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*Supplementary Information*

# Impact of declining renewable energy costs on electrification in low emission scenarios

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**Supplementary Table S1|Sensitivity scenarios.** The sensitivity scenarios listed below were conducted as variations to 1.5C-Elec to study the importance of specific technology assumptions in explaining differences between the 1.5C-Elec and 1.5C-Conv pathways. Results are shown in Suppl. Fig. S1.

| | |
|---|---|
| **HiBio** | Bioenergy according to agro-economic potential (up to 300 EJ), as in 1.5C-Conv. All other assumptions as in 1.5C-Elec. |
| **HiCCS** | Global CCS injection capacity of 20 $GtCO_2$/yr, as in 1.5C-Conv. All other assumptions as in 1.5C-Elec. |
| **HiBioCCS** | Global CCS injection capacity of 20 $GtCO_2$/yr and Bioenergy according to agro-economic potential (up to 300 EJ), as in 1.5C-Conv. All other assumptions as in 1.5C-Elec. All other assumptions as in 1.5C-Elec. |
| **ConvTrans** | No market introduction policies and infrastructure policies for electric vehicles resulting in prolonged dominance of combustion engine vehicles, as in 1.5C-Conv. All other assumptions as in 1.5C-Elec. All other assumptions as in 1.5C-Elec. |
| **HiIntCost** | Lower flexibility of electricity demand resulting in greater storage requirements for VRE integration, as in 1.5C-Conv. All other assumptions as in 1.5C-Elec. All other assumptions as in 1.5C-Elec. |
| **SlowPVLearning** | Lower learning rate (20%) and higher floor cost (200$/kW), resulting in a slower degression of solar PV capital cost to around 460 $2015/kW in 2050), as well as lower flexibility of electricity demand resulting in greater storage requirements for VRE integration (as in HiIntCost). All other assumptions as in 1.5C-Elec. |
| **NoPVLearning** | No further cost degression for PV technology from 2025, resulting in quasi-constant capital cost of ~930 $2015/kW. All other assumptions as in 1.5C-Elec. |

**Supplementary Table 2|Comparison of investment costs and emergent levelized costs of electricity with other literature for solar PV, wind energy, nuclear power and battery costs.** LCOEs only account for investment, operation and maintenance costs, fuel costs, but not for costs related to systems integration of variable renewable electricity. Comparison of LCOE is more straightforward than comparison of capital costs in $/kW, as the latter depend on system configuration details, e.g. hub heights in the case of wind power, or if solar photovoltaics are installed with fixed tilt or with tracking.

| ***A: Solar Photovoltaics*** | |
|---|---|
| ***This study*** | ***Other literature*** |
| **LCOE 2030:**<br>1.5C-Elec: 13-36 US$2015/MWh<br>1.5C-Conv: 21-56 $2015/MWh<br>Reference: 27-71 US$2015/MWh<br>**LCOE 2050:**<br>1.5C-Elec: 10-17 US$2015/MWh<br>1.5C-Conv: 19-34 $2015/MWh<br>Reference: 22-38 US$2015/MWh | **LCOE 2020:**<br>29-42 $/MWh US utility-scale (Lazard 2020[1])<br>63-94 $/MWh community (Lazard 2020[1])<br>24-41 $/MWh US utility-scale (NREL ATB 2020[2])<br><br>**LCOE 2030:**<br>18-30 $/MWh EU utility-scale (Vartiainen 2020[3])<br>11-36$/MWh US utility-scale (NREL ATB 2020[2])<br>**LCOE 2050:**<br>10-18 $/MWh EU utility-scale (Vartiainen 2020[3])<br>8-23 $/MWh US utility-scale (NREL ATB 2020[2]) |
| **Investment cost 2030:**<br>1.5C-Elec: 250-400 $2015/kW<br>1.5C-Conv: 400-640 $2015/kW<br>Reference: 510-830 $2015/kW<br>**Investment cost 2050:**<br>1.5C-Elec: 190 $2015/kW<br>1.5C-Conv: 380 $2015/kW<br>Reference: 440 $2015/kW | **Investment cost 2019:**<br>770 $/kW (median of 2019 market prices) (IEA PVPS 2020[4])<br><br>**Investment cost 2030:**<br>230-320 $/kW (Vartiainen et al 2020[3])<br><br>**Investment cost 2050:**<br>120-220 $/kW (Vartiainen et al 2020[3]) |

| *B: Onshore wind power* | |
|---|---|
| ***This study*** | ***Other literature*** |
| **LCOE 2030:**<br>1.5C-Elec: 60-140 $2015/MWh<br>1.5C-Conv: 60-135 $2015/MWh<br>Reference: 59-128 US$2015/MWh<br>**LCOE 2050*:**<br>1.5C-Elec: 39-69 $2015/MWh<br>1.5C-Conv: 38-67 $2015/MWh<br>Reference: 42-67 US$2015/MWh | **LCOE 2020:**<br>26-54 $/MWh US (Lazard 2020[1])<br>49-95 $/MWh India (Lazard 2020[1])<br>26-123 $/MWh US, class 1-10 (NREL ATB 2020[2])<br>**LCOE 2030:**<br>22-43 $/MWh (Wiser 2021)<br>20-38$/MWh (BNEF New Energy Outlook 2020[5])<br>16-101 $/MWh US, class 1-10 utility-scale (NREL ATB 2020[2])<br>**LCOE 2050:**<br>17-37 $/MWh (Wiser 2021[6])<br>15-28 $/MWh (BNEF New Energy Outlook 2020[5])<br>11-91 $/MWh US, class 1-10 utility-scale (NREL ATB 2020[2]) |
| **Investment cost 2030:**<br>1.5C-Elec: 1000-1350 $2015/kW<br>1.5C-Conv: 1100-1300 $2015/kW<br>Reference: 1170-1600 $2015/kW<br><br>**Investment cost 2050:**<br>1.5C-Elec: 1180-1190 $2015/kW<br>1.5C-Conv: 1180-1190 $2015/kW<br>Reference: 1200 $2015/kW | **Investment cost 2019:**<br>1050-1450 $/kW (Lazard 2020[1])<br>1170-1500 $/kW (25th-75th percentile) (Wiser 2021[6])<br><br>**Investment cost 2035:**<br>890-1670 $/kW (25th-75th percentile) (Wiser 2021[6]) |
| ** Note: Wind LCOE increase in 1.5C-Elec compared to other scenarios in some regions due to greater deployment resulting in greater reliance on inferior wind resource.* | |

| *C: Nuclear power* | |
|---|---|
| ***This study*** | ***Other literature*** |
| **LCOE 2030:**<br>70-115 $2015/MWh<br>**LCOE 2050:**<br>86-109 $2015/MWh | **LCOE 2020:**<br>129-198 $/MWh (Lazard 2020[1]) |
| **Investment cost 2030 (all scenarios):**<br>4700-8000 $2015/kW<br>**Investment cost 2050 (all scenarios):**<br>5900-7500 $2015/kW | **Investment cost 2020:**<br>7675-12500 $/kW (Lazard 2020[1])<br>Range of costs for reactors under construction or planned in EU & US*: 6000-11000 $/kW |
| **Note: In the US and Europe, new constructions (since 2000) have all experienced massive time and cost overruns. Costs for reactors currently under construction or recently finished are in the range of 6,000-11,000 $/kW. As even the latest European Prressurized Reactor in planning (Sizewell C) shows no reduction in costs compared to the previous constructions of the same kind, we only expect weak cost reductions in the future.*<br>*Furthermore, we assume that low costs currently reported for Russia and China are at least partially due to lower security and environmental regulation as well as cheap labor, and expect that as per-capita income grows in these regions, so will security and environmental regulations. Accordingly, we assume that ALL energy technology investment costs converge globally until 2070.* | |

| *D: Battery storage* | |
|---|---|
| ***This study*** | ***Other literature*** |
| **Investment cost 2030:**<br>1.5C-Elec: 71 $2015/kWh<br>1.5C-Conv: 91 $2015/kWh<br>Reference: 105 $2015/kWh<br><br>**Investment cost 2050:**<br>1.5C-Elec: 69 $2015/kWh<br>1.5C-Conv: 82 $2015/kWh<br>Reference: 86 $2015/kWh | **Investment cost:**<br>**2023:** ~100 $/kWh battery pack (BNEF, 2020[5])<br>**2030:**<br>**64-289** $/kWh Lithium-ion batteries (Schmidt et al 2017[7])<br>58 $/kWh battery pack (BNEF, 2020[5])<br><br>**2050**<br>**39-251** $/kWh Lithium-ion batteries (Schmidt et al 2017[7]) |

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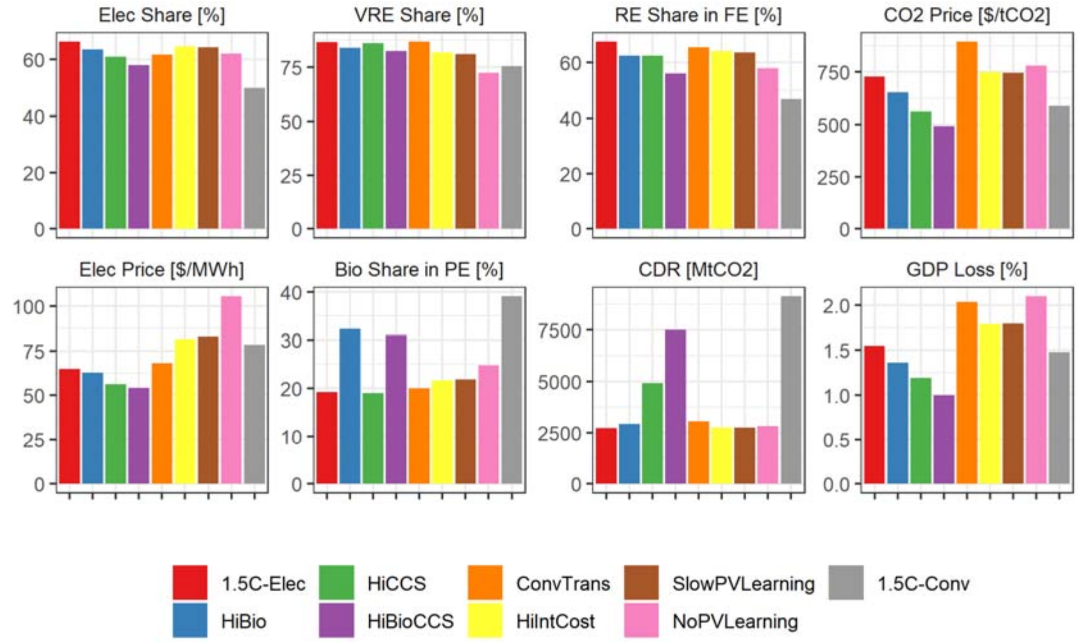
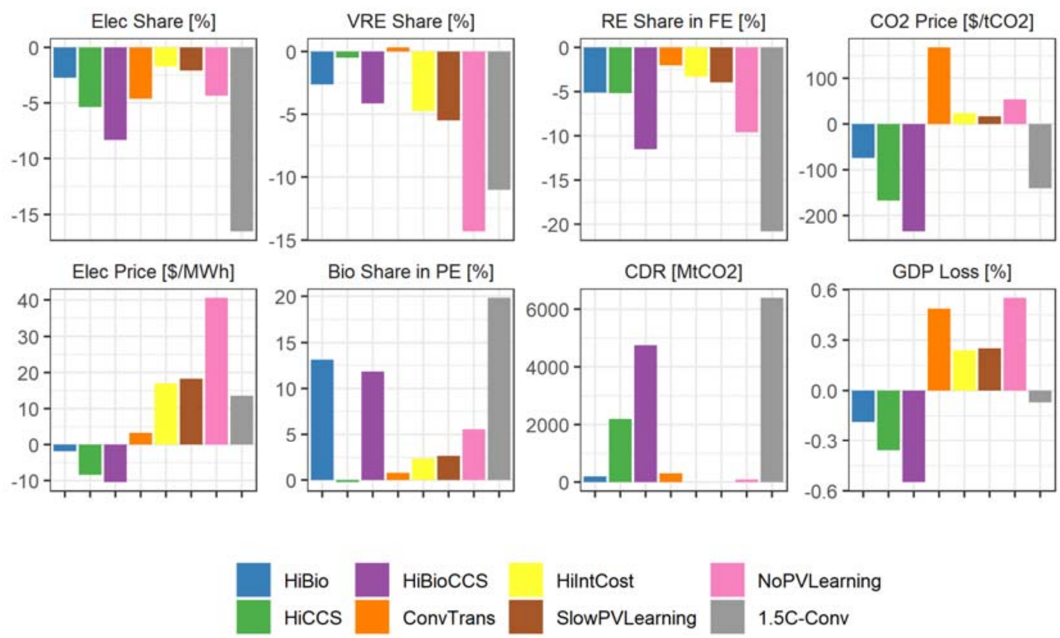
**Supplementary Table 3|Investment costs (IC) and conversion efficiencies (eff.) for crucial fossil and biomass-based technologies as well as hydrogen electrolysis.**

| Technology | | 2020 | 2035 | 2050 |
|---|---|---|---|---|
| Biomass Electricity (IGCC) w/o CCS | IC [$2015/kW] | 2600 | 2696 | 2780 |
| | $\eta$ [%] | 35 | 43 | 46 |
| Biomass Electricity (IGCC) w/ CCS | IC [$2015/kW] | 6672 | 3852 | 3967 |
| | $\eta$ [%] | 29 | 32 | 35 |
| Coal Electricity (pulverized coal) w/o CCS | IC [$2015/kW] | 1499 | 2147 | 2090 |
| | $\eta$ [%] | 41 | 45 | 46 |
| Coal Electricity (pulverized coal) w/ CCS | IC [$2015/kW] | 5612 | 5184 | 4614 |
| | $\eta$ [%] | 34 | 35 | 36 |
| Coal Elctricity (IGCC) w/ CCS | IC [$2015/kW] | 6012 | 5360 | 4555 |
| | $\eta$ [%] | 35 | 40 | 43 |
| Gas Electricity (IGCC) w/o CCS | IC [$2015/kW] | 983 | 790 | 892 |
| | $\eta$ [%] | 55 | 61 | 63 |
| Gas Electricity (IGCC) w/ CCS | IC [$2015/kW] | 3018 | 2459 | 2049 |
| | $\eta$ [%] | 49 | 54 | 56 |
| Biomass Hydrogen w/o CCS | IC [$2015/kW] | 3176 | 1892 | 1892 |
| | $\eta$ [%] | 61 | 61 | 61 |
| Biomass Hydrogen w/ CCS | IC [$2015/kW] | 4301 | 2345 | 2406 |
| | $\eta$ [%] | 55 | 55 | 55 |
| Coal Hydrogen w/o CCS | IC [$2015/kW] | 1884 | 1793 | 1748 |
| | $\eta$ [%] | 59 | 59 | 59 |
| Coal Hydrogen w/ CCS | IC [$2015/kW] | 3236 | 2022 | 2032 |
| | $\eta$ [%] | 57 | 57 | 57 |
| Gas Hydrogen w/o CCS | IC [$2015/kW] | 647 | 652 | 648 |
| | $\eta$ [%] | 73 | 73 | 73 |
| Gas Hydrogen w/ CCS | IC [$2015/kW] | 781 | 718 | 726 |
| | $\eta$ [%] | 70 | 70 | 70 |
| Electrolysis Hydrogen | IC [$2015/kW] | 1698 | 647 | 434 |
| | $\eta$ [%] | 80 | 80 | 80 |
| Biomass-to-Liquids (Fischer-Tropsch) w/o CCS | IC [$2015/kW] | 6422 | 3482 | 3508 |
| | $\eta$ [%] | 40 | 40 | 40 |
| Biomass-to-Liquids (Fischer-Tropsch) w/ CCS | IC [$2015/kW] | 8109 | 4363 | 4483 |
| | $\eta$ [%] | 41 | 41 | 41 |

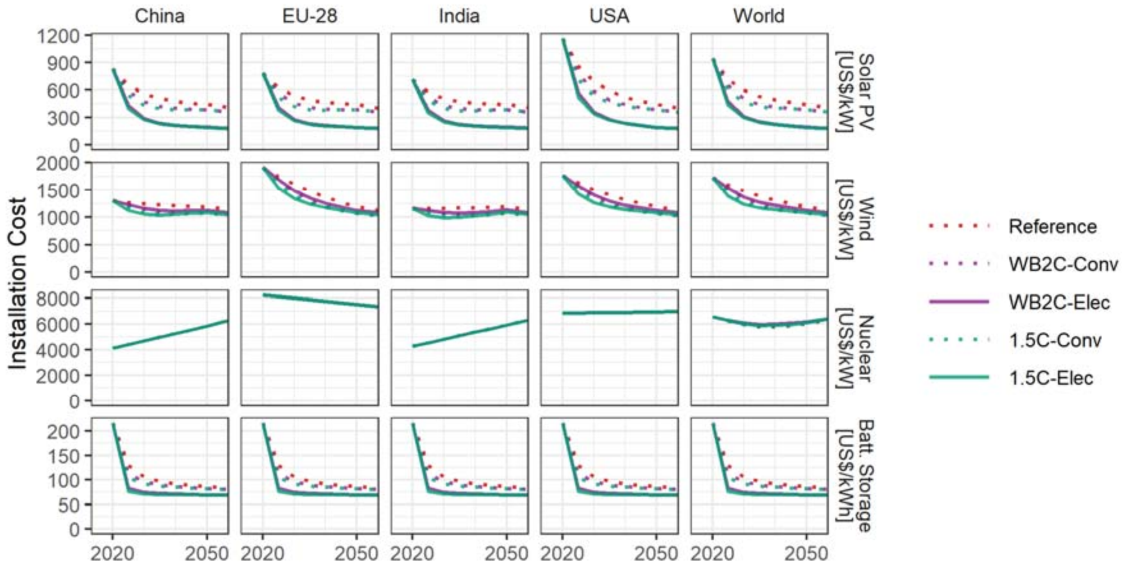
**a – indicators in absolute terms (2050)**

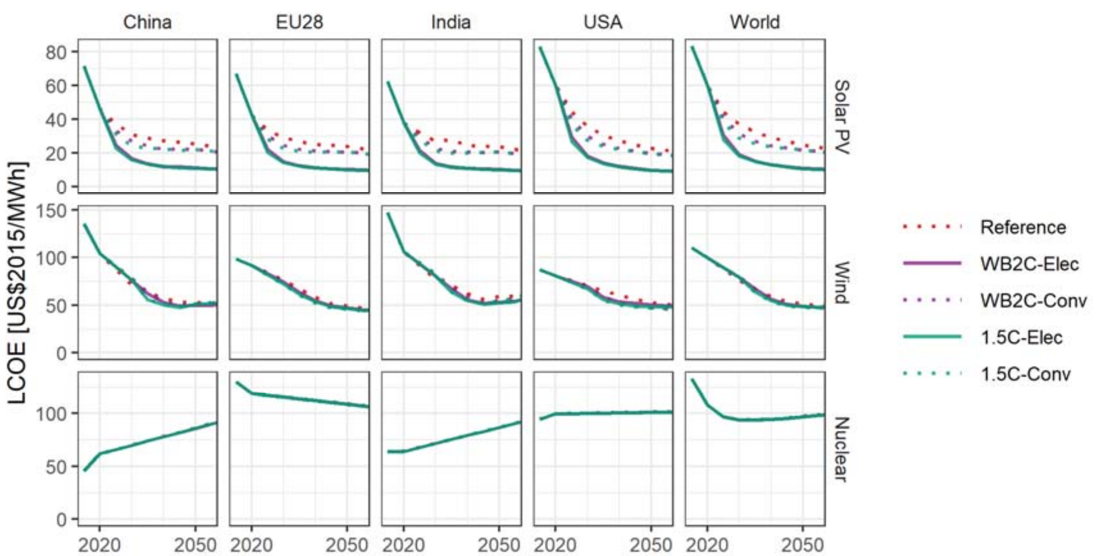



**b - difference to 1.5C-Elec (2050)**



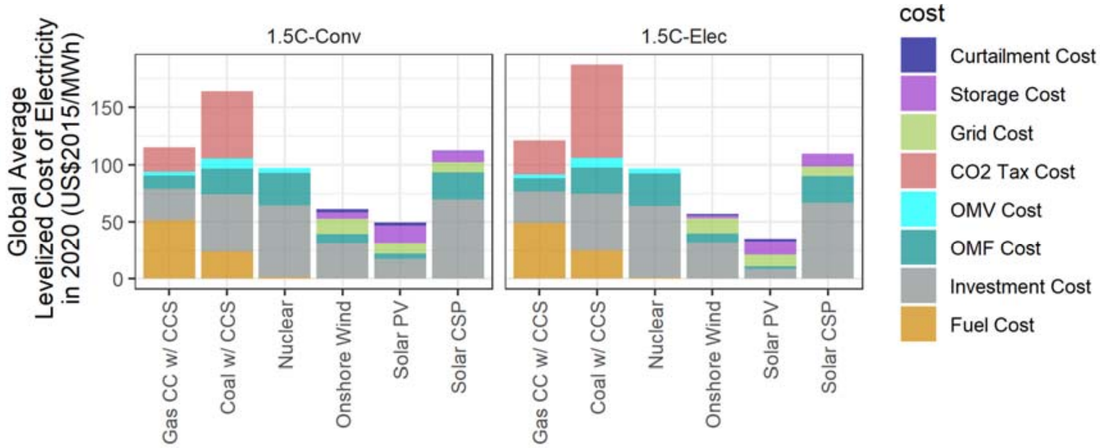

**Supplementary Figure 1|Transformation characteristics in 2050 for 1.5°C sensitivity scenarios with varying technology assumptions.** Sensitivity scenarios are variations of 1.5C-Elec, as defined in Table S1. (a) Absolute values of indicators. (b) Difference of indicators to 1.5C-Elec case. GDP effects are given as percentage losses relative to *Reference* in 2050.



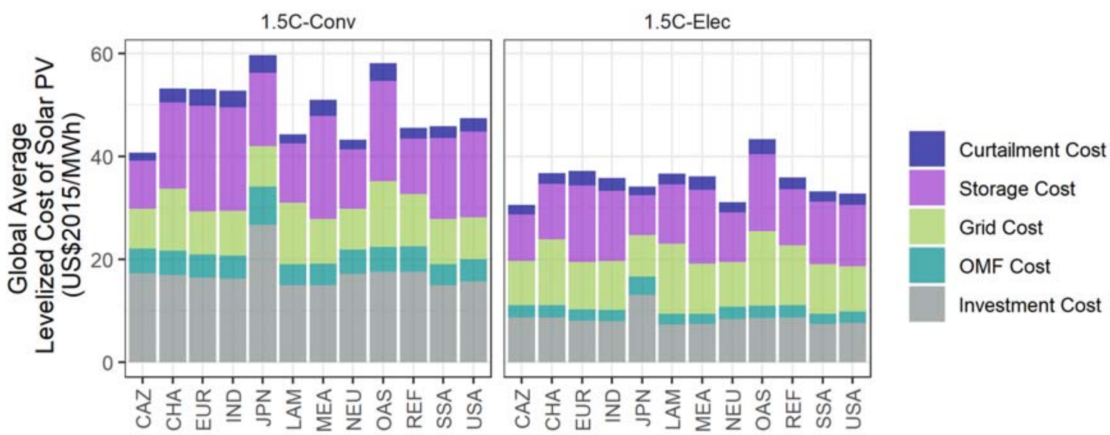




**Supplementary Figure 2| Installation costs and levelized cost of electricity for key regions.** (a) Evolution of installation costs for solar PV, wind power, nuclear power, and battery storage costs in the China, EU-28, India and USA model regions as well as the global average. (b) Resulting levelized costs of electricity generation from solar PV, wind and nuclear power. Note that LCOEs only account for investment, operation and maintenance costs, fuel costs, but not for costs related to systems integration of variable renewable electricity.

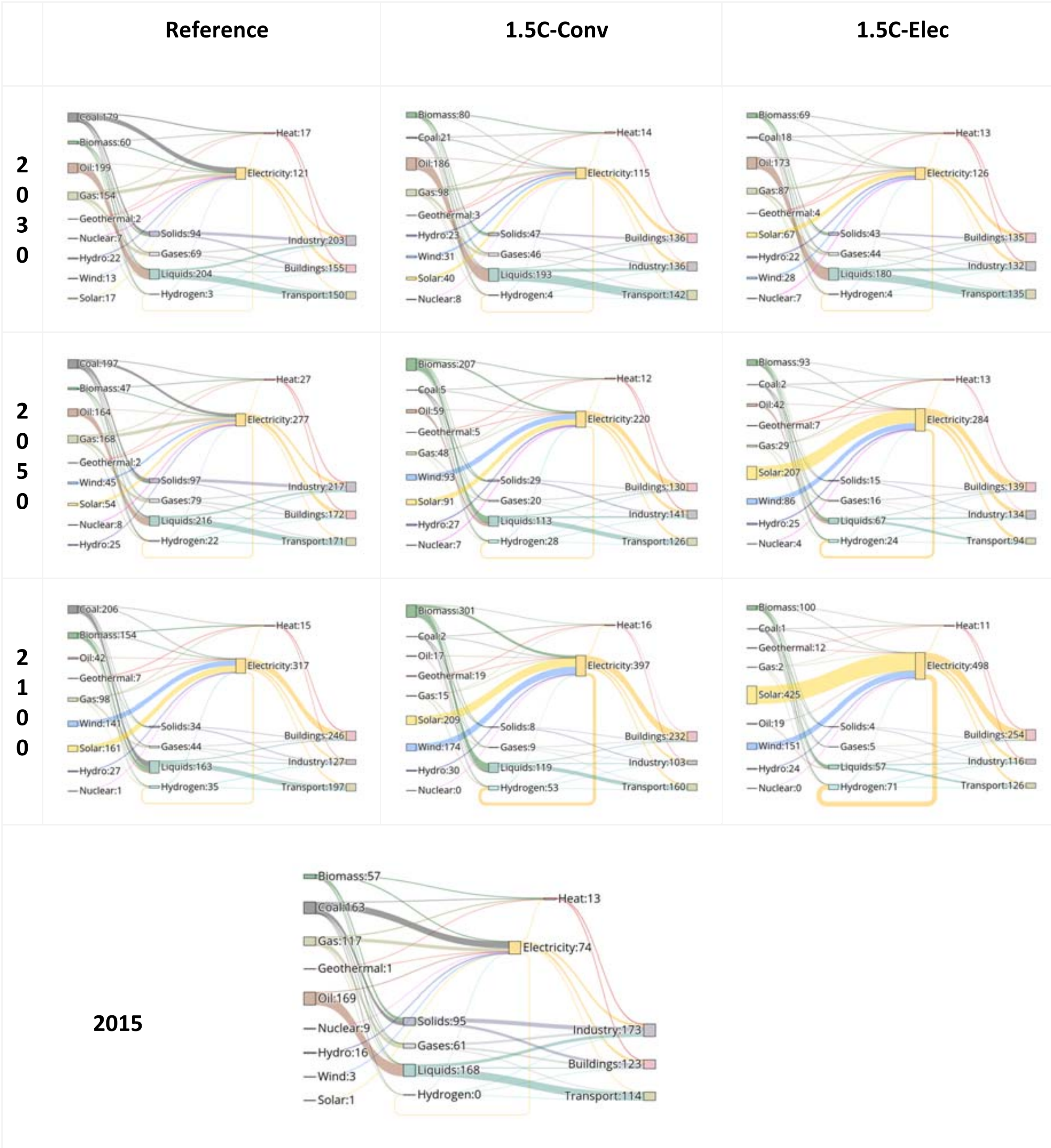
a




b

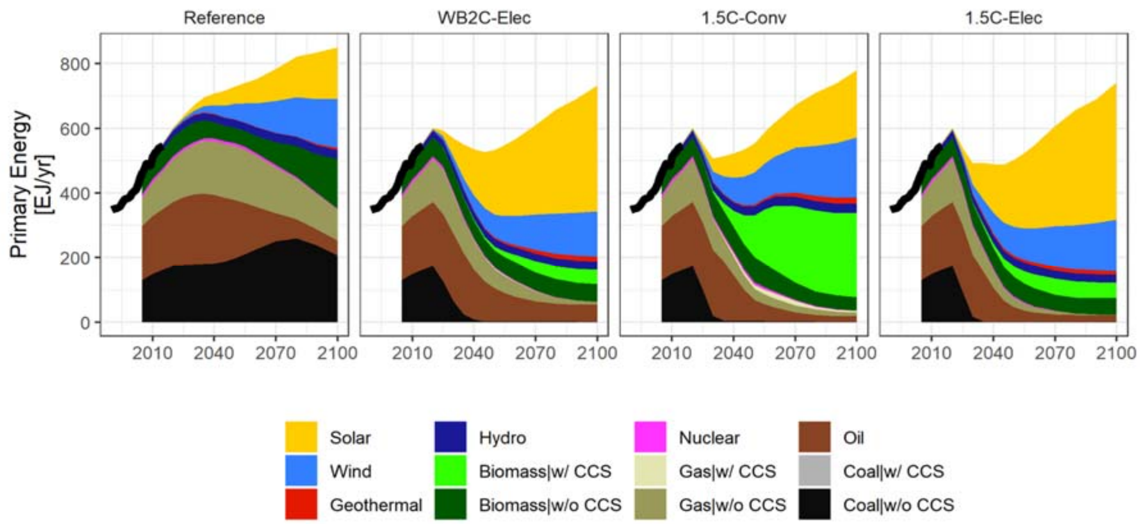



**Supplementary Figure 3| Direct levelized cost of electricity (LCOE) and systems LCOE for new installations in 2050.** (a) Overview of LCOEs for selected power sector mitigation technologies by and cost components. (b) regional differentiation of system LCOE of PV electricity. Systems LCOE for wind, solar PV and concentrating solar power (CSP) additionally account for induced system-level costs for storage, grid expansion and curtailment of overproduction when supply exceeds demand and storage capacity.

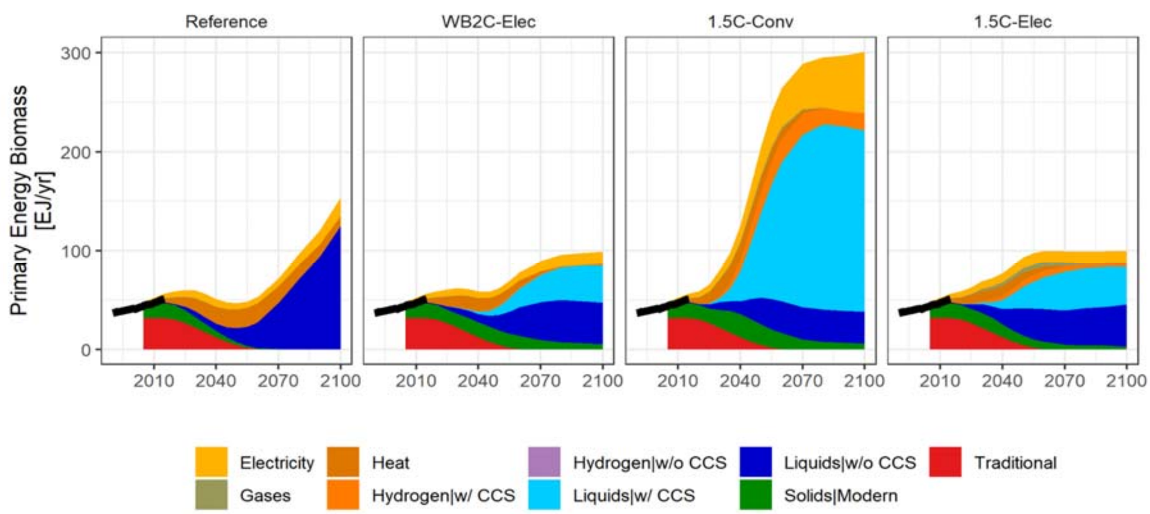



**Supplementary Figure 4| Sankey flow diagrams of global energy system structure** for Reference, WB2C-Elec, 1.5C-Elec and the years 2030, 2050, 2100. The lowest panel indicates modeled energy system flows for 2015. Energy flows are given in units of EJ per year and describe secondary energy generation by primary energy input (left to middle), and final energy provision by energy carrier (middle to right).

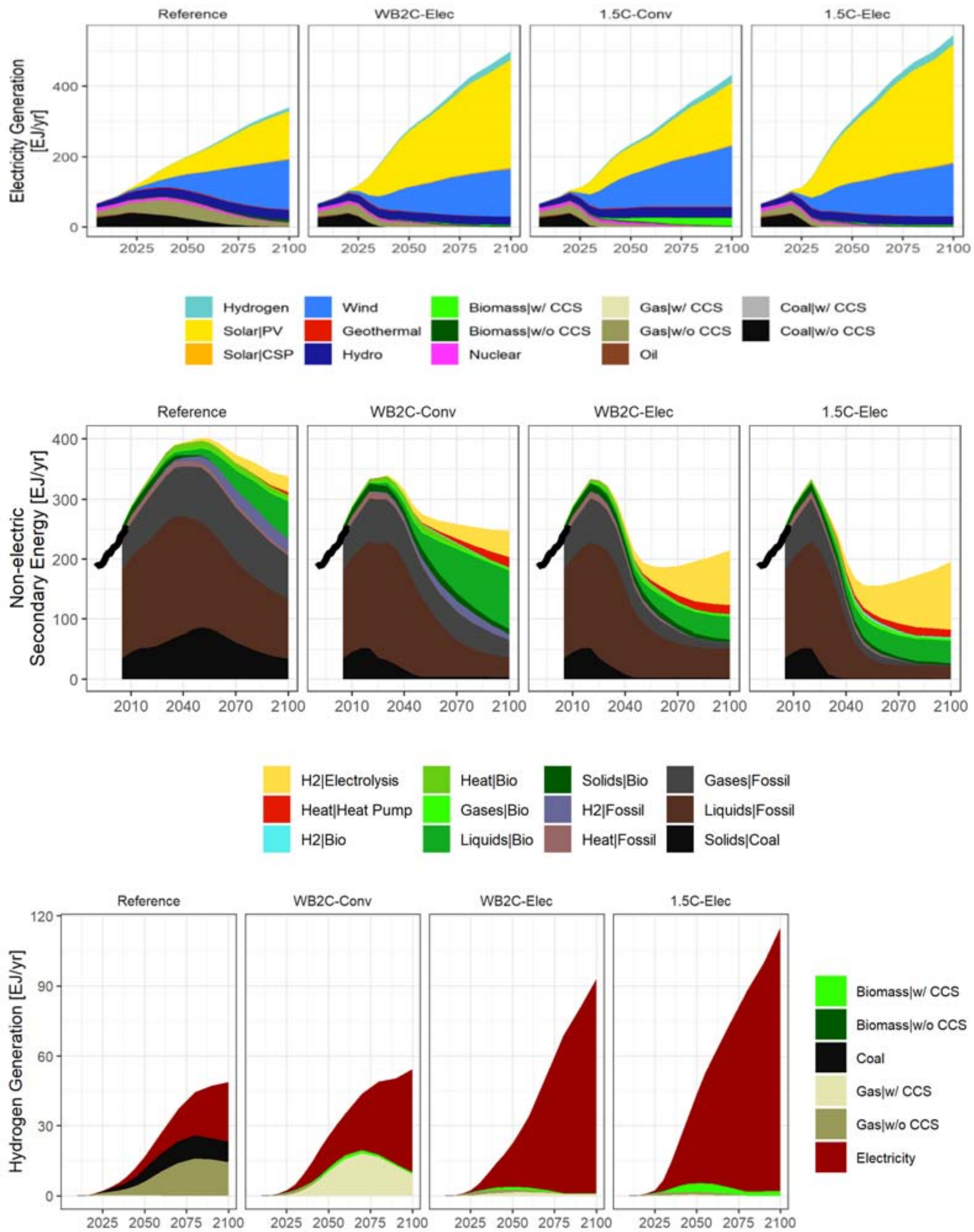
a



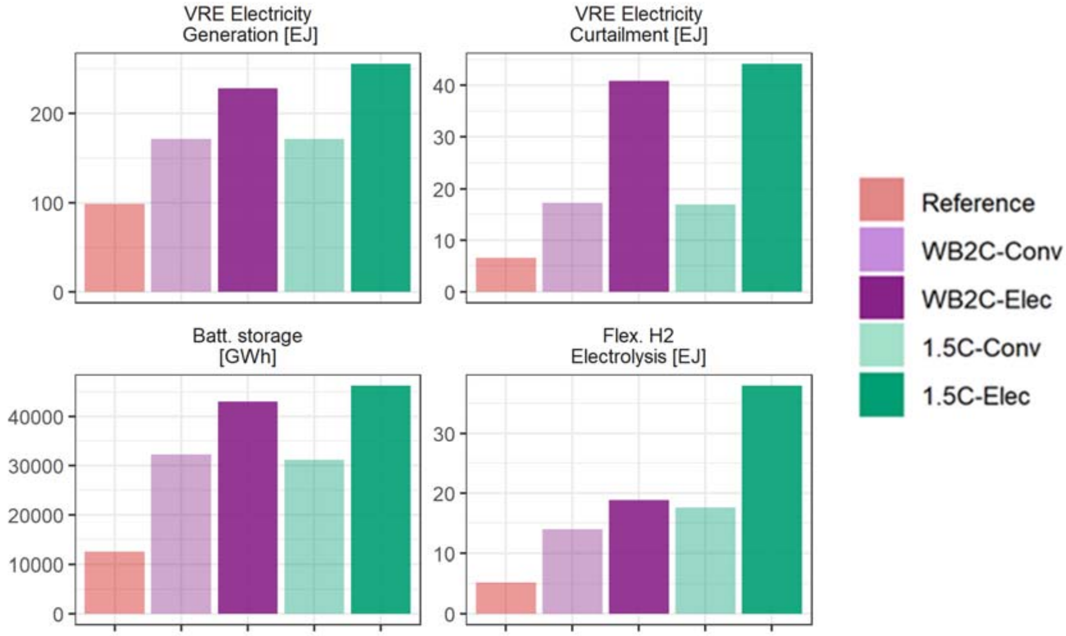

b




**Supplementary Figure 5| Primary energy in the Reference, WB2C-Elec, 1.5C-Conv, 1.5C-Elec scenarios.** (a) Global primary energy supply by energy carriers. (b) Breakdown of primary bioenergy by energy conversion pathway.

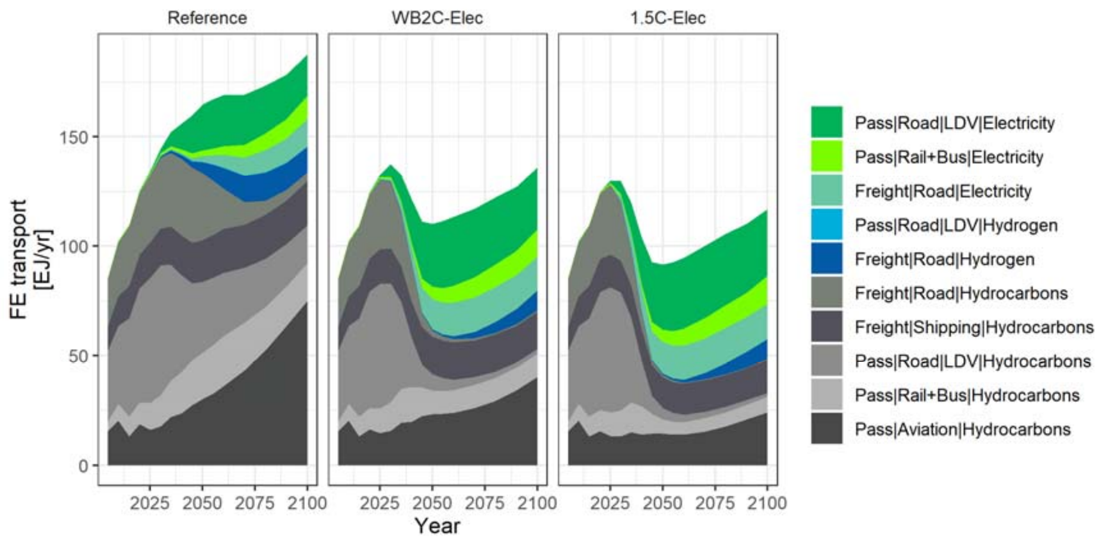



**Supplementary Figure 6| Transformation of secondary energy supply:** (a) Electricity generation mix, (b) non-electric secondary energy carriers, (c) focus on hydrogen generation.

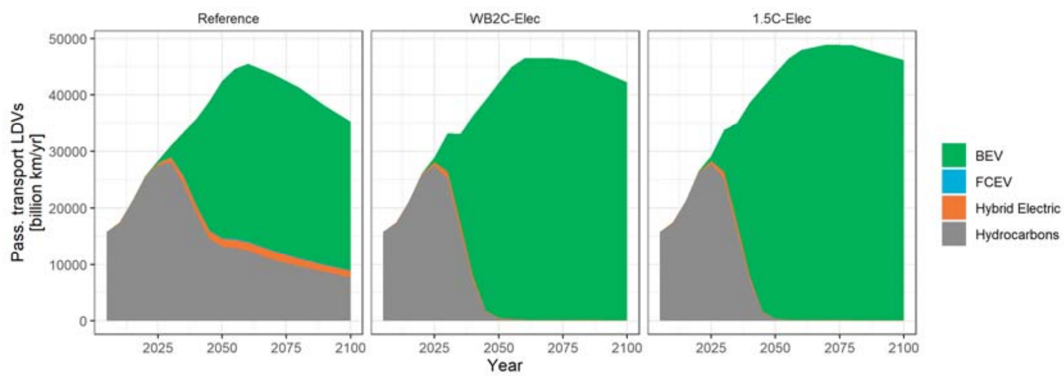



**Supplementary Figure 7| Total global electricity generation from VRE and associated integration challenges in 2050.** Curtailment of excess VRE supply increases disproportionately with increasing VRE share and reaches close to 20% in the 1.5C-Elec scenario. Battery storage requirements in the Elec scenarios is only modestly higher than in corresponding Conv scenarios due to the assumption of greater demand-side flexibilization. Hydrogen electrolysis can be operated as flexible load and therefore contributes to VRE integration.

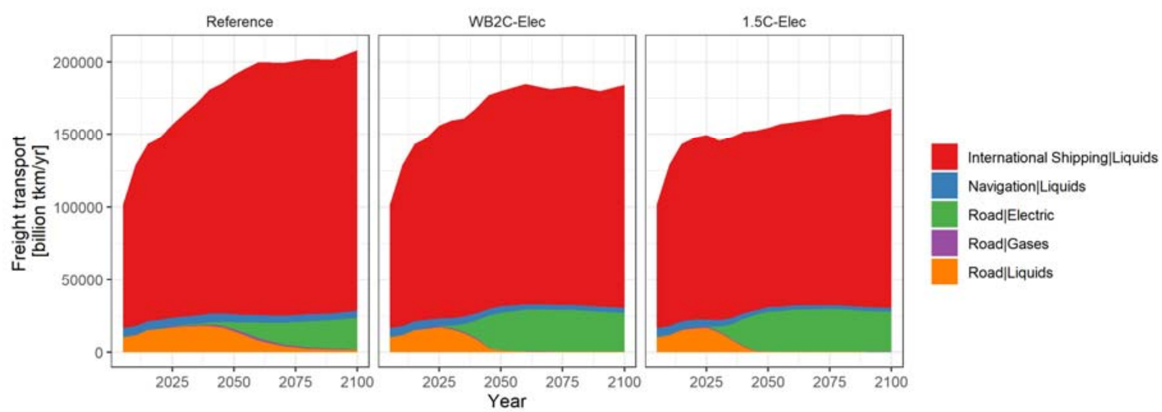
**a** - Transport Final Energy Demand



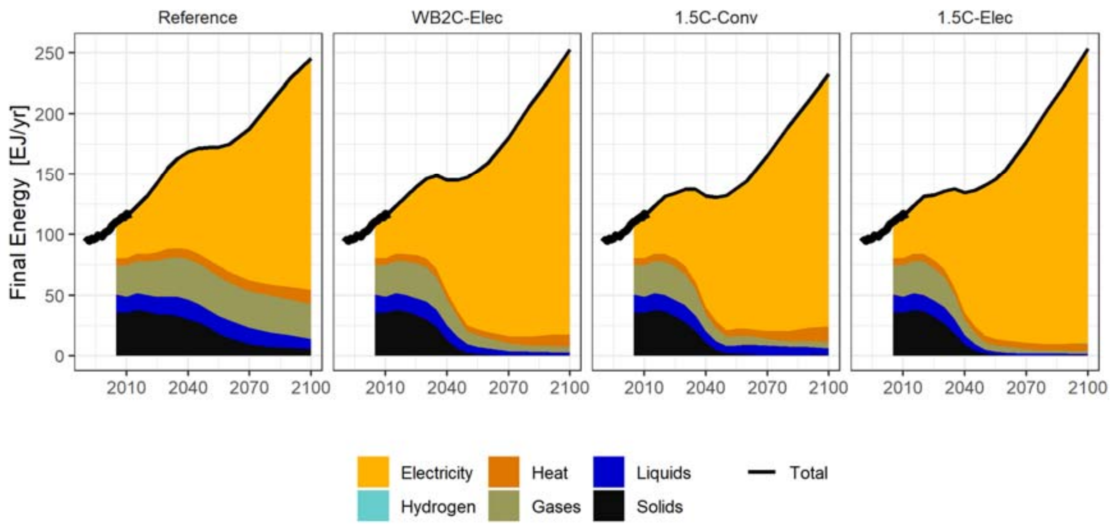

**b** -Light Duty Vehicles



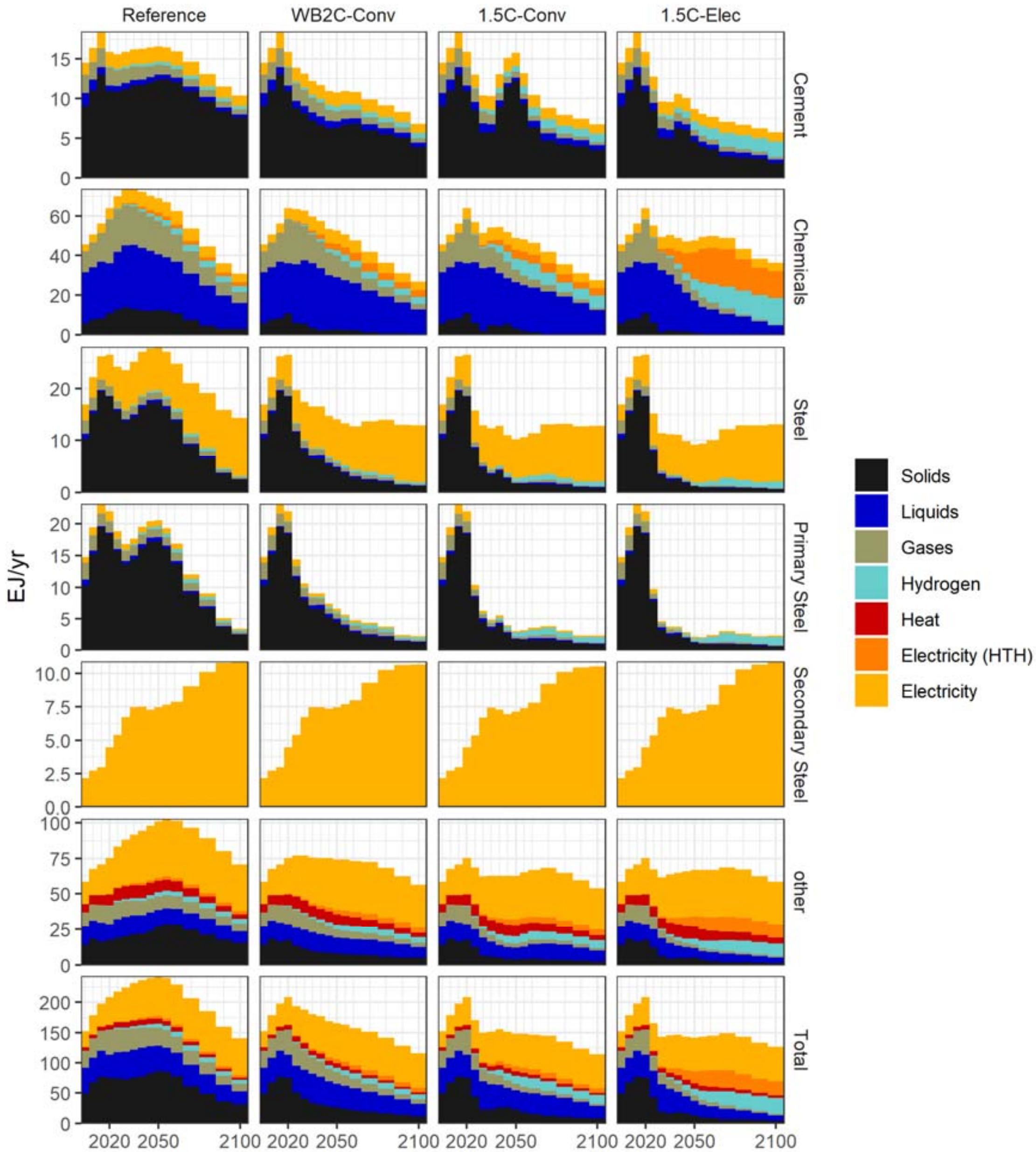

**c** -Freight Transport



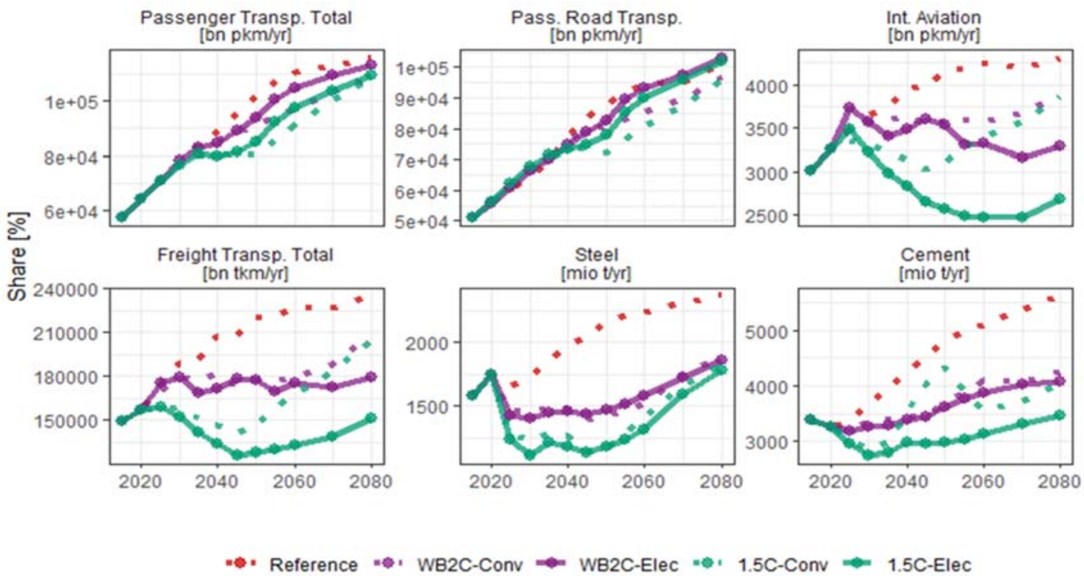

**Supplementary Figure 8| Transformation of the mobility sector.** Global evolution in the Reference, WB2C-Elec and 1.5C-Elec scenarios of (a) final energy demand by end-use and energy carrier, (b) passenger transportation in light duty vehicles, and (c) freight transport.



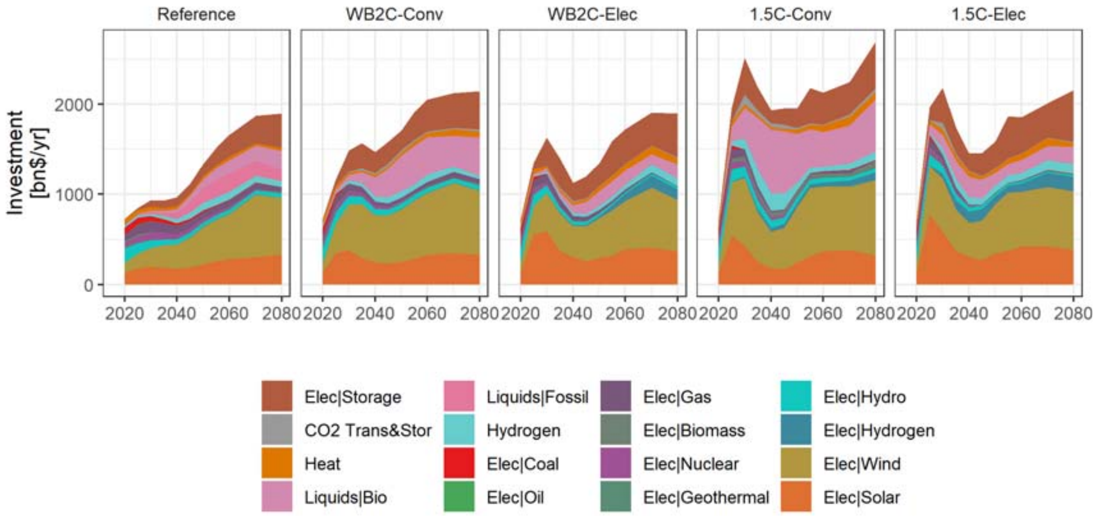

**Supplementary Figure 9| Final energy demand in the buildings sector in the Reference WB2C-Elec and 1.5C-Elec scenarios.**




**Supplementary Figure 10| Transformation of the industry final energy demand.** Global evolution of final energy demand by end-use and energy carrier in industrial sub-sectors.

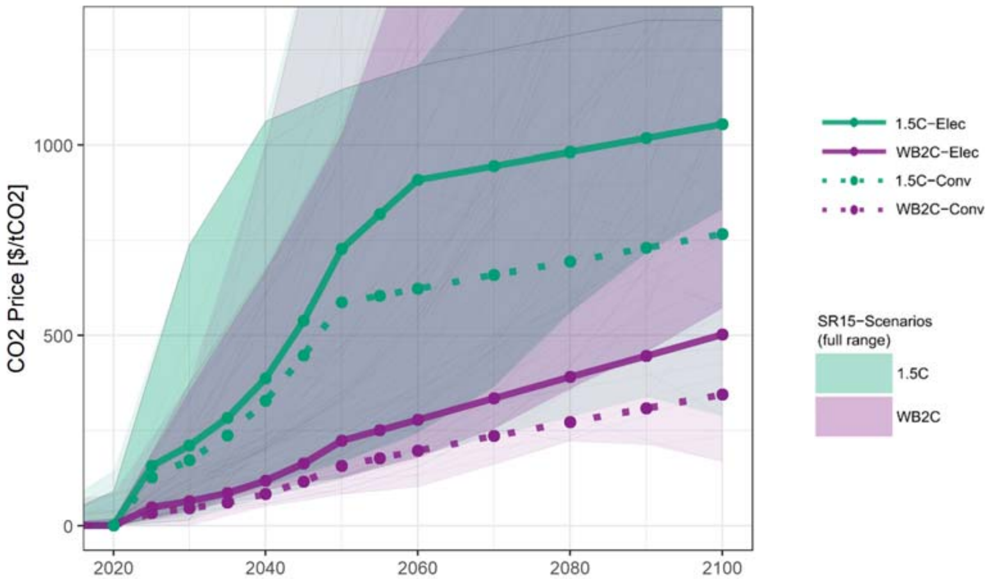



**Supplementary Figure 11|Energy service and material demands.** Developments of passenger transport in terms of total global passenger transport, road passenger transport, international aviation (top row), as well as freight transport, total steel production and cement production (bottom row).

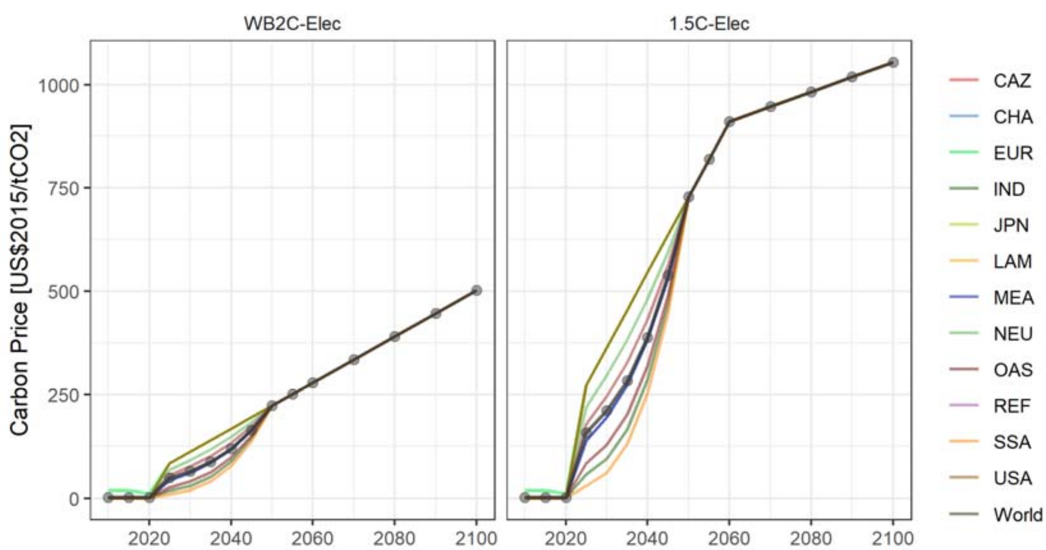



**Supplementary Figure 12|Global Energy Supply Investments.** Mitigation pathways in line with the 1.5-2°C climate targets are characterized by a rapid ramp-up in overall energy supply investments. Overall investments in the 1.5C-Conv scenario tend to be higher than in 1.5C-Elec due to more pessimistic assumptions about further cost degression for solar power as well as additional investment cost into biomass-to-liquids conversion. Note that investments into fossil resource extraction are not included.

**a** Globally averaged carbon price




**b** Regional carbon price trajectories




**Supplementary Figure 13| Carbon price development.** (a) Evolution of globally averaged carbon prices in the four climate change mitigation scenarios 1.5C-Elec, 1.5C-Conv, WB2C-Elec and WB2C-Conv. Funnels in the background indicate $CO_2$-price levels from SR15 scenarios with comparable climate stabilization targets. (b) Regional carbon prices in the WB2C-Elec and 1.5C-Elec scenarios. Global averages were calculated by weighting regional prices with the share in global gross fossil emissions (net of carbon dioxide removal).