Devising mineral resource supply pathways for a decarboning electricity generation to 2100

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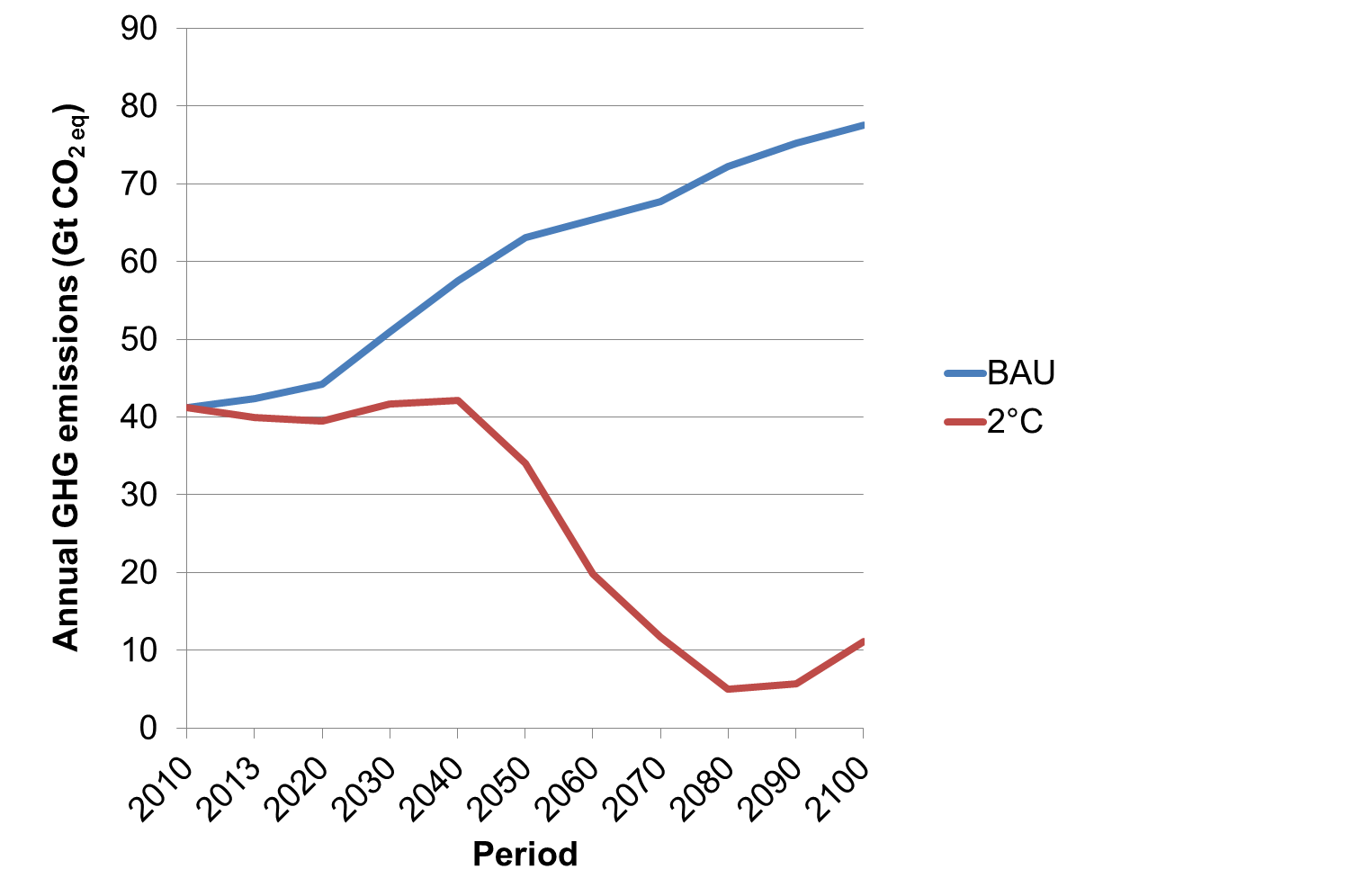
Supplementary material

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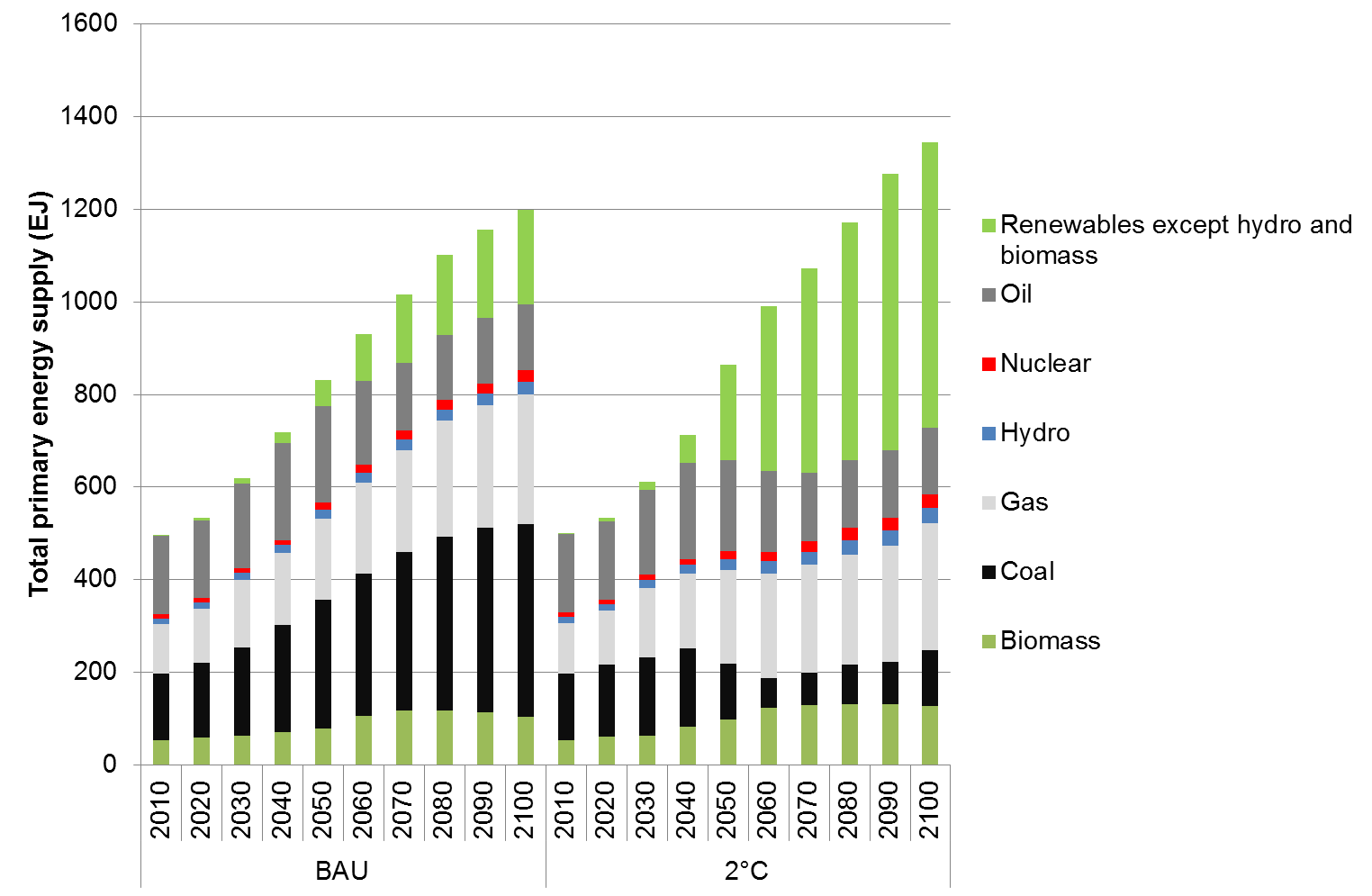
**1. SSP2: baseline and 2°C scenarios**

Figure S1 shows the evolution of the GHG emissions in the baseline and 2°C scenarios. GHGs increase from 41 Gt CO2,eq in 2010 to 78 Gt CO2,eq by 2100 in the baseline scenario, whereas they decrease to 5 Gt CO2,eq by 2070 and reach 10 Gt CO2,eqby 2100 in the 2°C scenario. Figure S1 shows GHG emissions in both scenarios.

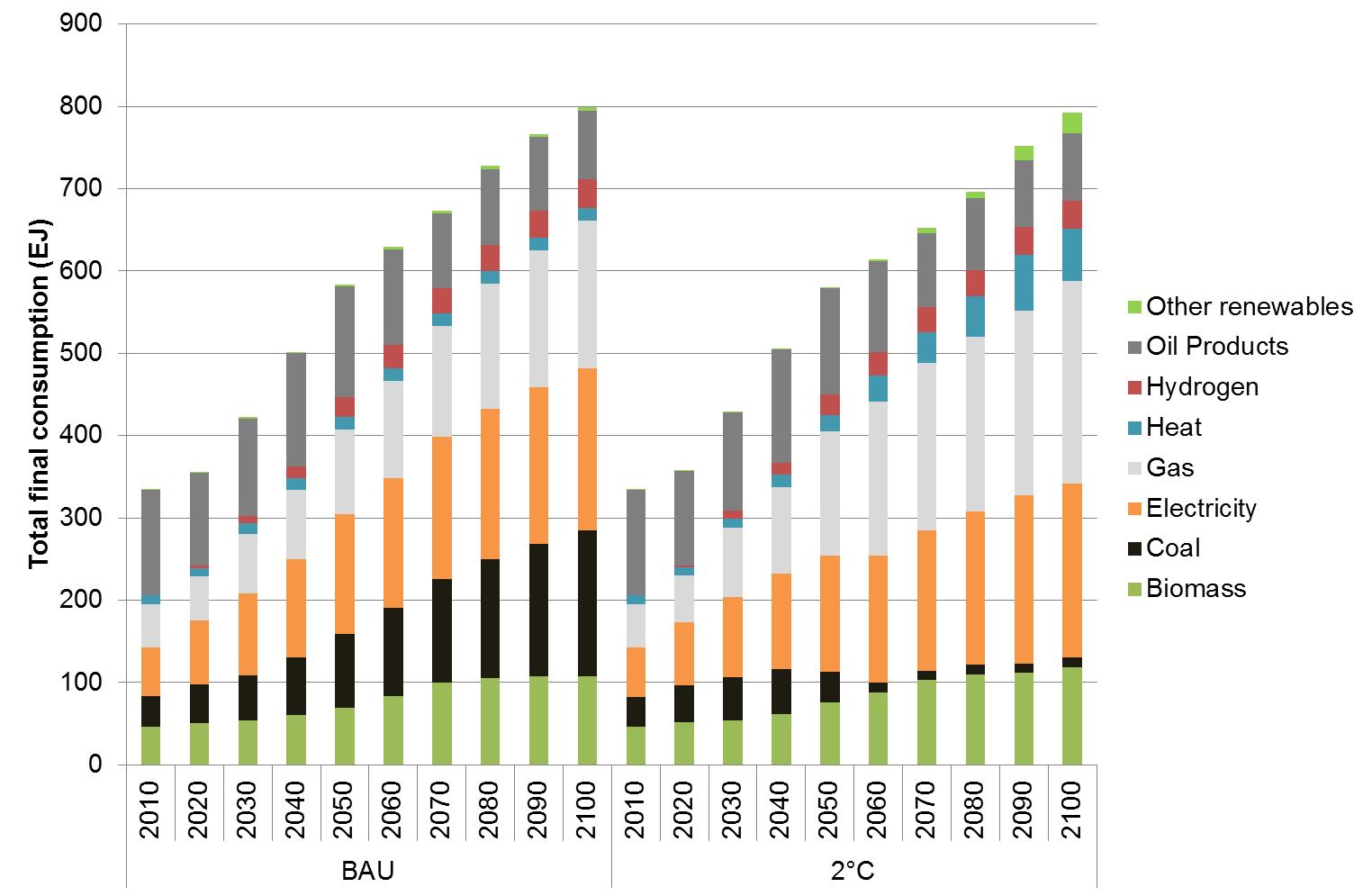


*Figure S1. Global anthropogenic GHG emissions in the baseline and 2°C scenarios*

The radiative forcing by 2100 is 5.6 W m−2 in the baseline scenario, and 2.8 W m−2 in the 2°C scenario. In the latter, a 0.1°C target overshoot leads to a temperature rise of 2.1°C in 2070 and a peaking CO2 concentration of 483 ppm in 2060, which both relax to 2°C and 444 ppm by 2100, respectively. At the end of the century, the emission mitigation efforts made to maintain global warming below 2.1°C during the 2040-2060 period are relaxed, and this translates into slightly higher GHG emissions during the 2090 and 2100 periods.



*Figure S2. Total primary energy supply in the baseline and 2°C scenarios. Table data can be found in the supplementary material*

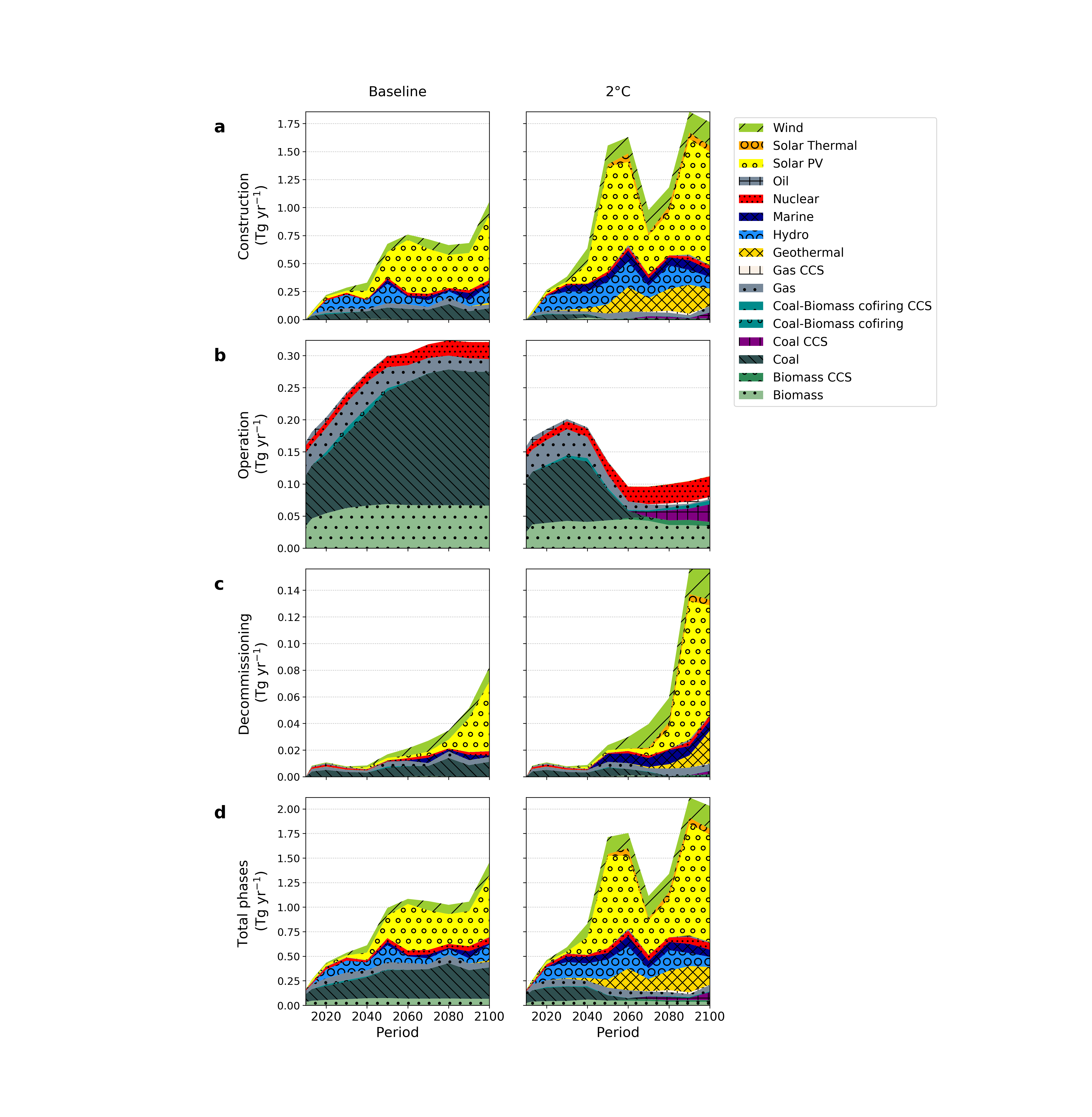


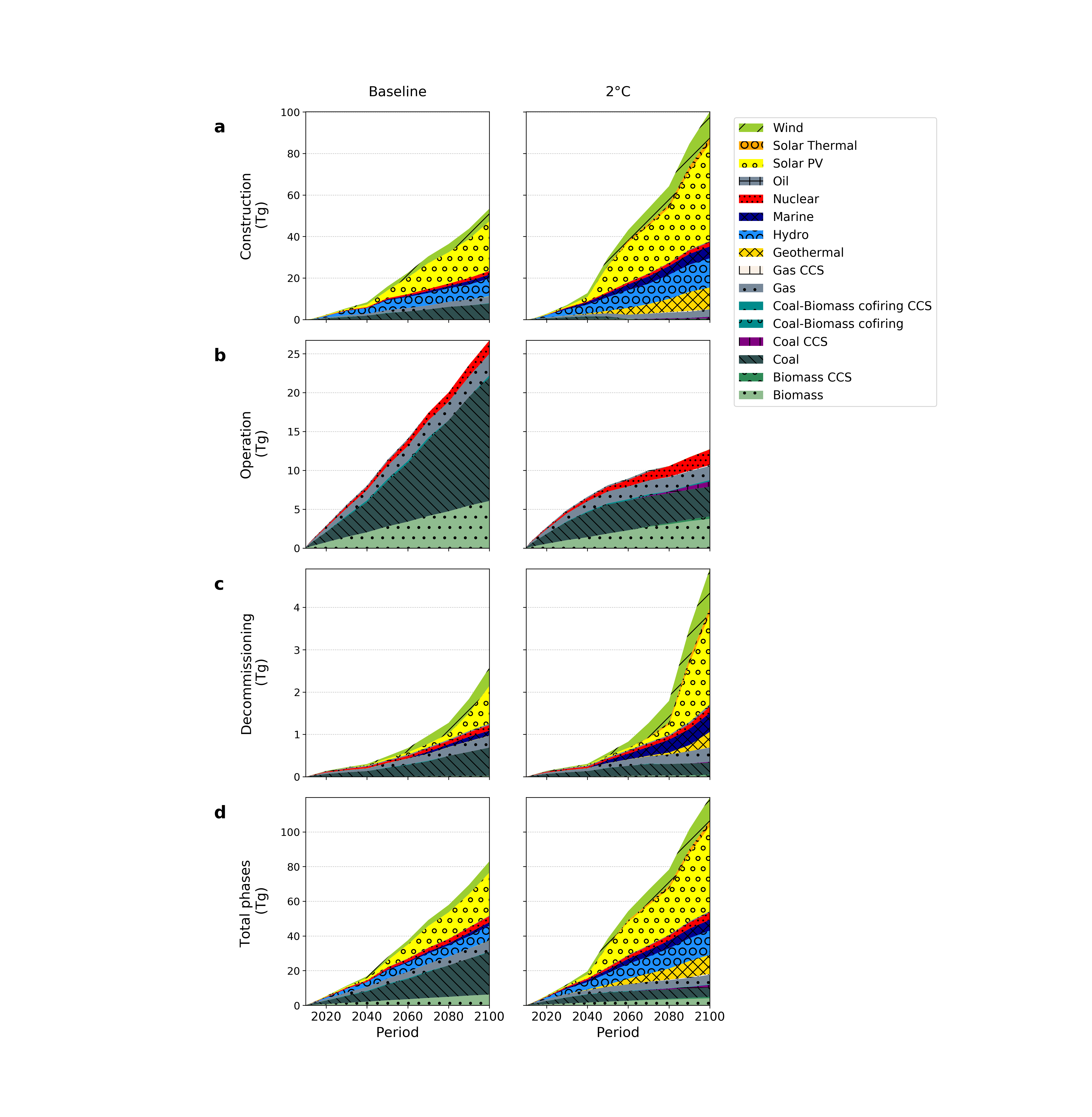
*Figure S3. Total final consumption in the baseline and 2°C scenarios. Table data can be found in the supplementary material*

In the baseline scenario, total primary energy supply grows from 500 EJ (in 2010) to 1200 EJ (in 2100) as shown in supplementary Figure S2. Coal and natural gas production increase, while shares of oil and bioenergy are slowly replaced by renewables in the second half of the century. In the 2°C scenario, primary supply shares are maintained until 2040, with the strong development of natural gas and renewable energy sources covering the energy previously supplied by oil and coal. Total final consumption reaches about 800 EJ in 2100 in both scenarios (Figure S3). While gas (mixed with 15% hydrogen) becomes the most consumed energy after 2060, electricity ranks second, with only a moderate increase (+ 13 EJ) compared to the baseline case in 2100 (196.8 EJ). Heat, hydrogen, and other renewables jointly produce 123 EJ in 2100 in the 2°C scenario. The shares of electricity in the 2100 final consumption are 24.6% and 26.6% in the baseline and 2°C scenarios, respectively.

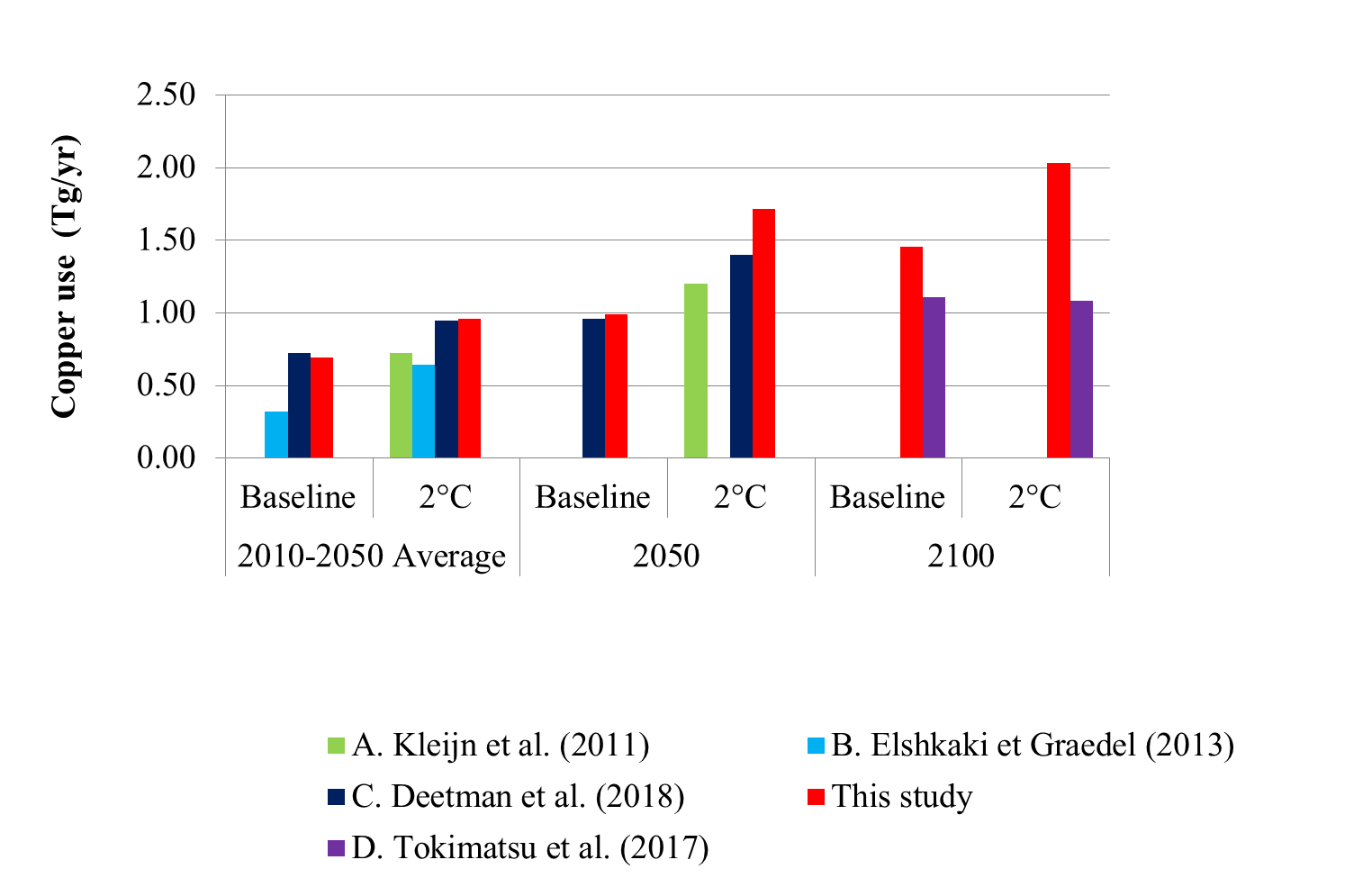
**2. Copper usage scenarios for electricity generating technologies**

Figure S4 shows the evolution of the demand for copper in the baseline and 2°C scenario. Figure S5 shows the cumulative copper usage. Copper usage increases in both scenarios, to 0.99 Tg/yr in 2050 in the baseline and to 1,71 Tg/yr in the 2°C. Most of the copper requirements are accountable to coal, hydropower and solar PV, but also geothermal and wind power plants in the 2°C scenario. Copper usage during operations decreases in this scenario, but increases in the decommissioning phase after 2040. Copper usage during construction represents 85%—90% of total use. In 2100, total use of copper due to EG technologies is 1.46 Tg/yr in the baseline scenario and close to 2.03 Tg/yr in the 2°C scenario.

*Figure S4: Copper use in three life phases in the baseline and 2°C scenarios, by technology*

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*Figure S5: Cumalive copper use in the three phases and the total use in the baseline and 2°C scenarios*



*Figure S6: Prospective copper use by global electricity generating technologies according to different studies1–3. For convenience, scenarios "Market First" and "Policy First" studied by Elshkaki et Graedel are renamed in "Baseline" and "2°C", respectively. IEA's BLUE Map scenario used by Kleijn et al. is renamed in "2°C". "COAL&NUC" and "GAS&REN" scenarios by Tokimatsu are renamed in "baseline" and "2°C".Values from Deetman et al. correspond to their medium estimates.*

Figure S6 shows a comparison between our results with a previous study on the life-cycle metal requirements of EG technologies1 (A), and three studies2–4 (B, C, and D, respectively) on the direct metal demand of EG technologies (thus excluding indirect consumption).

Our results show good agreement with those of study C, although study C does not account for indirect use of copper. The average requirements over the 2010-2050 period range from 0.64 Tg/yr to 0.96 Tg/yr across studies A, B, and C. Study D provides similar estimates (around 1.10 Tg/yr) for the 2100 period of both scenarios. These are 25%-50% lower than our estimates.

### Note

As natural gas and gas from coal mining values are expressed in cubic meters, we convert these into unit mass with the following volumic masses: 0.68 kg m-3 for natural gas and 0.58 kg m-3 for coal gas.

**References**

1. Kleijn, R., van der Voet, E., Kramer, G. J., van Oers, L. & van der Giesen, C. Metal requirements of low-carbon power generation. *Energy* **36,** 5640–5648 (2011).

2. Elshkaki, A. & Graedel, T. E. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *J. Clean. Prod.* **59,** 260–273 (2013).

3. Deetman, S., Pauliuk, S., van Vuuren, D. P., van der Voet, E. & Tukker, A. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environ. Sci. Technol.* **52,** 4950–4959 (2018).

4. Tokimatsu, K. *et al.* Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 °C target. *Appl. Energy* **207,** 494–509 (2017).