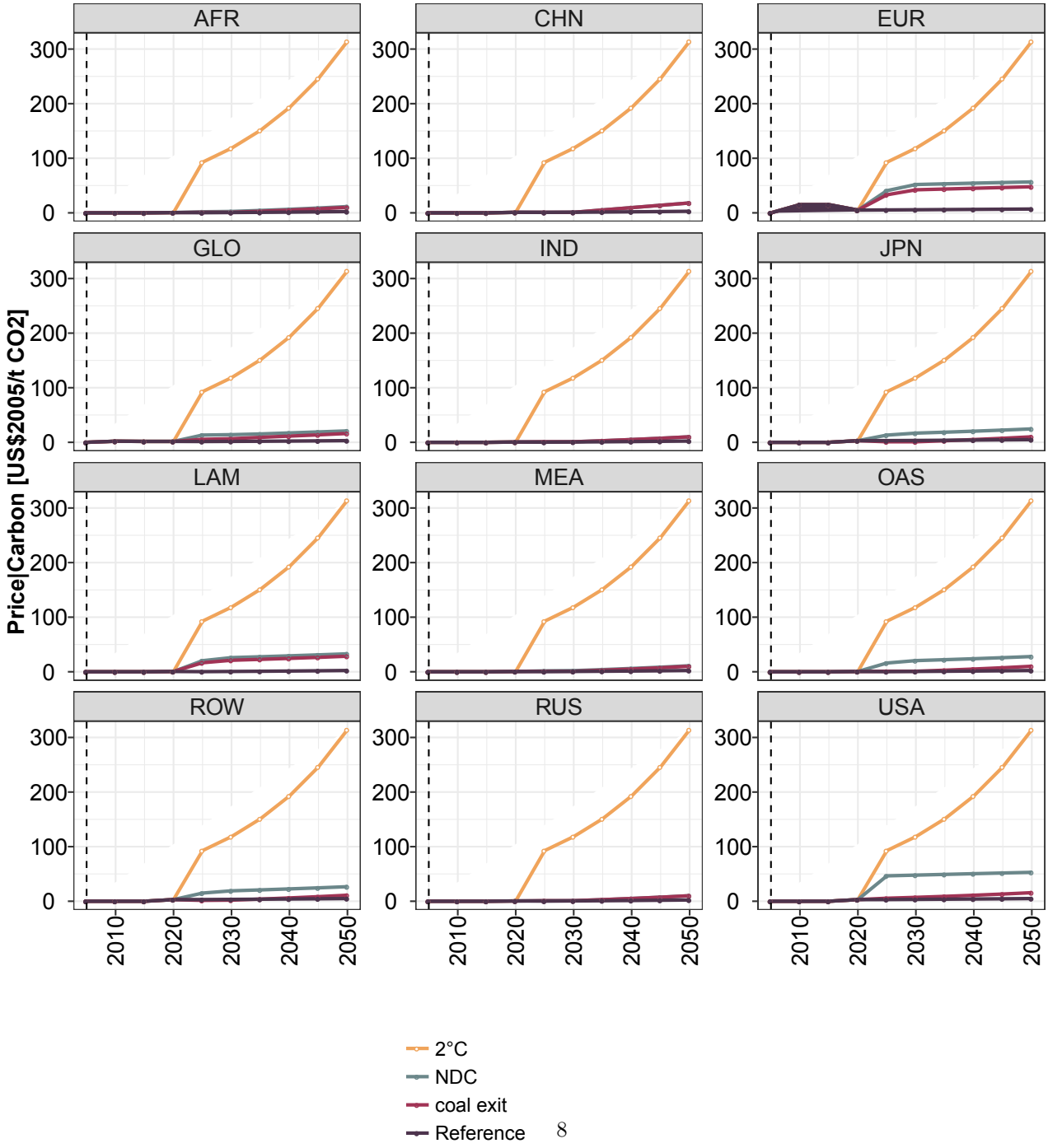
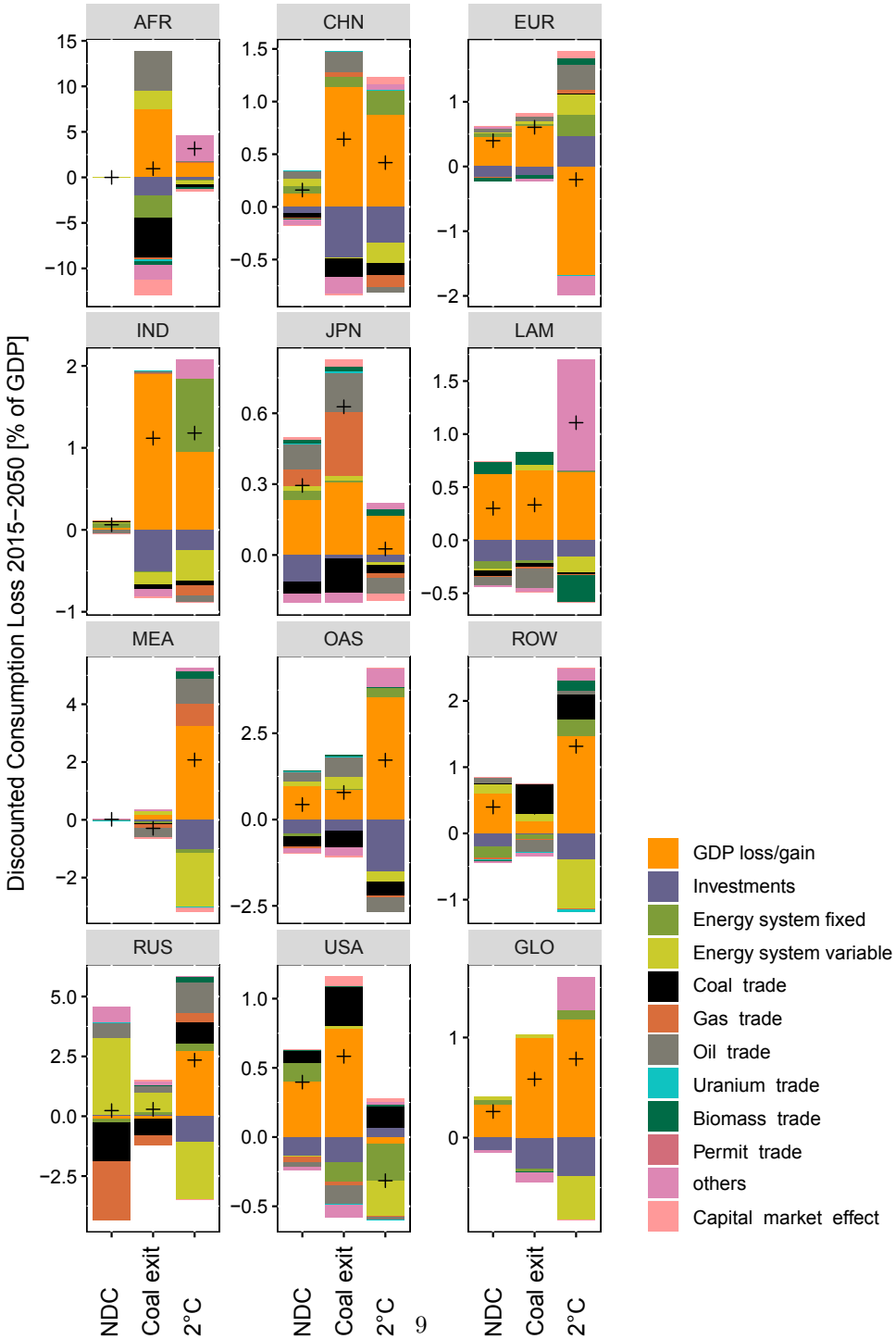


Figure SI-7: |**Decomposition of mitigation cost.** Decomposition of regional mitigation cost until 2050 for the NDC, 2°C and coal exit scenario compared to the Reference case relative to GDP PPP discounted with a rate of 5%.



GDP loss and energy system related investment cost dominate the mitigation cost in the coal exit and 2 °C scenario for India, China and globally. Global cost savings are mostly comprised of lower non-energy investment cost and additionally less variable cost of the energy system in the 2 °C scenario. The impact of exiting coal on consumption is most prominent in coal exporting regions such as the USA and ROW (including Australia) through lower revenues and higher cost for alternative fuel for coal importing regions such as Japan and China.

SI-1.3. Air pollution

We find that exiting coal leads to similar air pollution health impact reductions as the 2°C scenario. The substitution of coal with gas and oil leads to slightly higher emission; however, emission factors for gas decrease substantially in the long term and biomass related air pollution emissions are higher in the 2°C scenario.

Phasing out coal leads to substitution effects, especially gas substitute coal in the power sector and oil, gas and biomass in the industry and buildings sector. However, there are effects that further lower air pollution emissions: India, for example is a fast growing economy that is expected to double its GDP in the next 15 years while continuing the trend of a growing population. This results in a tripling of transport demand from until 2040, which is the major emitter of NOx. In this context, the coal exit significantly increases the oil price compared to the 2°C scenario (22% in 2030), which has a twofold effect leading to lower air pollution emission: 1) The higher price for liquids based final energy reduces the transport demand (37% in 2030) and 2) leads to a substitution of oil with electricity based mobility (65% higher rate of electrification).

Figure SI-8: |**Air pollution concentration.** Global mean annual $PM_{2.5}$ concentration [$\mu g/m^3$] for the year 2015 and 2050 of the NDC, 2°C and coal exit scenario. Bars represent the population living under concentrations of >50 $\mu g/m3$ (red), 50>x>35 $\mu g/m3$ (orange), 35>x>20 $\mu g/m3$ (light orange), 20>x>10 $\mu g/m3$ (yellow) and <10 $\mu g/m3$ (green)

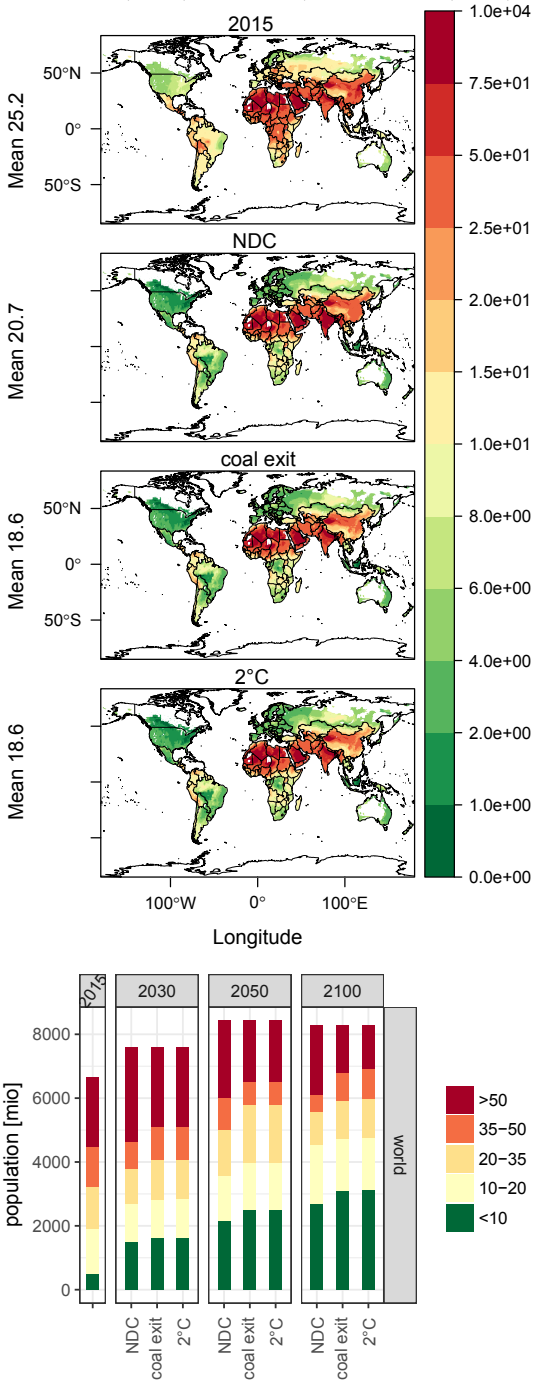
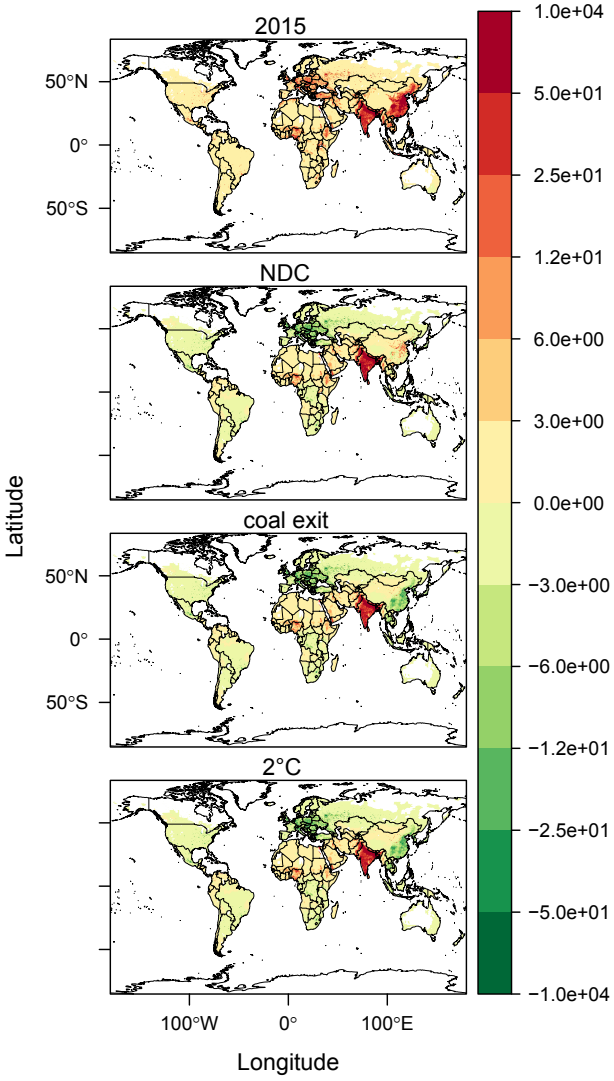


Figure SI-9: |**Air pollution health impact.** Global health impact of $PM_{2.5}$ and O_3 in terms of annual premature deaths $[cases/km^2]$ for the year 2015 and relative to 2015 for the year 2050 of the NDC, 2°C and coal exit scenario. Markers represent values for stringent ($\otimes$) and fixed emission factor ($+$) sensitivity cases, see Rauner, S. et al. Air Quality Co-benefits of Ratcheting-up the NDCs. Climatic Change (in review) for a description of sensitivity cases.



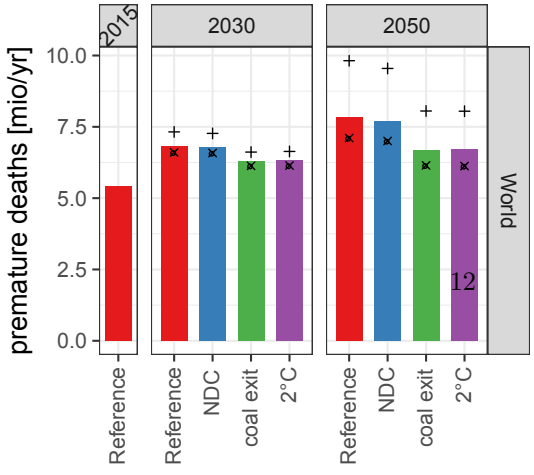


Figure SI-10: |**Air pollution impact on Secondary Energy level [DALY].** Air pollution impact on Secondary Energy level for the NDC, Coal exit and 2°C scenario relative to the Reference until 2050.

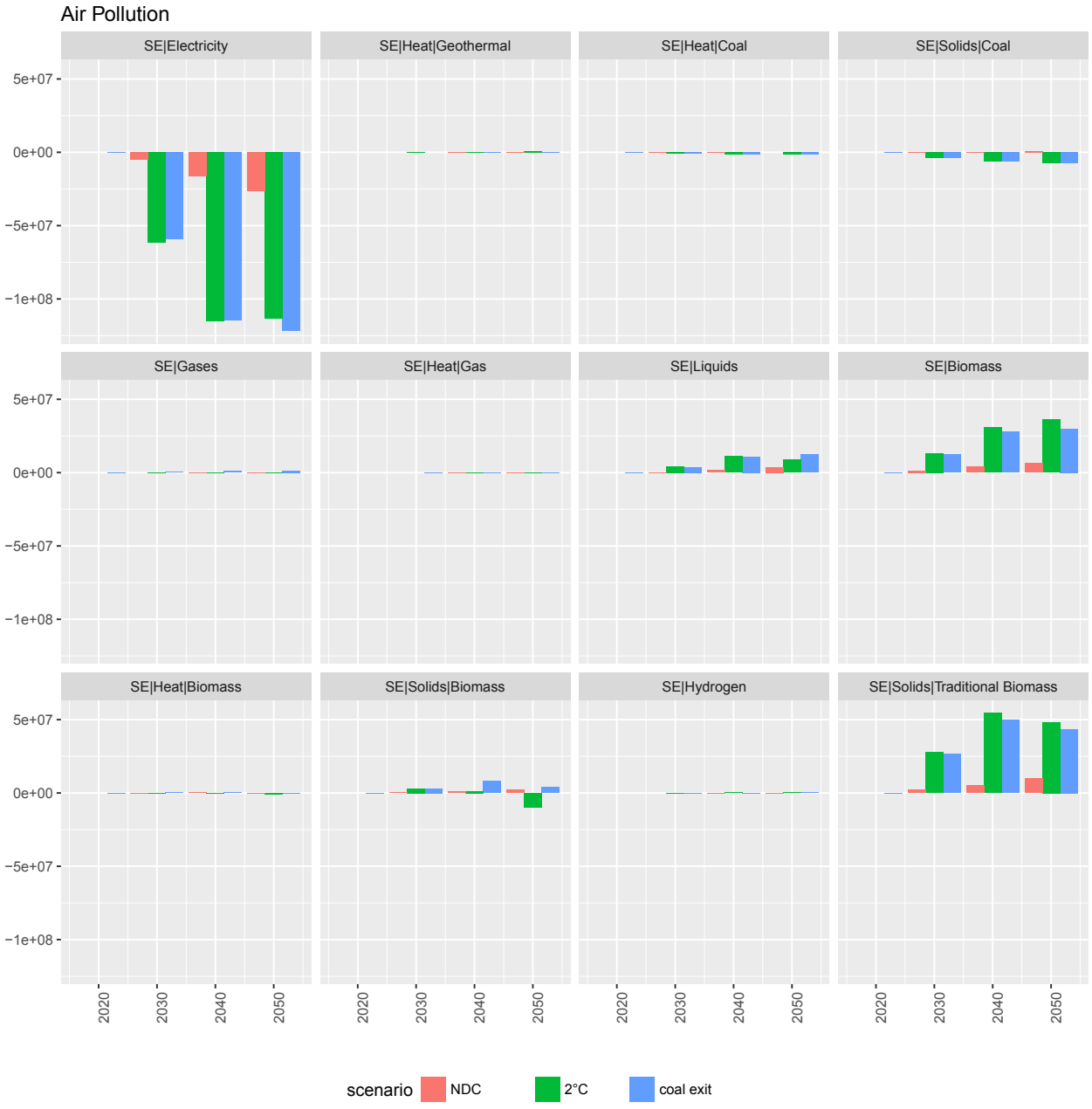


Figure SI-11: |**Regional Air pollution impact [DALY/capita].** Regional Air pollution impact for the Reference, NDC, Coal exit and 2°C scenario until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

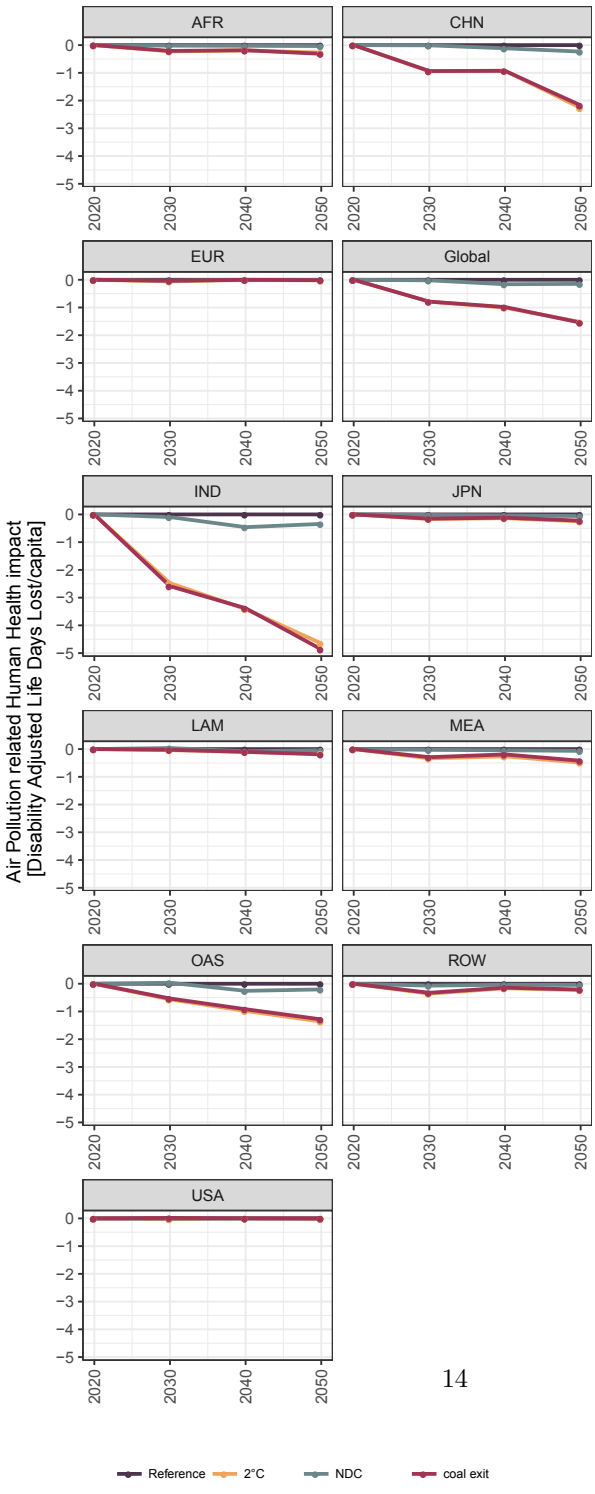


Figure SI-12: |**Total global absolute impacts.** Total global absolute impacts for the NDC, Coal exit and 2°C scenario relative to the Reference until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

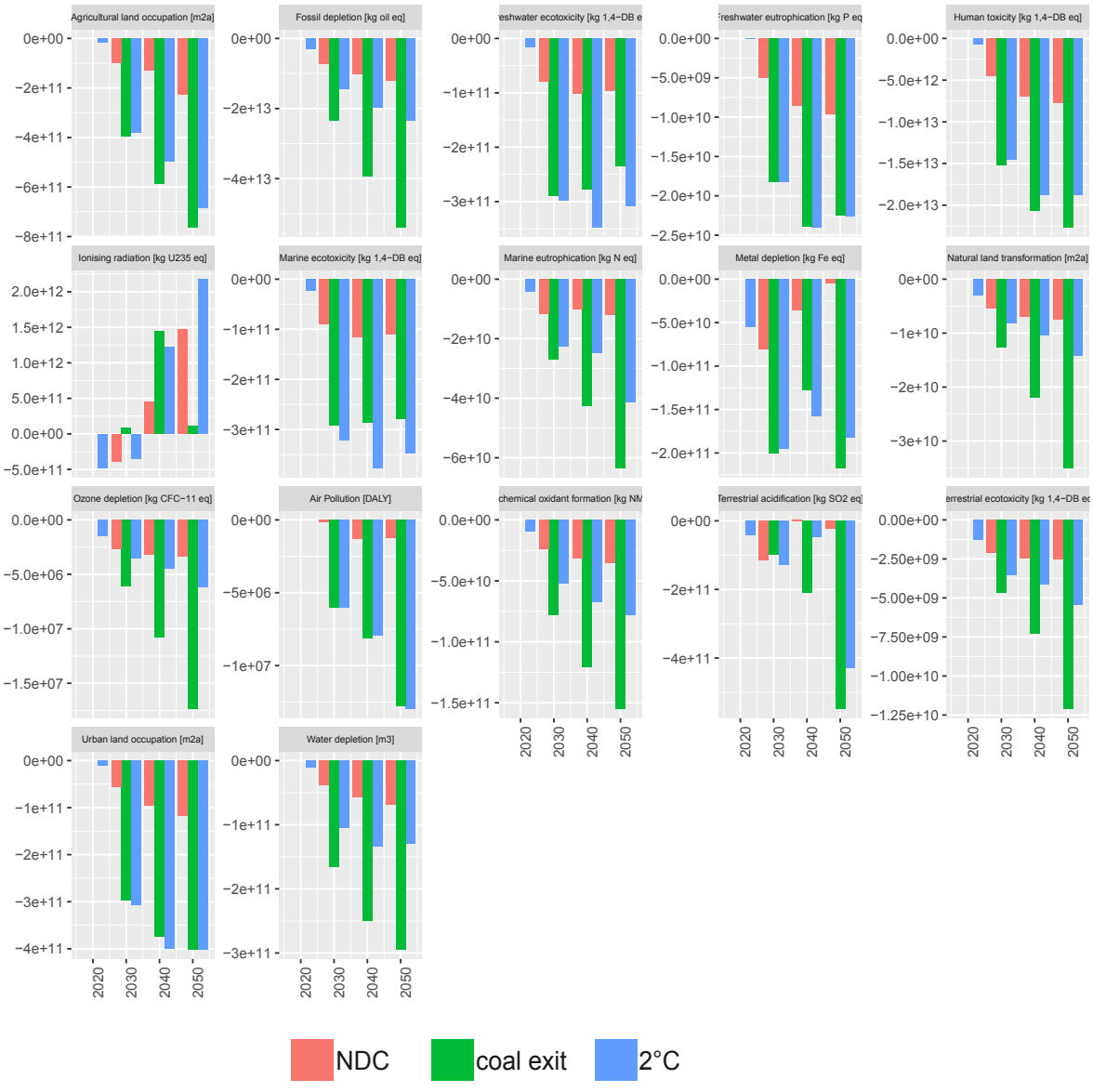


Figure SI-13: |**Global absolute impacts of Secondary Energy - Electricity.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

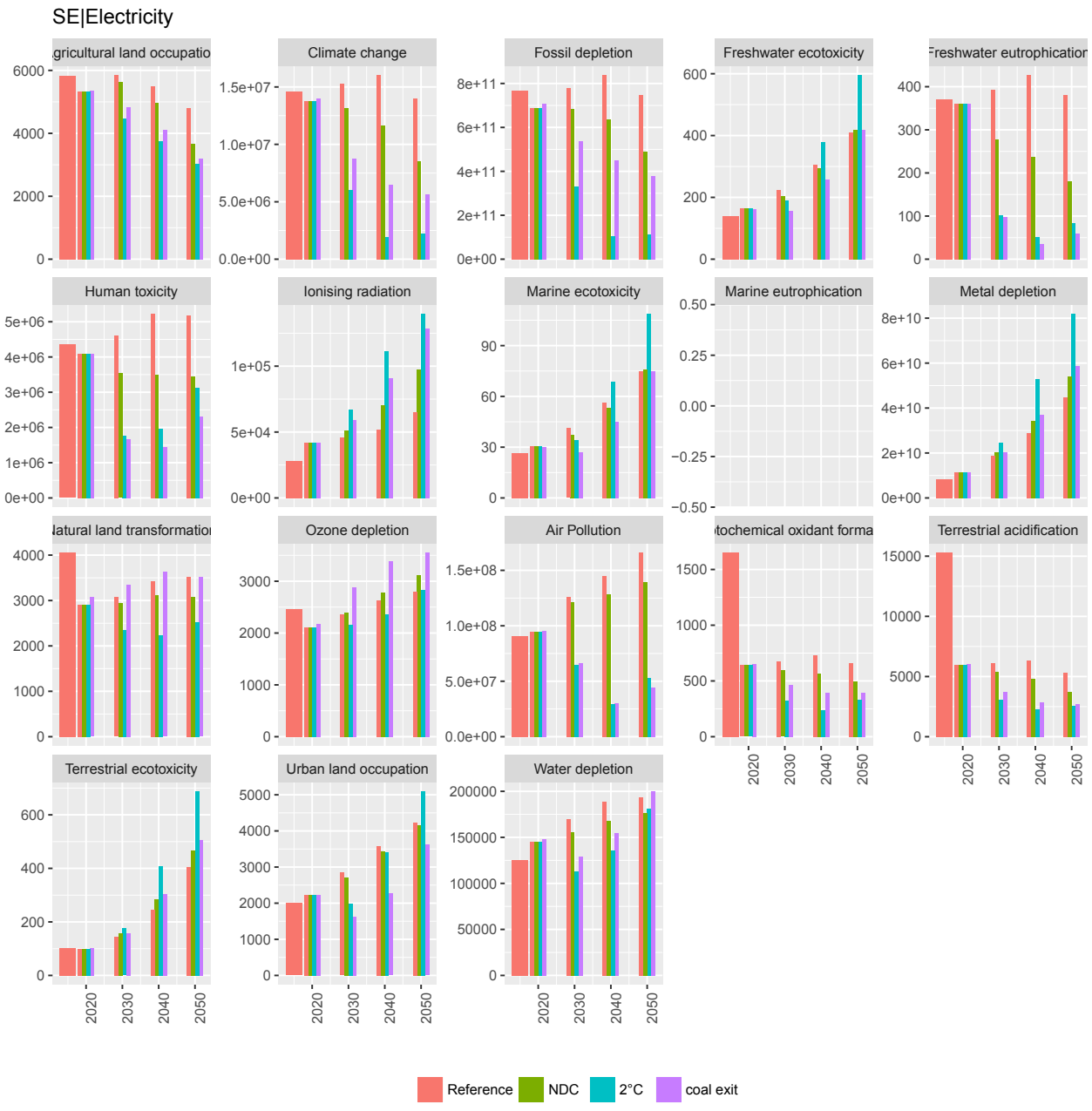


Figure SI-14: **|Global absolute impacts of Secondary Energy - Heat|Geothermal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

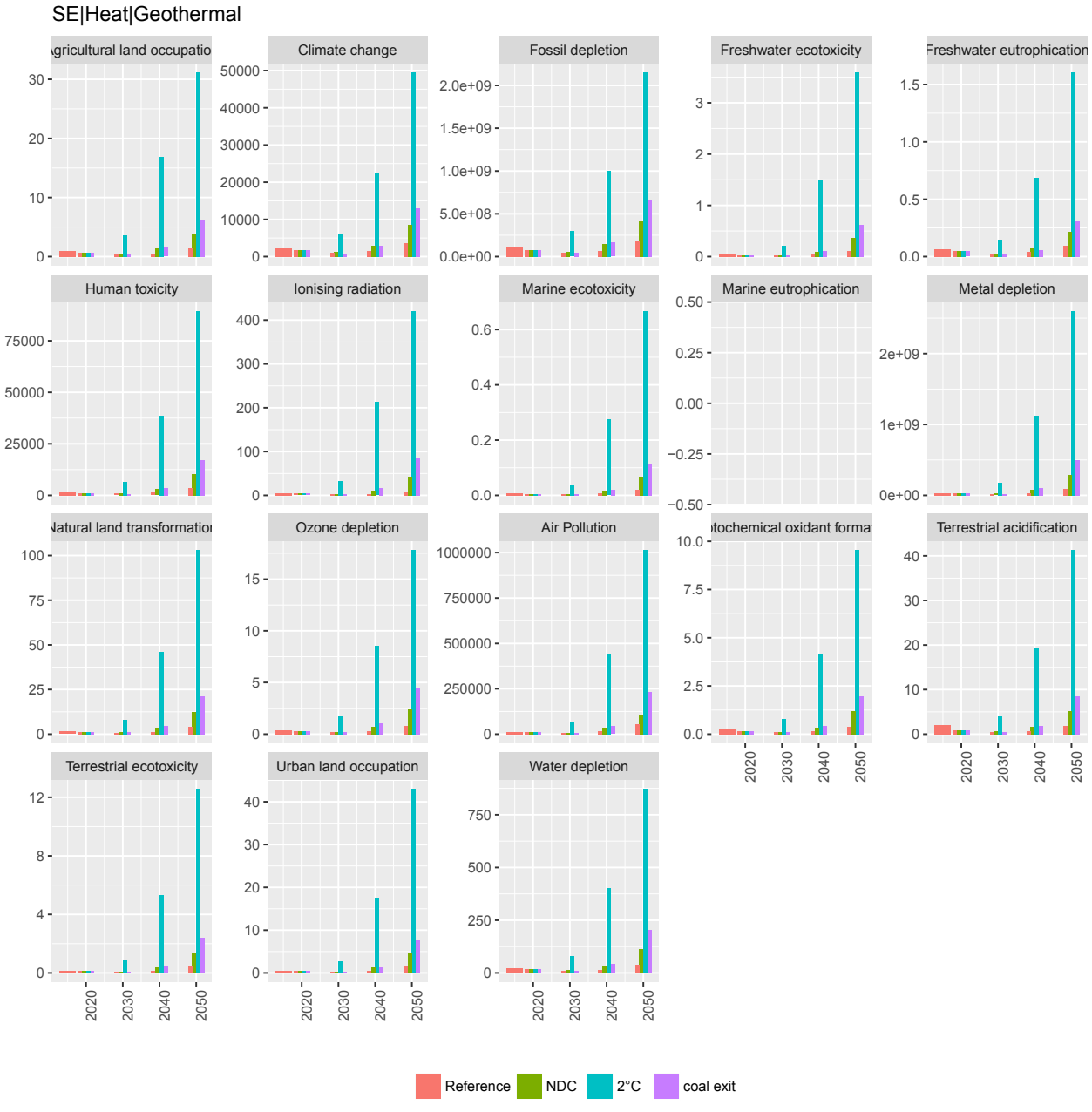


Figure SI-15: **|Global absolute impacts of Secondary Energy - Heat|Coal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

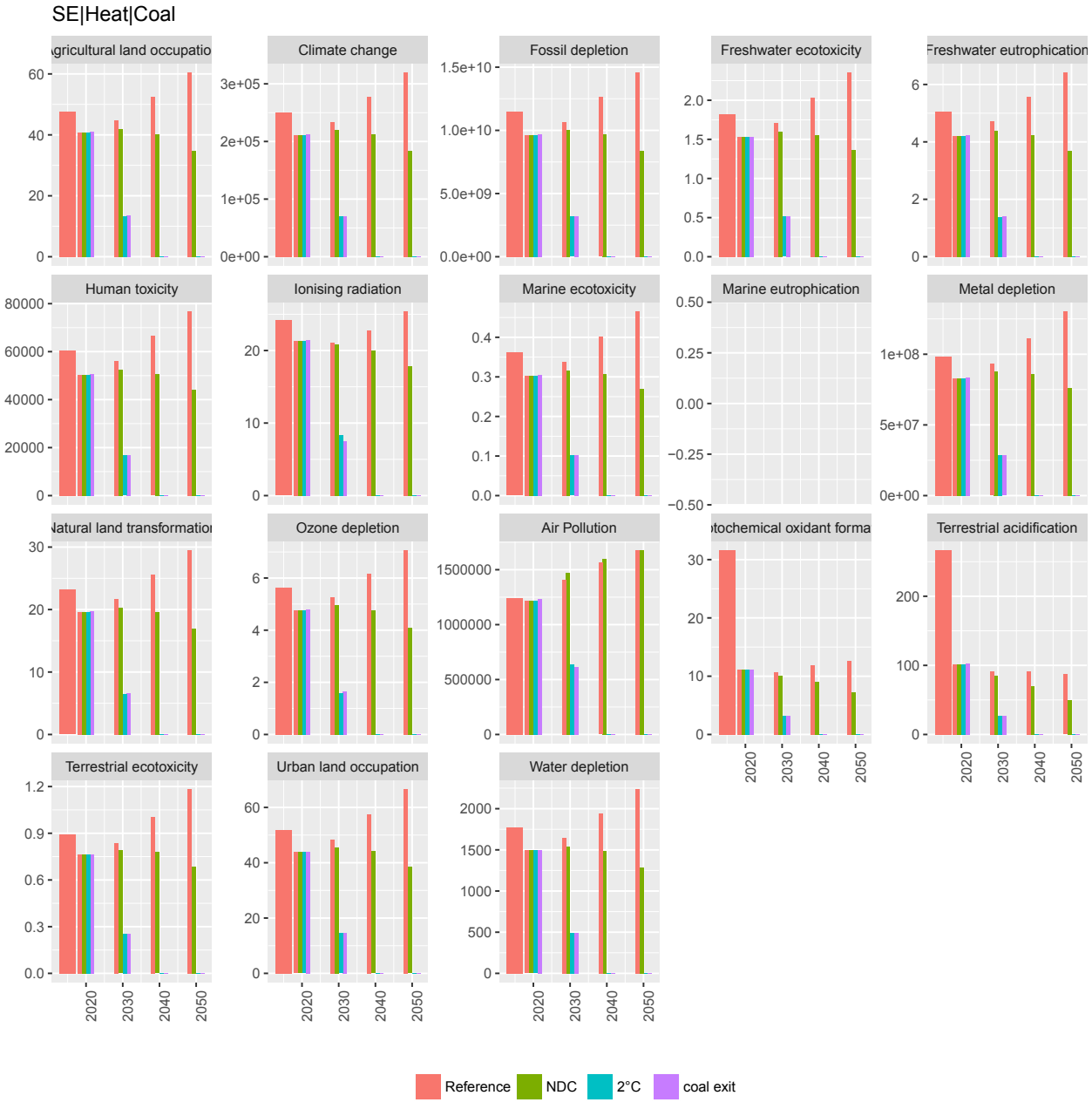


Figure SI-16: **|Global absolute impacts of Secondary Energy - Solids|Coal.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

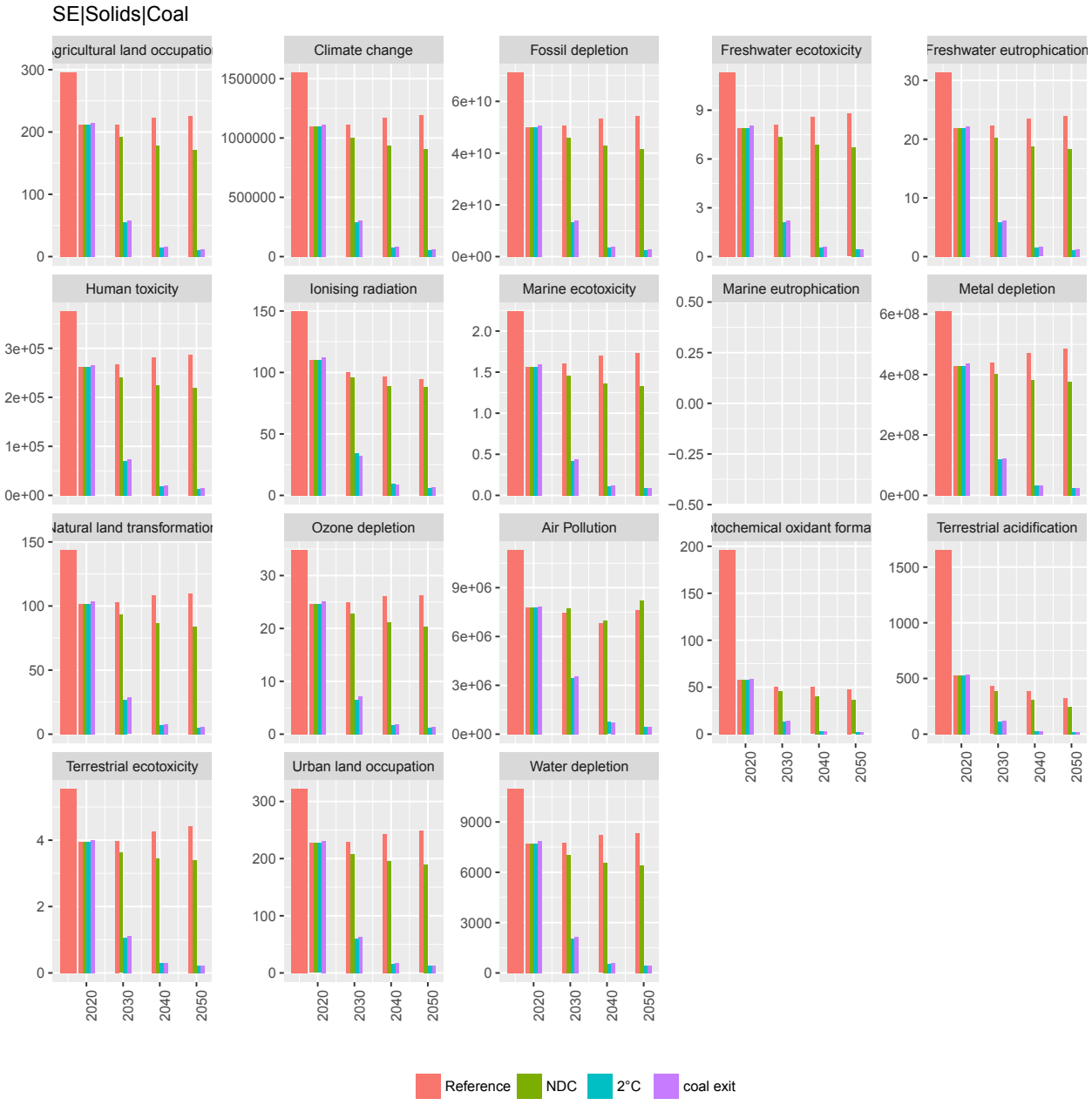


Figure SI-17: **|Global absolute impacts of Secondary Energy - Solids|Gases.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

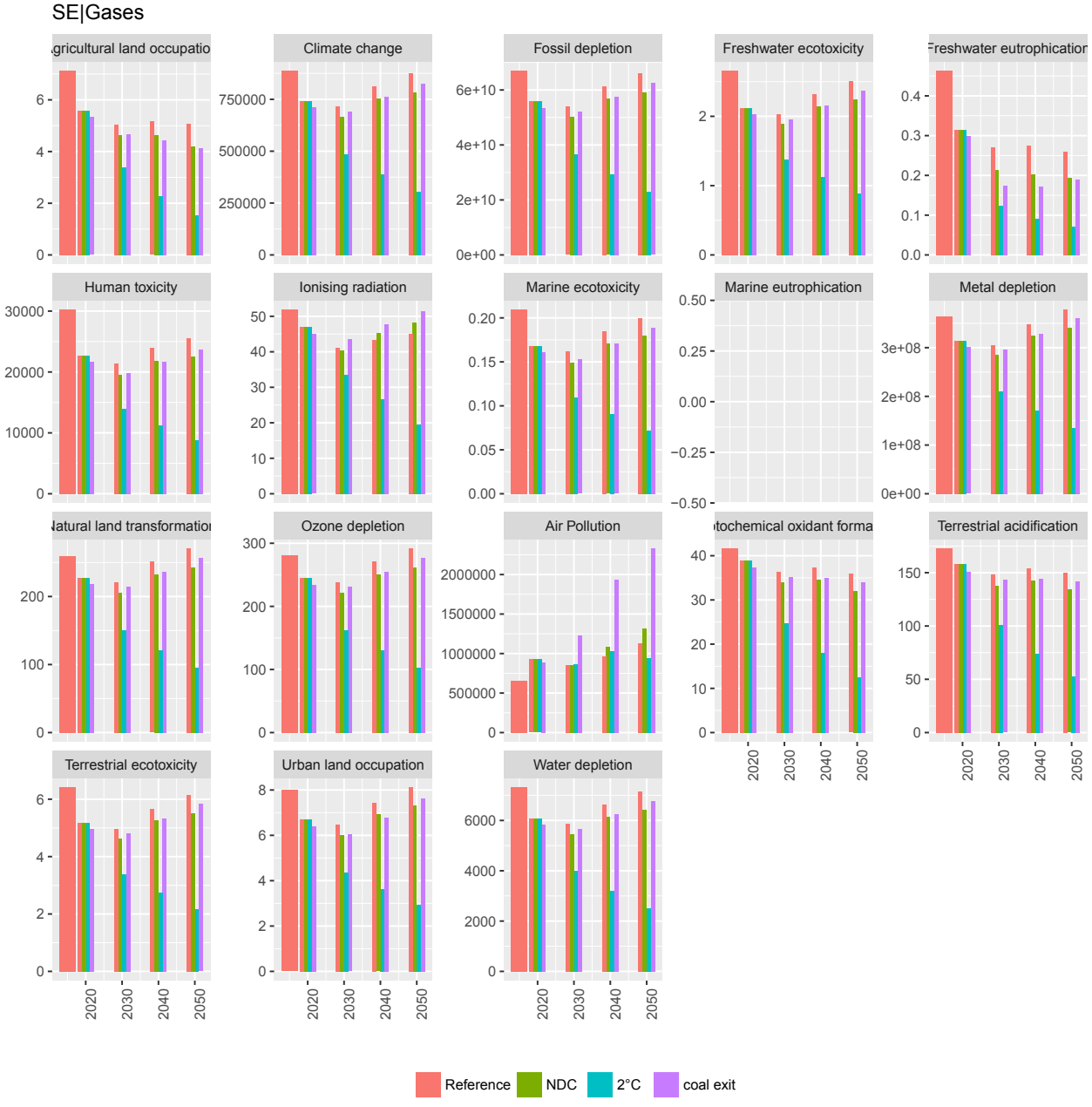


Figure SI-18: **|Global absolute impacts of Secondary Energy - Heat|Gas.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

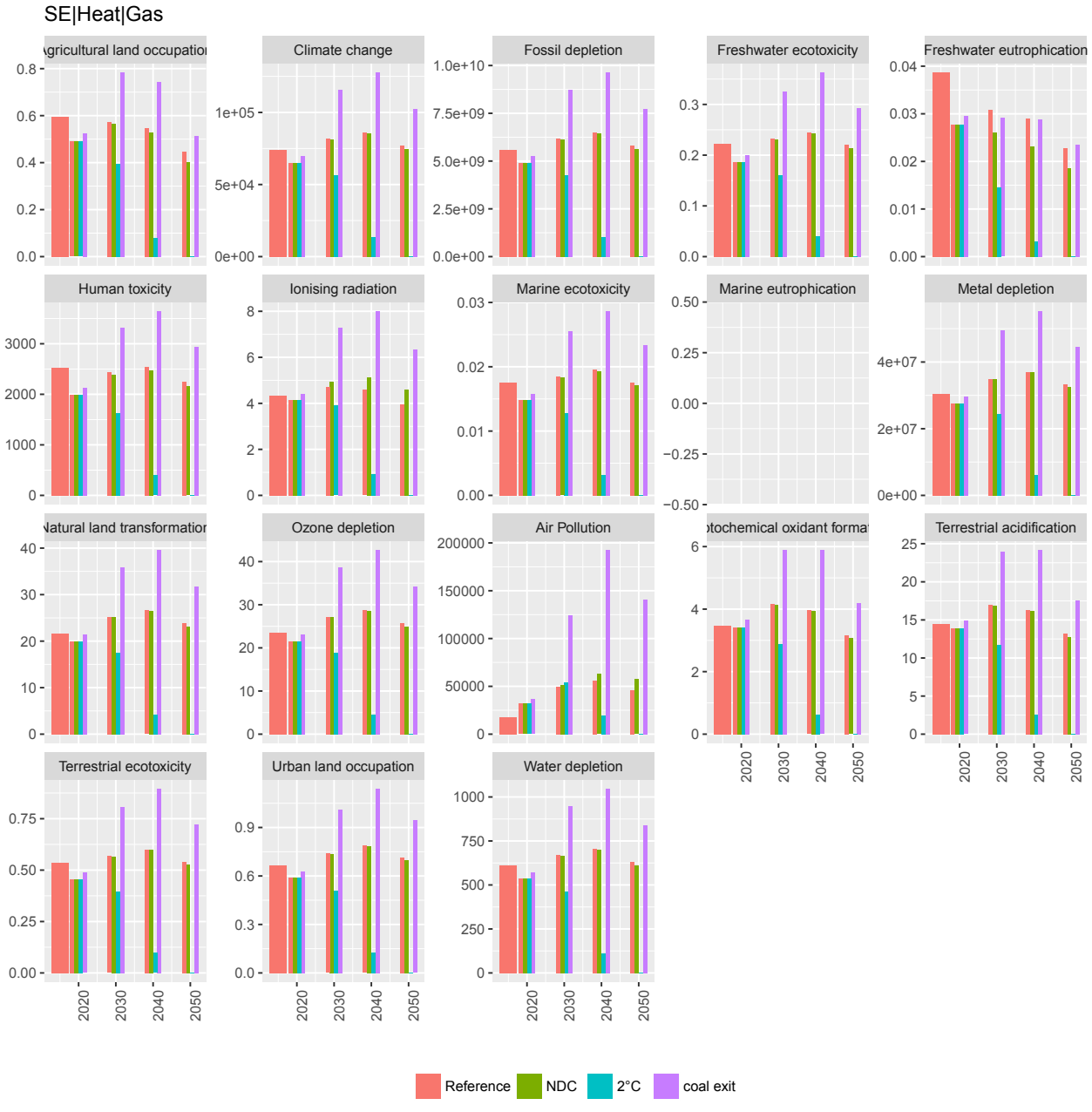


Figure SI-19: |**Global absolute impacts of Secondary Energy - Liquids.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

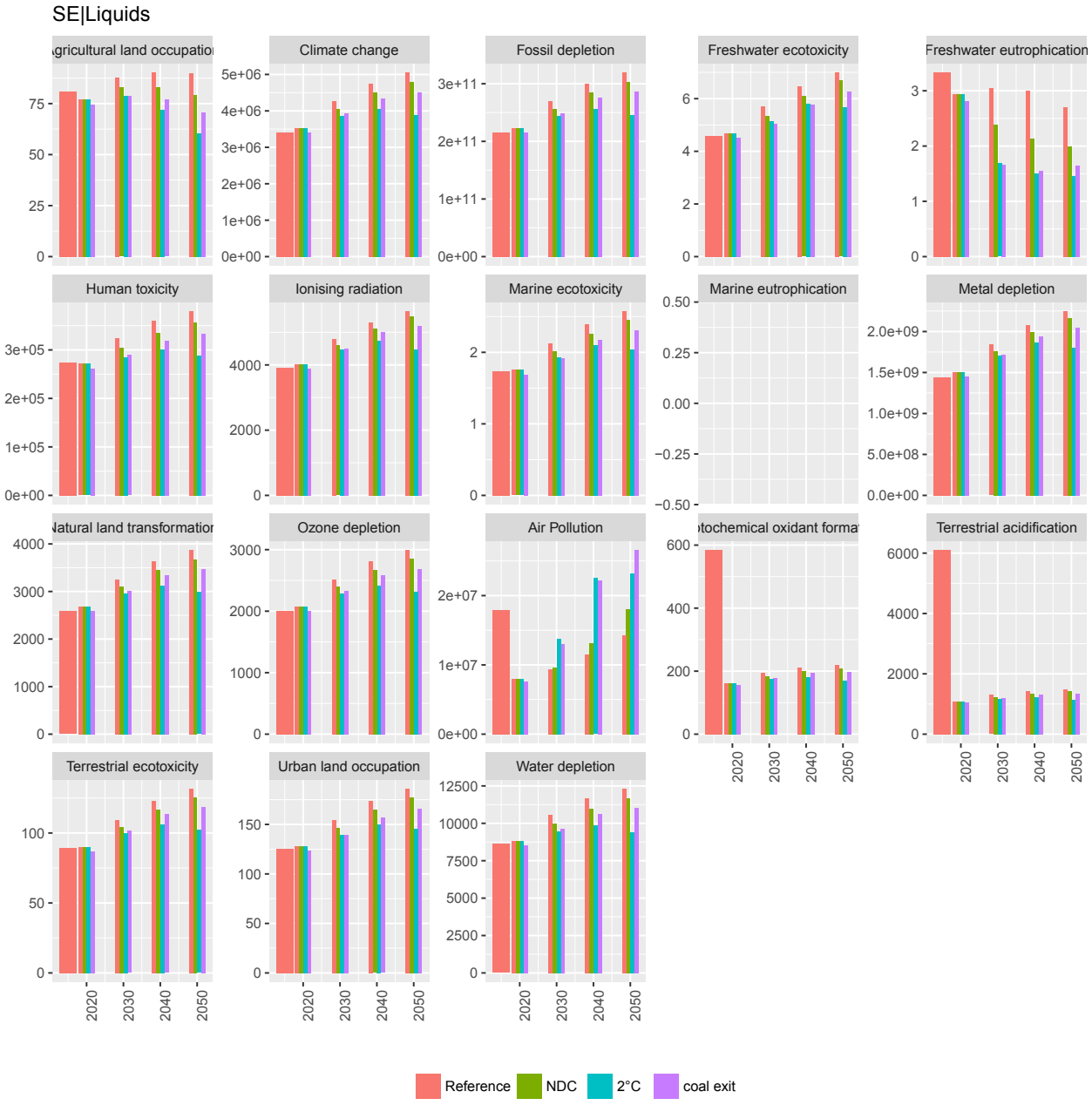


Figure SI-20: **|Global absolute impacts of Secondary Energy - Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

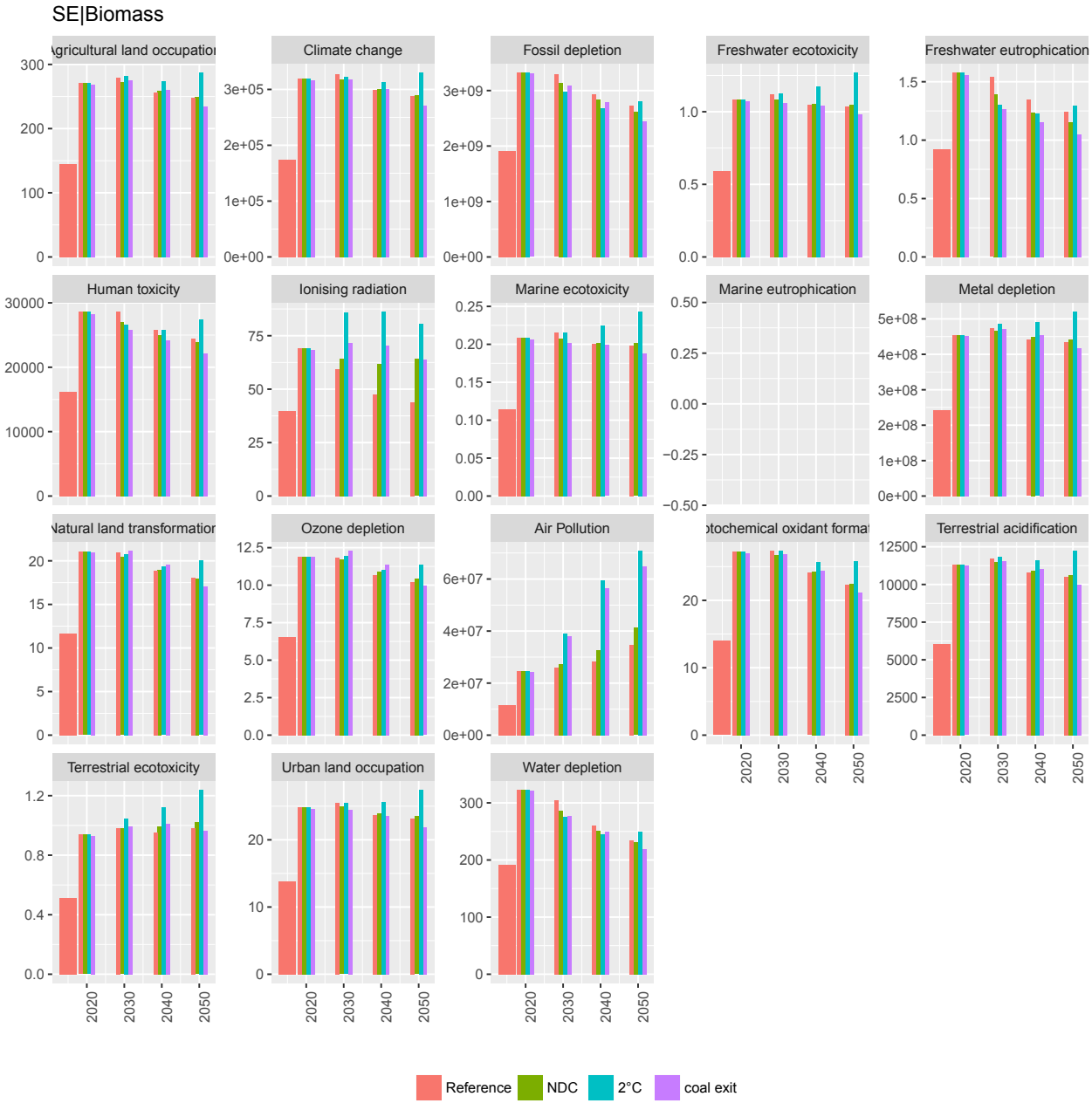


Figure SI-21: **|Global absolute impacts of Secondary Energy - Heat|Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

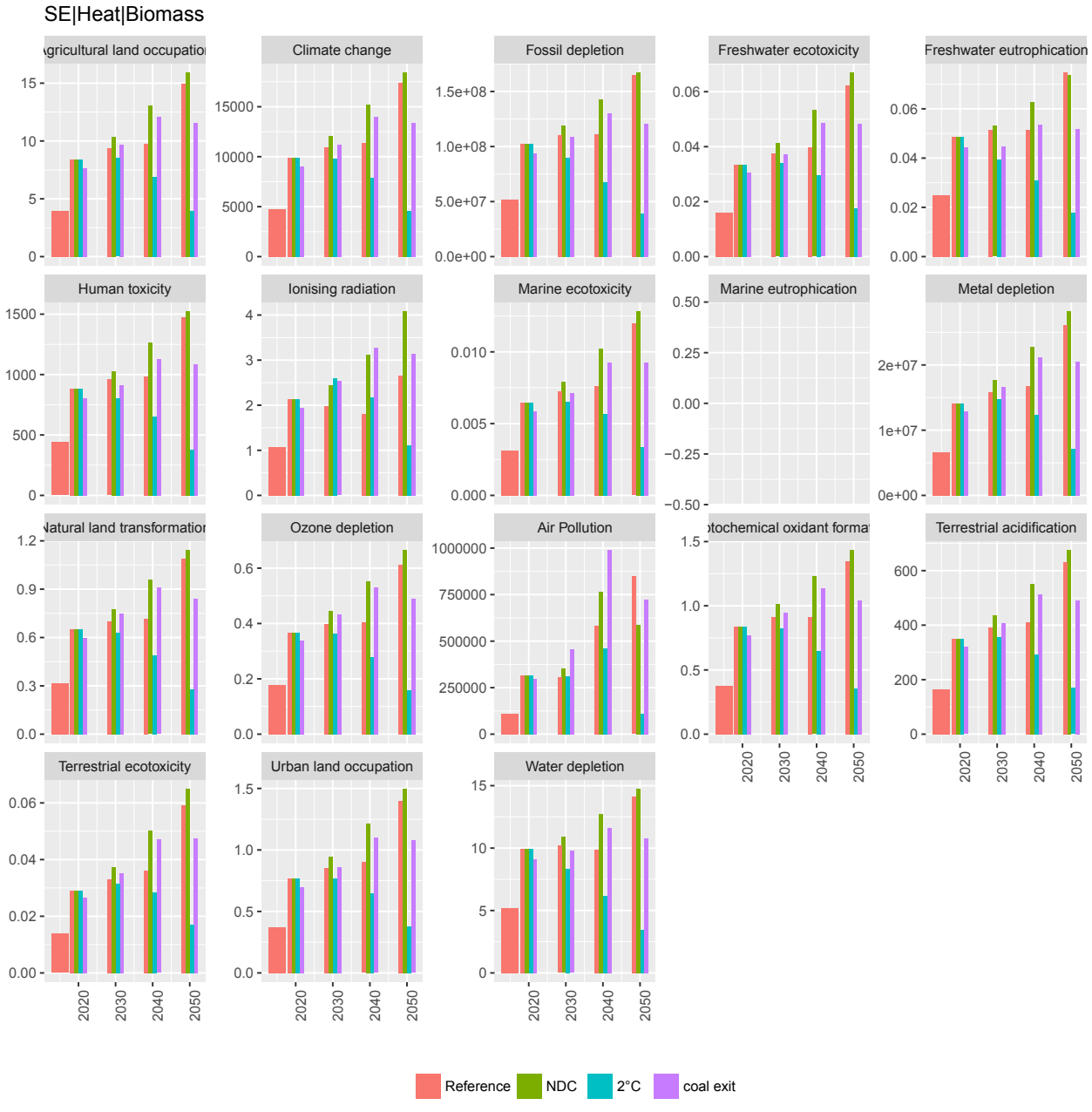


Figure SI-22: |**Global absolute impacts of Secondary Energy - Solids|Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

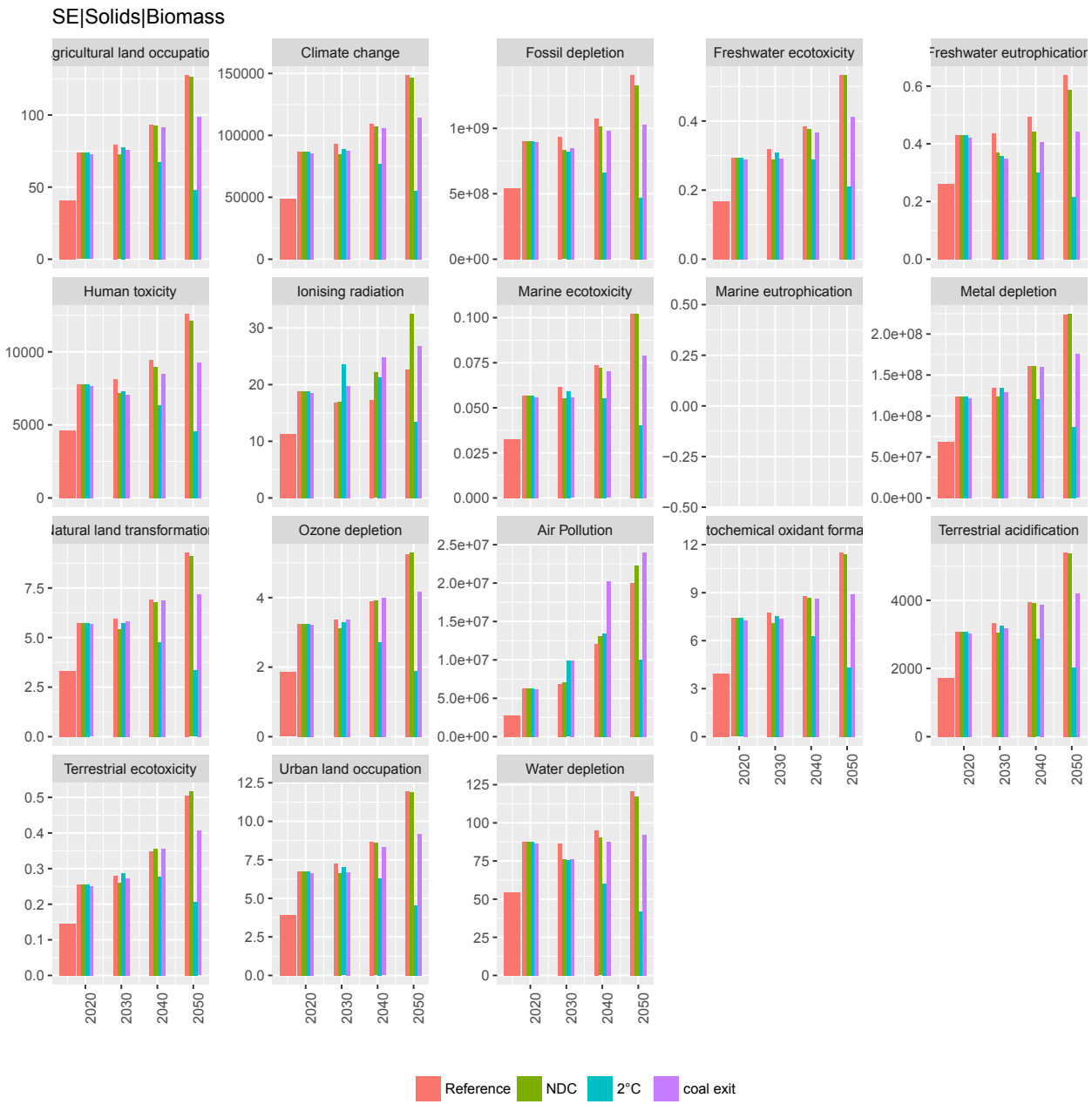


Figure SI-23: |**Global absolute impacts of Secondary Energy - Hydrogen.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

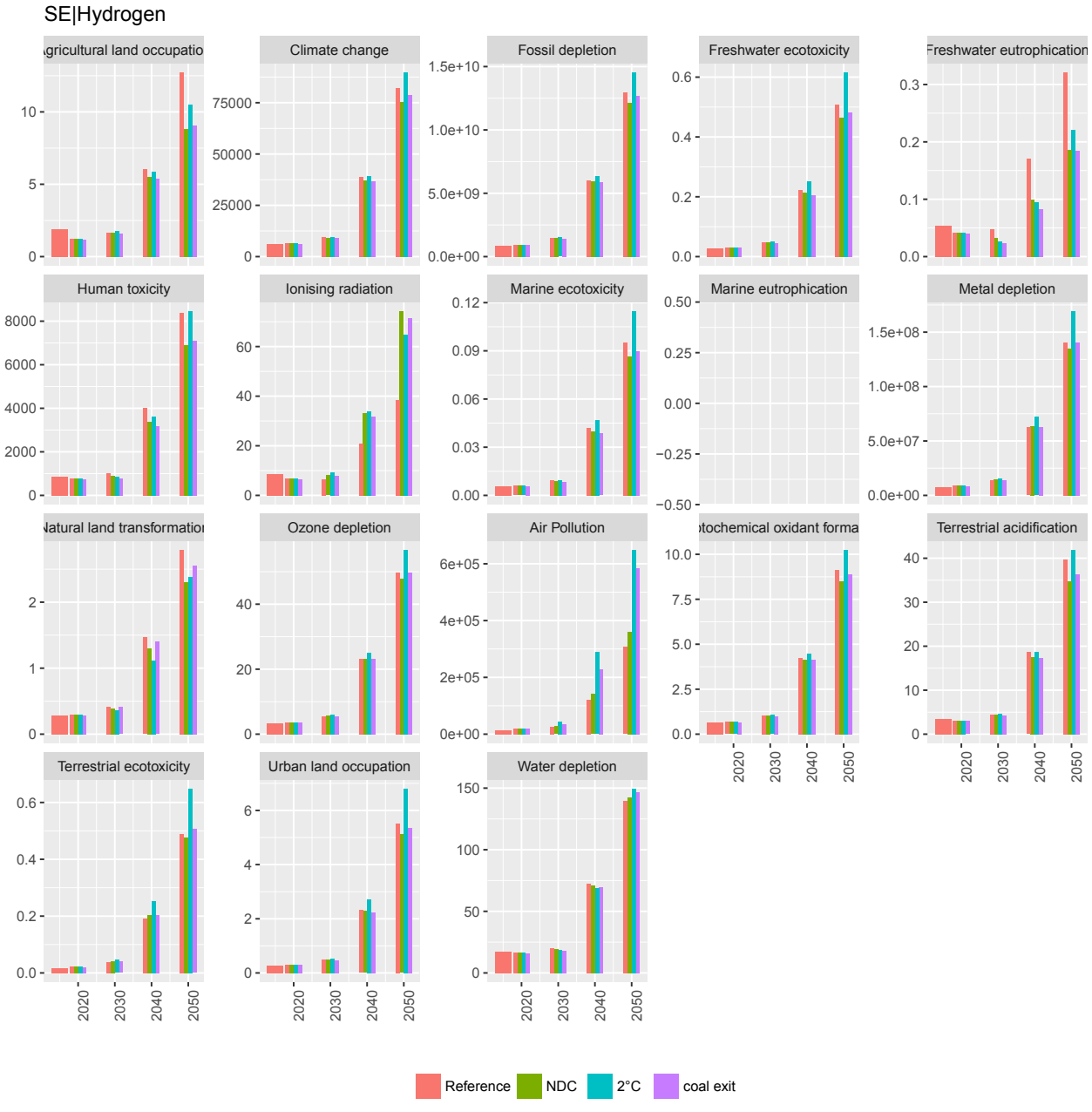


Figure SI-24: **|Global absolute impacts of Secondary Energy - Solids|Traditional Biomass.** Global absolute impacts for the Reference, NDC, Coal exit and 2°C scenario until 2050 of Fossil depletion [kg oil eq], Freshwater ecotoxicity [kg 1,4-DB eq], Freshwater eutrophication [kg P eq], Human toxicity [kg 1,4-DB eq], Ionising radiation [kg U235 eq], Marine ecotoxicity [kg 1,4-DB eq], Marine eutrophication [kg N eq], Air Pollution [DALY], Metal depletion [kg Fe eq], Natural land transformation [m2] and Ozone depletion [kg CFC-11 eq].

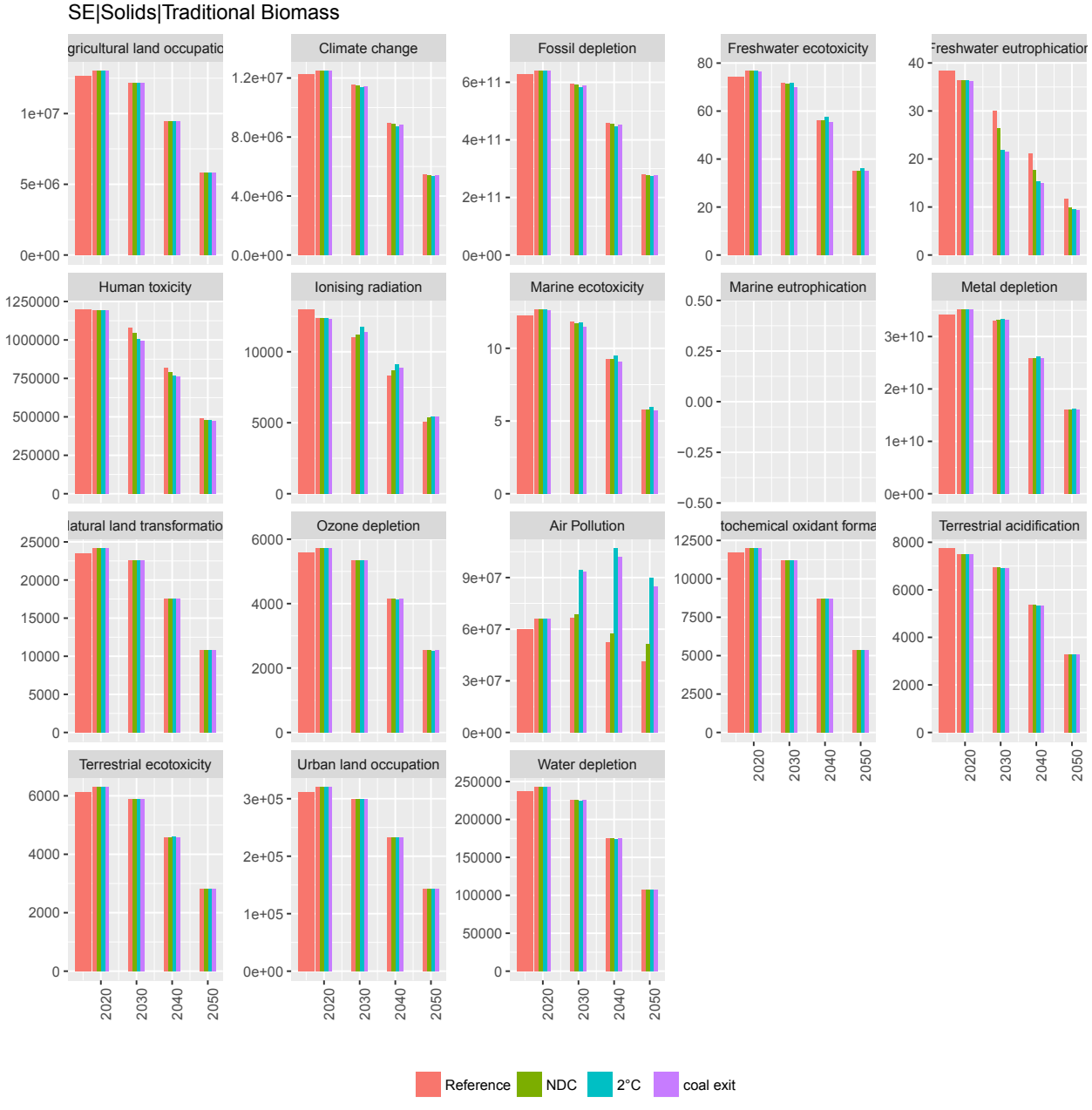


Figure SI-25: **|Global absolute cost of Secondary Energy - Electricity [US$].** Global absolute cost of Secondary Energy - Electricity for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050.

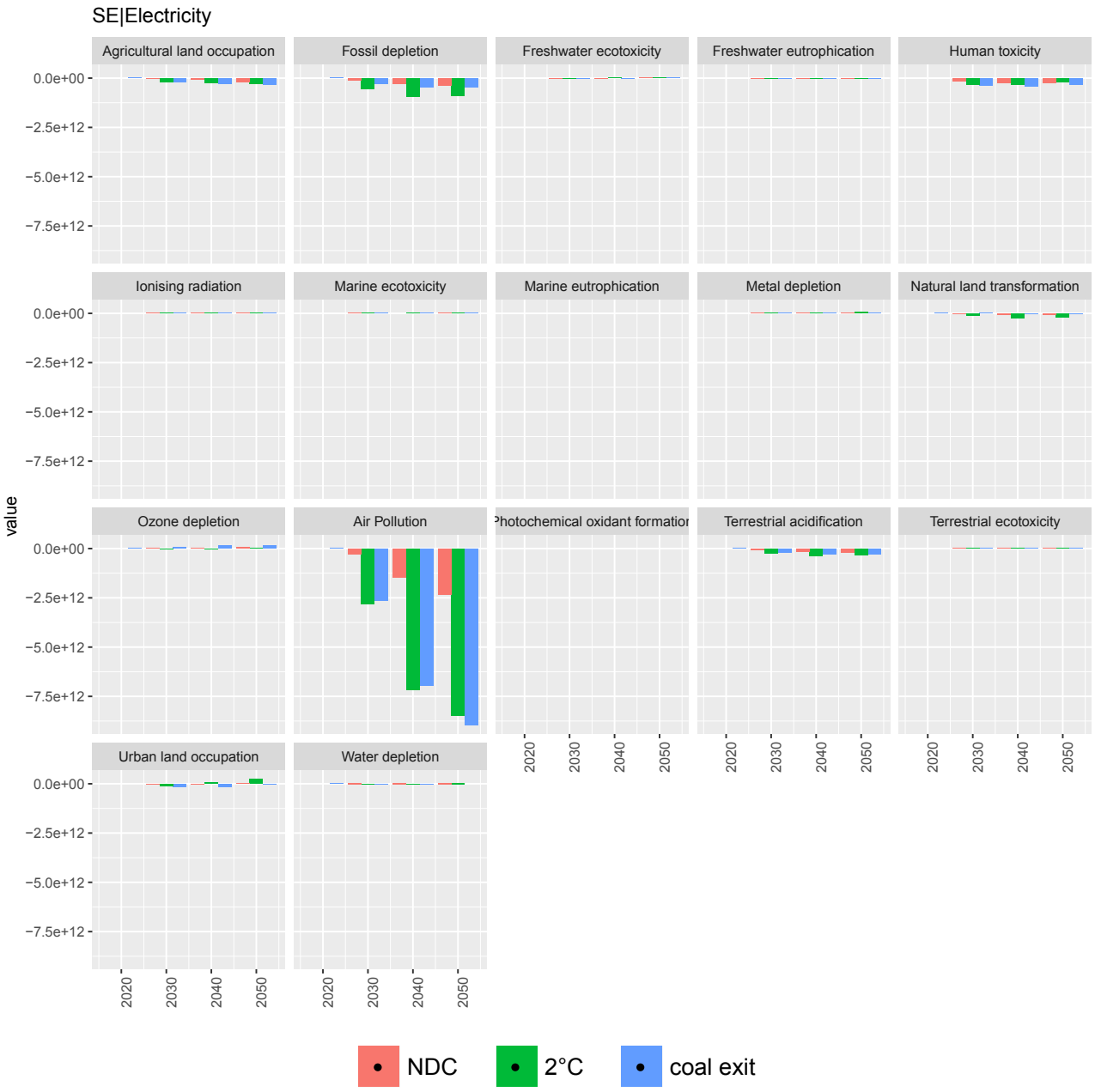


Figure SI-26: |**Regional local monetized impacts as a share of GDP PPP.** Regional local monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

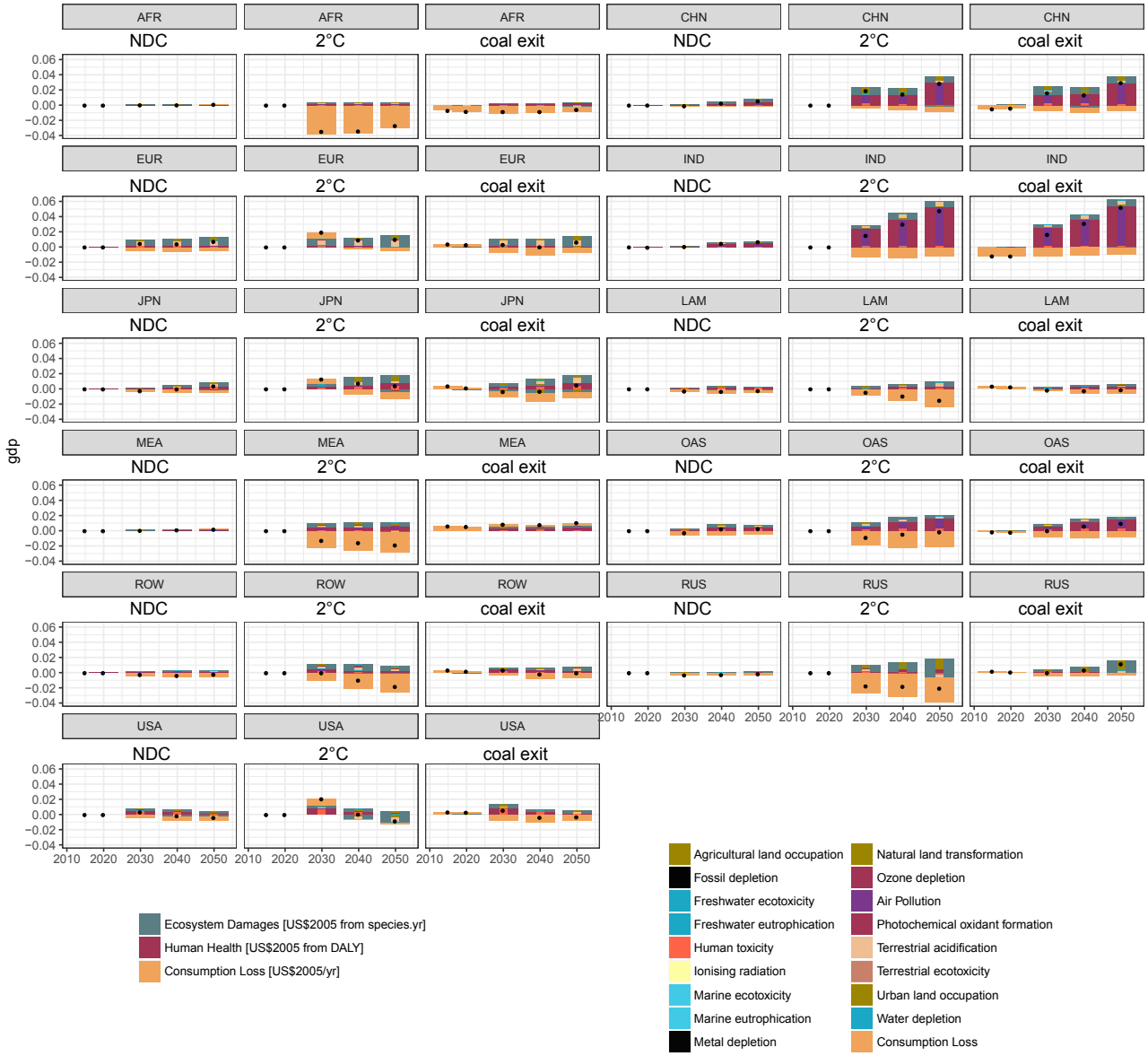


Figure SI-27: |**Regional local monetized impacts.** Regional local monetized impacts for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

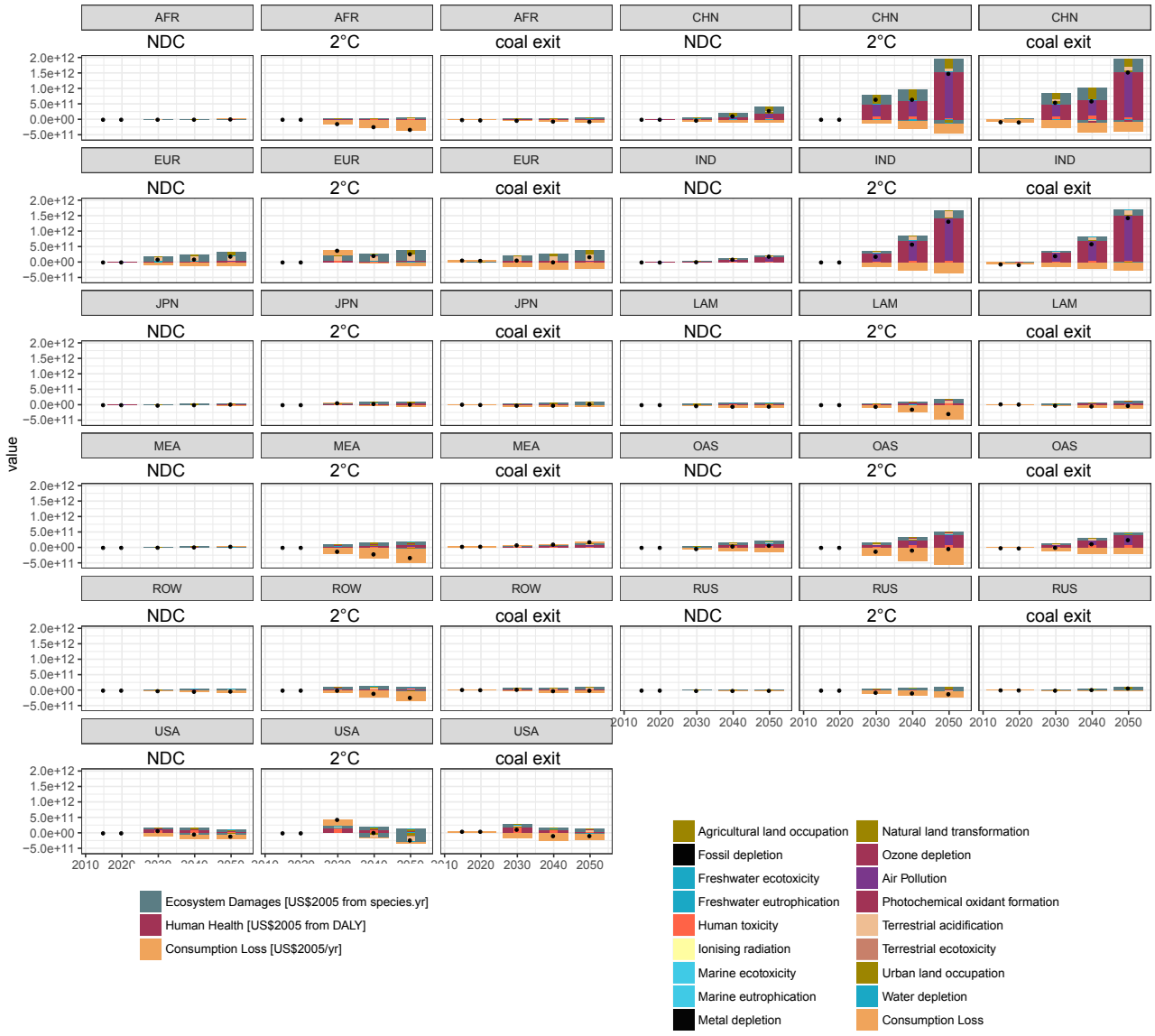


Figure SI-28: |**Regional local and global monetized impacts as a share of GDP PPP.** Regional local and global monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

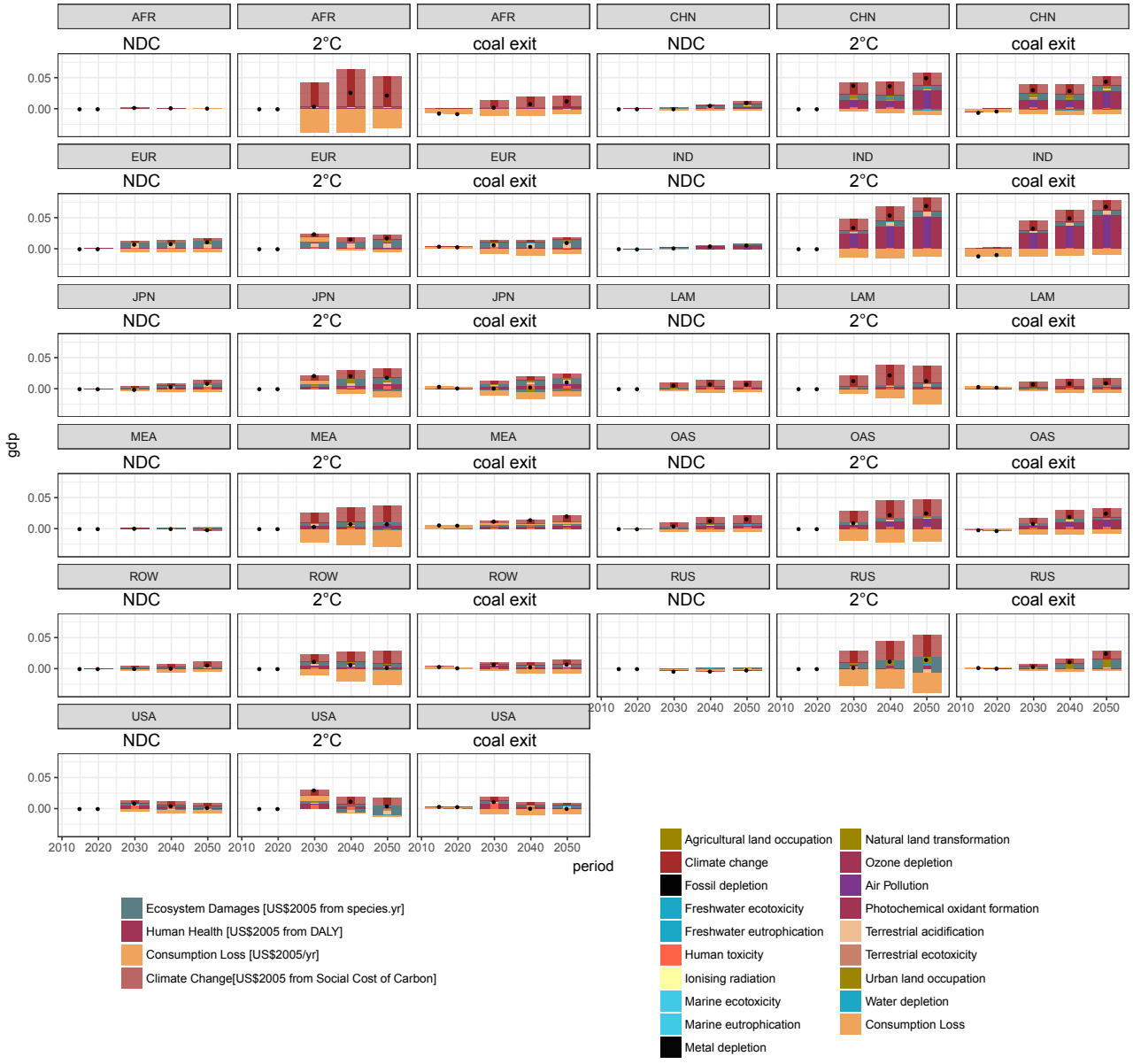


Figure SI-29: |**Global local and global monetized impacts as a share of GDP PPP.** Global local and global monetized impacts as a share of GDP PPP for the NDC, Coal exit and 2°C scenario relative to the Reference case until 2050 for EUR (Europe), CHN (China), IND (India), JAP (Japan), the USA, OAS (other Asia), MEA (Middle East, North Africa, central Asia), RUS (Russia), LAM (Latin America), AFR (Sub-Saharan Africa (excl. Republic of South Africa)), ROW (Rest of the World) and the World.

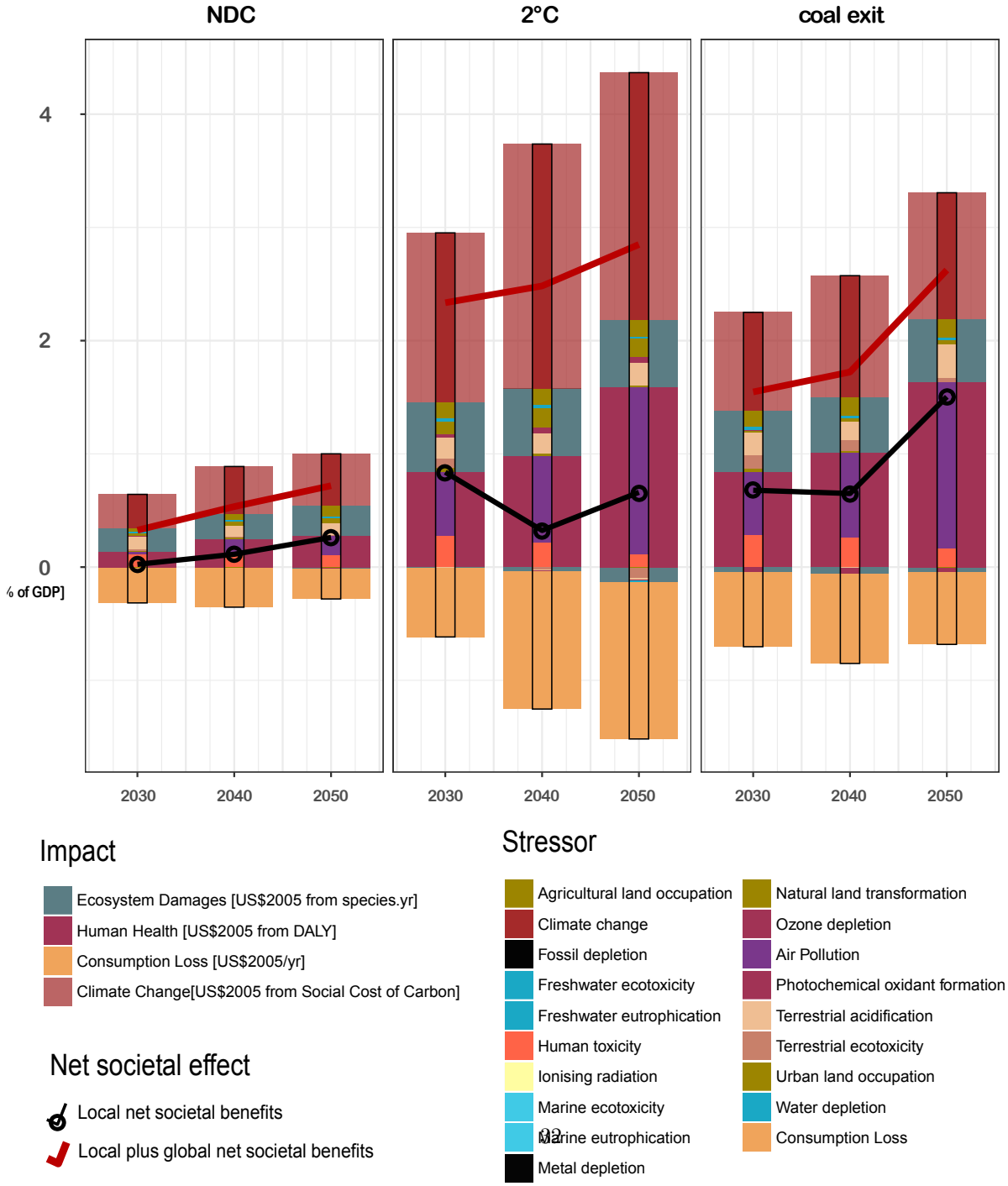
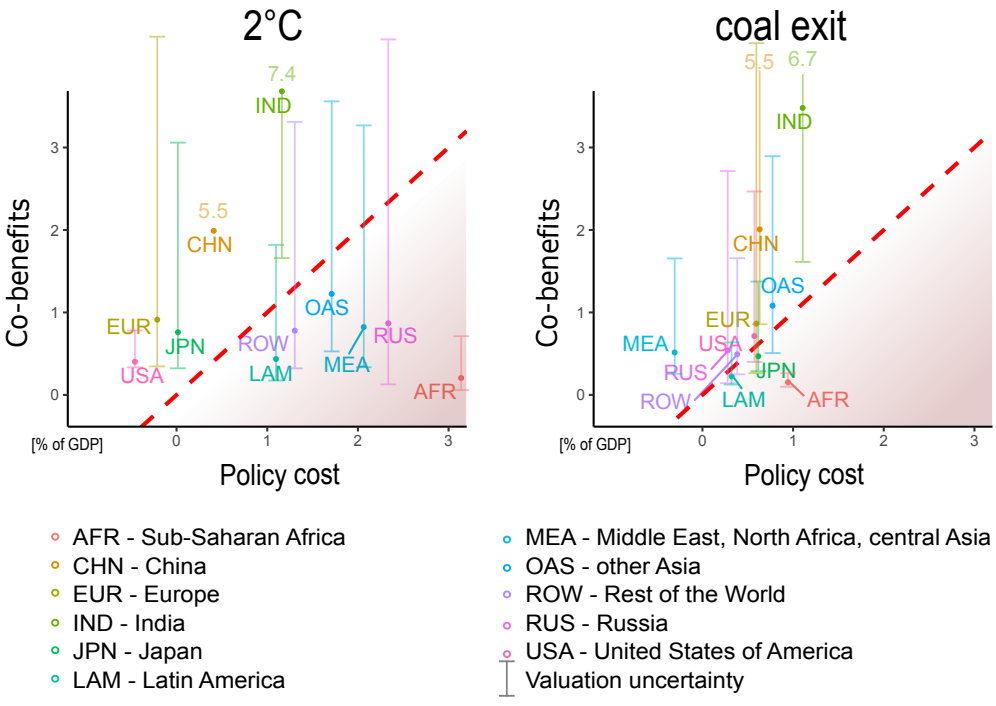


Figure SI-30: |**Regional analysis of local co-benefits and direct policy cost relative to GDP PPP.** Discounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits. The whiskers indicate the uncertainty ranges of human health and environmental impact translation into social cost.



- AFR - Sub-Saharan Africa
- CHN - China
- EUR - Europe
- IND - India
- JPN - Japan
- LAM - Latin America
- MEA - Middle East, North Africa, central Asia
- OAS - other Asia
- ROW - Rest of the World
- RUS - Russia
- USA - United States of America
- Valuation uncertainty

Figure SI-31: |**Regional analysis of local and global co-benefits and direct policy cost relative to GDP PPP.** Discounted local, global co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rate of 5%. The dashed line indicates the break-even between cost and benefits.

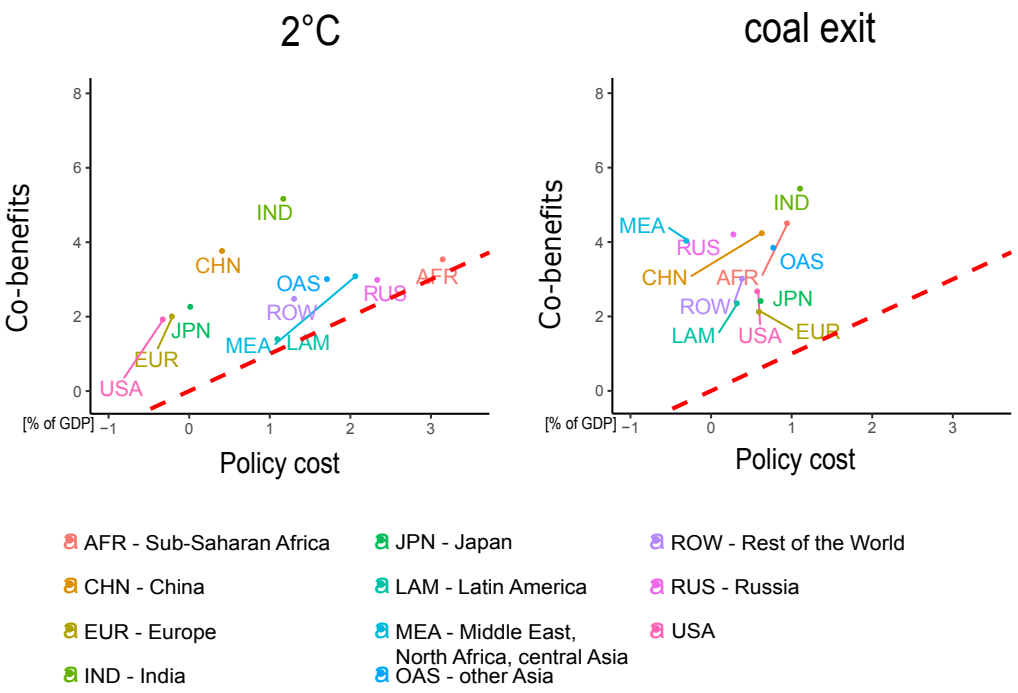


Figure SI-32: |**Regional analysis of local co-benefits and direct policy cost relative to GDP PPP.** Undiscounted co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP. The dashed line indicates the break-even between cost and benefits.

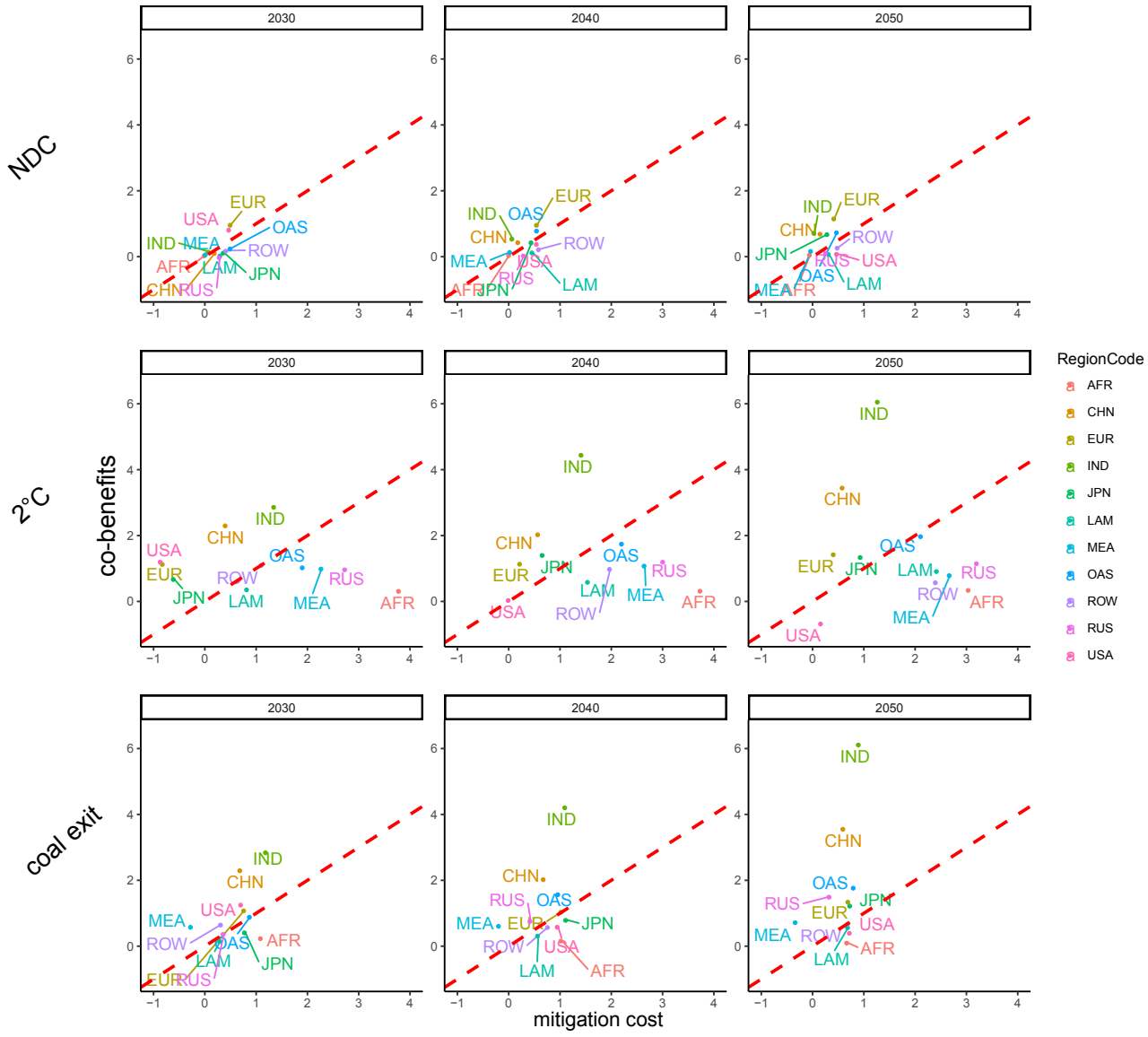


Figure SI-33: |**Regional analysis of local and global co-benefits and direct policy cost relative to GDP PPP.** Discounted local, global co-benefits and direct policy cost for all world regions in the 2°C and coal exit scenarios in % of GDP PPP with a discount rates of 2.5, 5 and 7.5%. The dashed line indicates the break-even between cost and benefits. The whiskers indicate the uncertainty ranges of human health and environmental impact translation into social cost.