Supplementary Information

Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand

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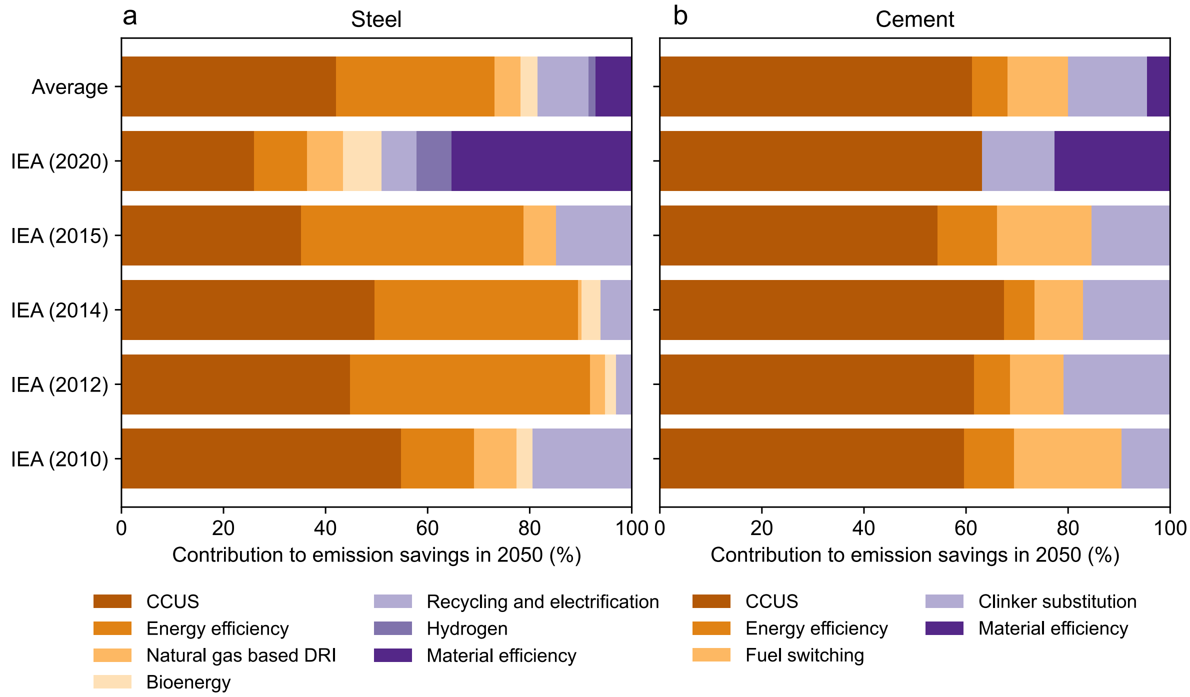
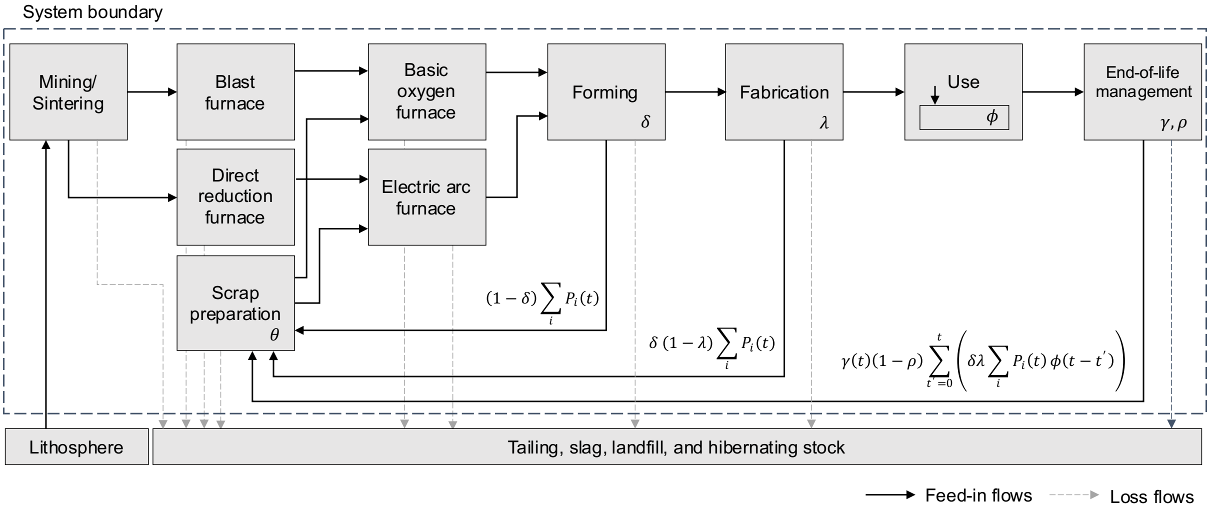


Supplementary Fig. 1 Contributions of different strategies to 2050 emission savings in the steel and cement sectors. (a) Steel. (b) Cement. Emission savings are calculated as the difference between the baseline and mitigation scenarios (e.g., 6DS and 2DS). We examined all Energy Technology Perspectives reports [1–9] and obtained the available data from those reports. Some reports are therefore not included in this figure.

Supplementary Table 1 Summary of system variables and parameters.

Symbol	Description	Data
P_i	Material production in route i	Optimization variables
$\mathrm{CI}_i^{(f)}$	Emission intensity of material production in route i due to fuel combustion and chemical process.	Tables S2 and S3
EI_i	Electricity intensity of material production in route i	Tables S2 and S3
$\mathrm{CI}^{(e)}$	Emission intensity of electricity use	Fig. 1f in the main text
CC	Captured carbon through CCUS	Fig. 1c in the main text
$\mathrm{EI}_{\mathrm{cc}}$	Energy penalty of carbon capture technologies	Table S4
$\mathrm{Cap}_{\mathrm{Carbon}}$	Carbon budget	Figure S3 and S4
$\mathrm{Cap}_{\mathrm{Electricity}}$	Maximum electricity supply	Fig. 1e in the main text
$\mathrm{Cap}_{\mathrm{F\_DRI}}$	Maximum production via fossil DRI-EAF route	Figure S5
$\mathrm{Cap}_{\mathrm{EAF}}$	Maximum production via scrap-EAF route	Mass-balancing
$\mathrm{Pre}_{\mathrm{EAF}}$	Recovered pre-consumer scrap for use in scrap-EAF route	Mass-balancing
Post	Recovered post-consumer scrap	Mass-balancing
θ	EAF production yield	96% (Ref [10])
δ	Forming yield	93% (Ref [11])
λ	Fabrication yield	86% (Ref [11])
ω	Ratio of scrap in total BOF input	20% (Ref [10])
γ	Recovery rate of post-consumer scrap	Figure S6 (calculated based on Refs [10,11])
ρ	Hibernation ratio of end-of-life products	15% (Ref [12])
ϕ	Lifetime distribution	Note

Note: We assume a normal distribution with a mean of 38 years for steel and 50 years for cement and a standard deviation of 30% of the mean [13–15].



Supplementary Fig. 2 Conceptual flow chart of iron and steel flows. The symbols at the bottom right of the process show the associated coefficients; the three equations show scrap estimation formulas based on simple mass balance. θ: EAF production yield. δ: Forming yield. λ: Fabrication yield. ϕ: Lifetime distribution. γ: Recovery rate of post-consumer scrap. ρ: Hibernation ratio of end-of-life products.

Supplementary Table 2 Key parameters that determine the emission intensity of crude steel production. Data are based on Refs [12,16–19]. Note that the data for the H2 DRI-EAF process include electricity use for green hydrogen production. The system is based on Ref [19] with an electrolyzer efficiency of 45 kWh/kg H_2 and a hydrogen mass flow rate of 1.5 (i.e., 50% oversupply of hydrogen for full conversion of iron ore in the shaft [20]).

	Fuel combustion and chemical process (kg-CO2/t-steel)	Electricity use (kWh/t-steel)
BF-BOF	1,996	328
BF-BOF with top gas recycling and coke substitution	1,680	305
Fossil DRI-EAF	840	117
H2 DRI-EAF	153	3,768
Scrap-EAF	100	508

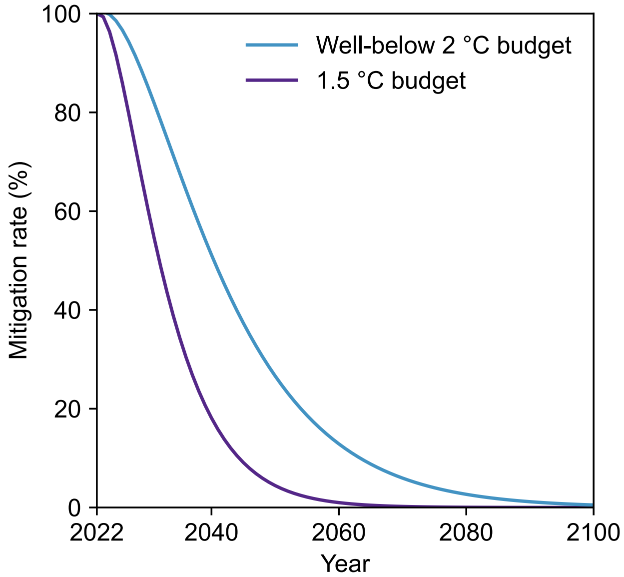
Supplementary Table 3 Key parameters that determine the emission intensity of cement production. Data are based on Refs [21–23].

	Current	Target	Unit
Clinker-to-cement ratio	72	57	%
Thermal efficiency in the cement kiln	3.4	3.0	GJ/t-clinker
Milling/grinding electrical efficiency	102	85	kWh/t-cement
Carbon intensity of fuel mix	85	58	kg-CO_2/GJ

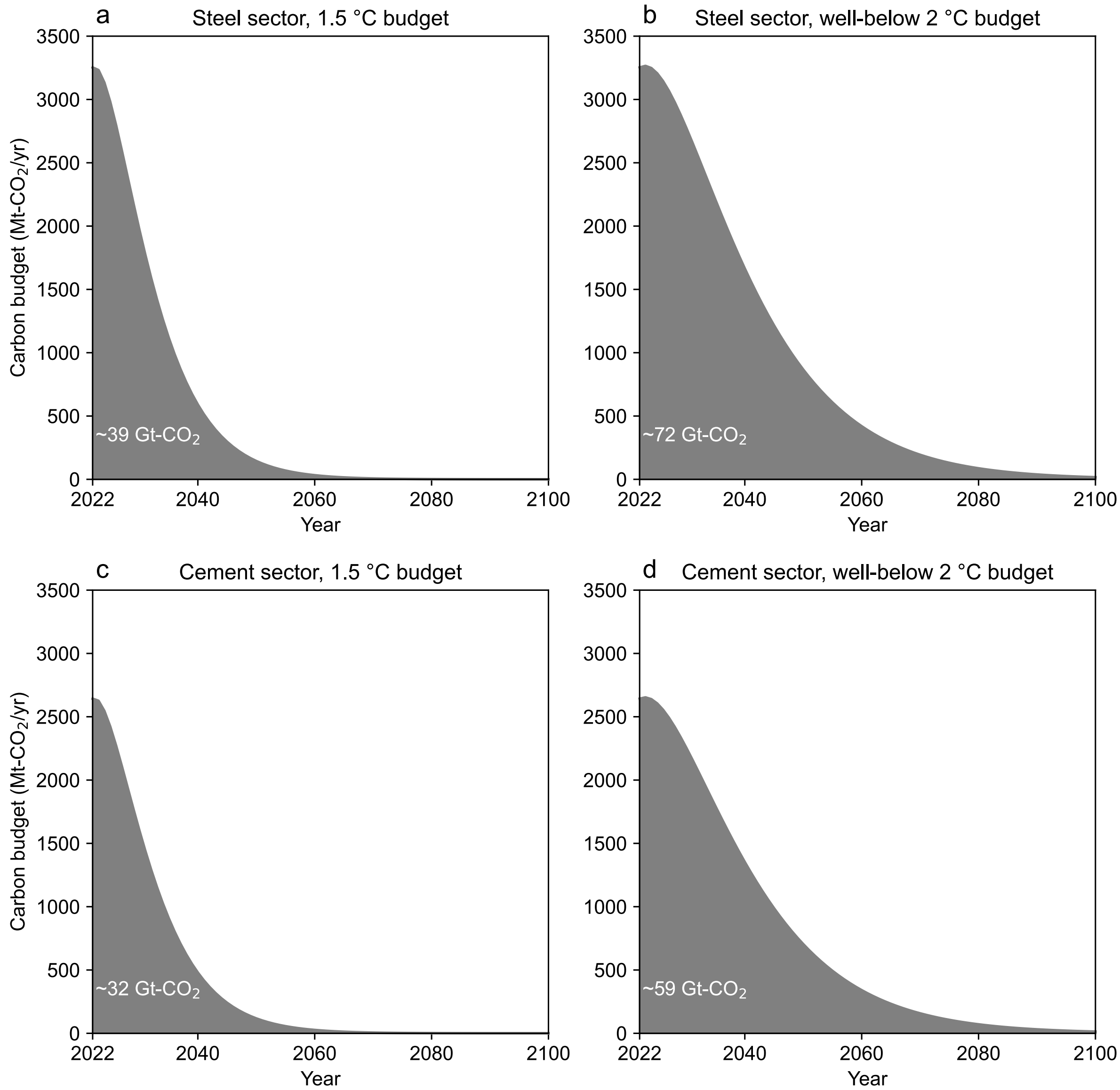
Supplementary Table 4 Overview of carbon capture technologies and energy penalties. Data are based on Refs [24,25]. Note that our simplified model does not take into account detailed processes within the plant (e.g., CO_2 purity and capture rates). Therefore, the model only considers the potential range of total carbon capture in the sector and the energy penalty to estimate the maximum global materials production within Paris-compliant carbon budgets.

	Overview	Value
Steel sector	This study assumes the use of post-combustion with membranes due to the high technology readiness level [24] (*). The system can be effectively operated using electrical energy.	1.8 GJ/t-CO_2
Cement sector	This study assumes the use of membrane-assisted CO_2 liquefaction, which has the advantage of being easily retrofitted and requires only electricity as an input to the process [25].	3.2 GJ/t-CO_2

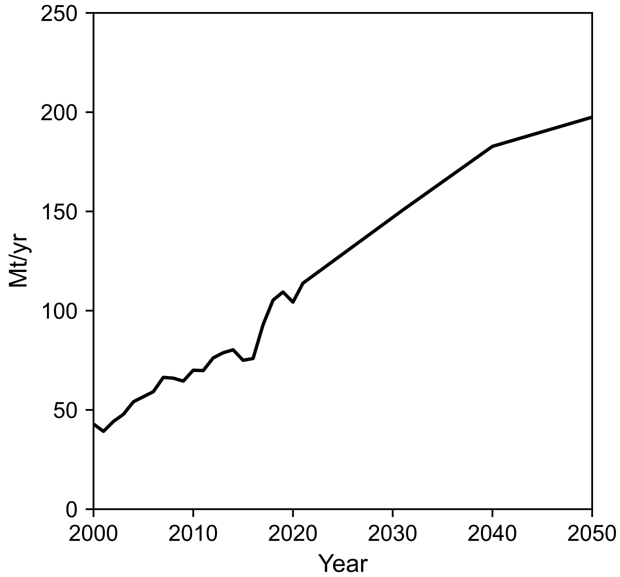
(*) It should be noted that many previous studies have assumed post-combustion with chemical absorption as the carbon capture technology in the steel sector [24]. Therefore, there is significant uncertainty in the energy penalty of post-combustion with membranes, which can be up to 4.4 GJ/CO_2. We explore the impact of this uncertainty in the form of a sensitivity analysis (**Supplementary Fig. 8**).



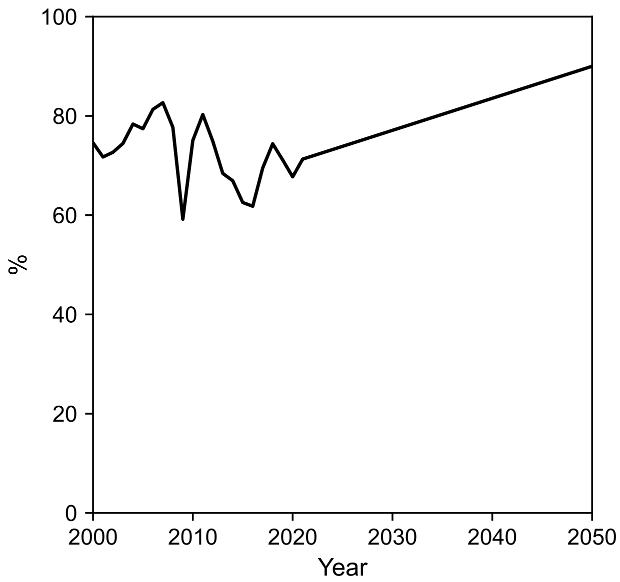
Supplementary Fig. 3 Annual emissions mitigation rate for Paris-compliant carbon budgets. The carbon budget is based on limiting the global mean temperature rise within 1.5 °C with a 50% probability, consistent with the Paris Agreement pledges (~420 Gt-CO_2) [26]. We also consider a carbon budget for a 50% probability of 1.7°C (equivalent to an 83% probability of 2.0°C), which corresponds to "well below 2°C" (~770 Gt-CO_2) [27]. The annual emissions mitigation rate is determined using equation 3 in Ref [28].



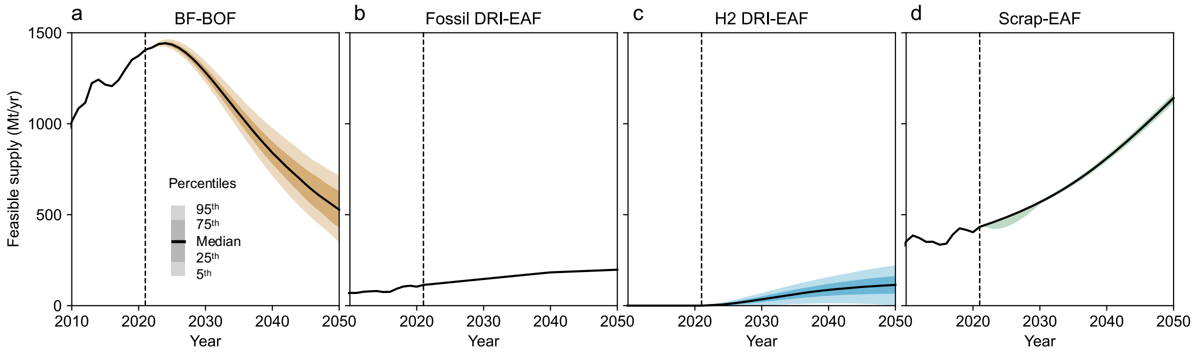
Supplementary Fig. 4 Paris-compliant carbon budgets for the steel and cement sectors. (a) Steel sector, 1.5 °C budget. (b) Steel sector, well-below 2 °C budget. (c) Cement sector, 1.5 °C budget. (d) Cement sector, well-below 2 °C budget. We allocate the total carbon budgets to the global steel and cement sectors by multiplying the current emissions of the steel and cement sectors by the annual emissions mitigation rate shown in **Supplementary Fig. 3**.



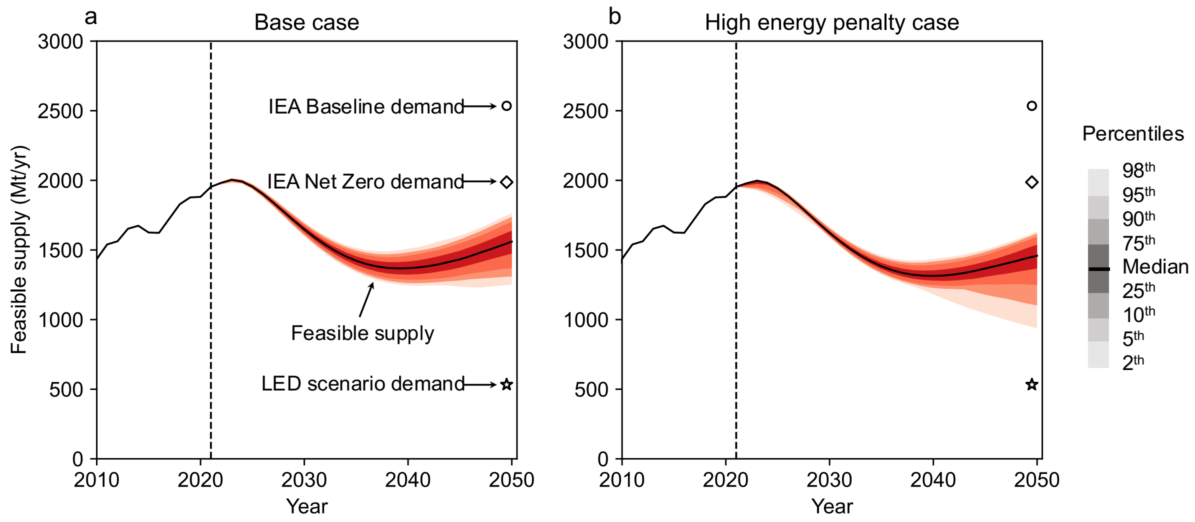
Supplementary Fig. 5 Maximum deployment of fossil DRI-EAF route. Fossil fuel-based DRI production is strongly influenced by regional factors and has been predominantly deployed in the Middle East and India, where significant fossil fuel reserves exist [29]. In this study, the maximum deployment of fossil fuel-based DRI production is determined exogenously based on a detailed analysis conducted by the IEA [7]. The IEA's analysis takes into account various factors such as regional fossil fuel availability, technological feasibility, and environmental considerations to establish the upper limit for the deployment of this production technology.



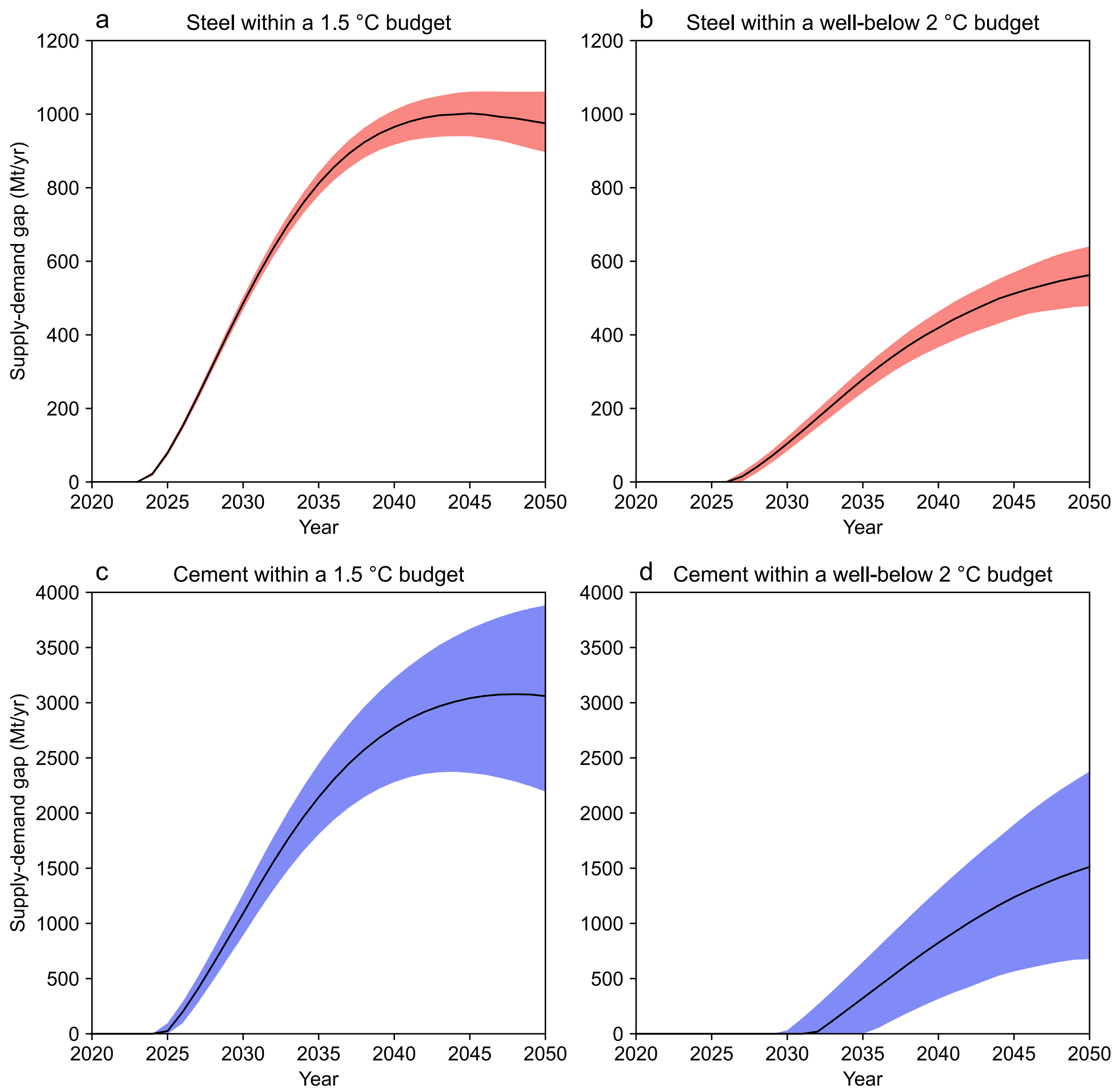
Supplementary Fig. 6 Recovery rate of post-consumer scrap. The historical data are calculated based on Ref [11] and the 2050 target value is based on Ref [10].



Supplementary Fig. 7 Global crude steel production per process within a well-below 2 °C budget by 2050. (a) BF-BOF: blast furnace and basic oxygen furnace route. (b) Fossil DRI-EAF: fossil fuel-based direct reduced iron and electric arc furnace route. (c) H2 DRI-EAF: hydrogen-based direct reduced iron and electric arc furnace route. (d) Scrap-EAF: scrap-based electric arc furnace route.



Supplementary Fig. 8 Sensitivity of feasible steel supply within a 1.5 °C budget to the energy penalty of carbon capture technologies. (a) Base case: 1.8 GJ/t-CO_2. (b) High energy penalty case: 4.4 GJ/t-CO_2. The high energy penalty case has a wider range of feasible supply uncertainty and a median in 2050 that is about 7% lower than the base case.



Supplementary Fig. 9 Gap between feasible supply and expected baseline demand. (a) Steel sector within a 1.5 °C budget. (b) Steel within a well-below 2 °C budget. (c) Cement within a 1.5 °C budget. (d) Cement within a well-below 2 °C budget. The solid black line shows the median, and the colored bands around it show the interquartile range. We assume that the gap between feasible supply and expected demand for steel and cement will be filled by the current emission-intensive production processes (i.e., BF-BOF). This would entail carbon emissions of approximately 2.1 t-CO_2/t-steel or 0.6 t-CO_2/t-cement. The consequences of such emissions would be severe, potentially resulting in cumulative emissions of up to ~160 Gt-CO_2 by 2050. This amount represents ~40% of the remaining 1.5°C budget or ~20% of the remaining well-below 2°C budget.

Supplementary Table 5 Material saving potential through a range of material efficiency strategies in the construction sectors. Potential savings are multiplicative rather than additive across the strategies. Estimates are based on weighted averages for each use. Data are based on Refs [30–38].

Strategy	Description	Buildings	Infrastructure	Construction sectors
Efficient design	Reduced overdesign, optimized design	20-50%	20-30%	20-45%
Fabrication yield improvement	Prefabrication, better specification, use of over-ordered materials for other purposes	1-2%	1-2%	1-2%
More intense use	Smaller residences, larger household sizes, fewer second homes, dual-use spaces, shared or multi-purpose office spaces, centralization of urban functions	20-50%	0-10%	15-35%
Lifetime extension	Proactive maintenance, repurposing, reuse, remanufacturing, changing consumer preferences	10-20%	0-5%	5-15%
Total		40-80%	20-40%	35-70%

Supplementary Table 6 Material saving potential through a range of material efficiency strategies in the manufacturing sectors. Potential savings are multiplicative rather than additive across the strategies. Data are based on Refs [30,32,39–44].

Strategy	Description	Vehicles	Machinery	Consumer goods	Manufacturing sectors
Efficient design	Light-weighting, right-sizing	25-45%	30%	30%	30-35%
Fabrication yield improvement	Improved blanking and stamping process, reduced material overlap, nested parts design	5-10%	5%	10%	5-10%
More intense use	Car-sharing, ride-sharing, better scheduling and coordination	25-40%	10%	0%	10-15%
Lifetime extension	Reuse, remanufacturing, changing consumer preferences, revised inspection system	10-20%	10%	50%	25-30%
Total		50-75%	45%	70%	55-65%

Supplementary References

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