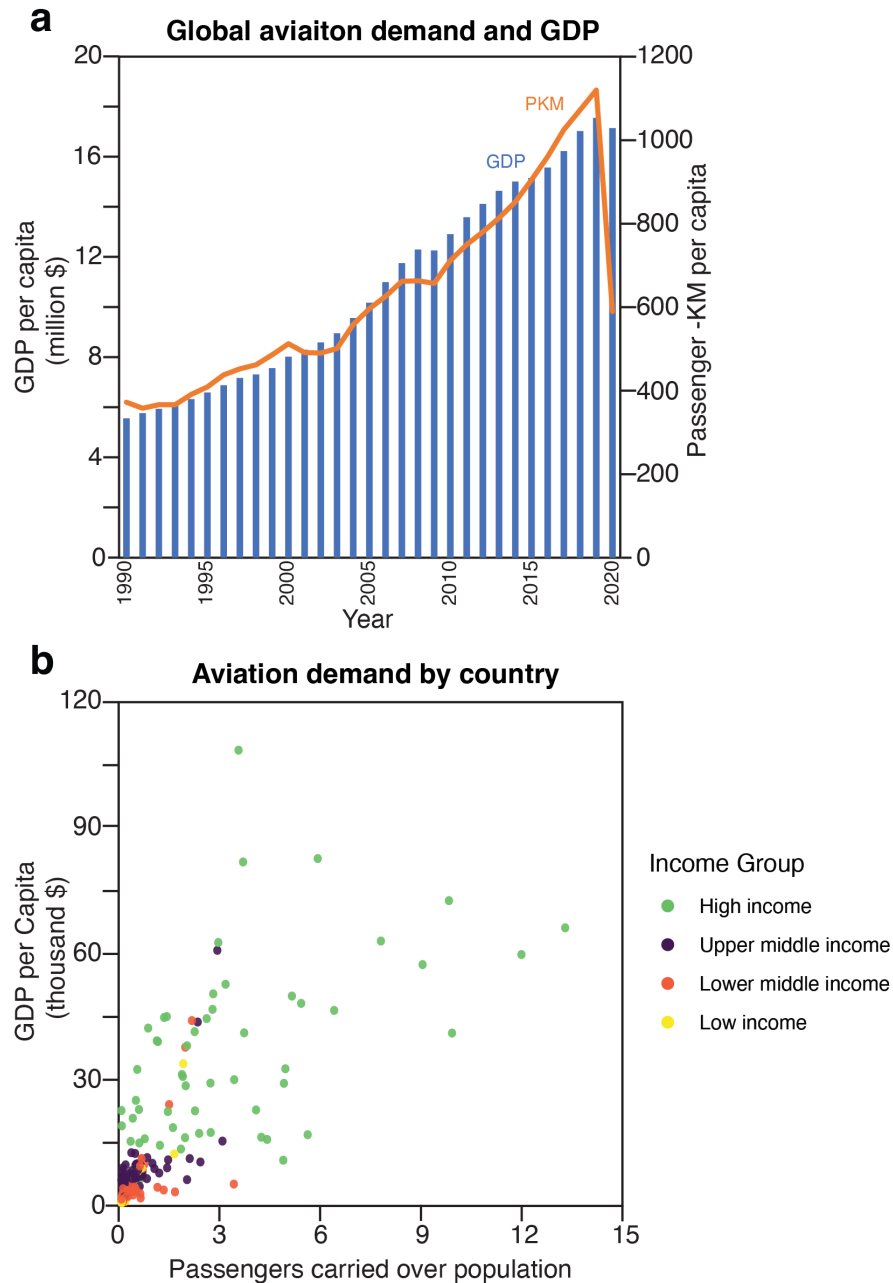

Pathways to net-zero emissions from aviation

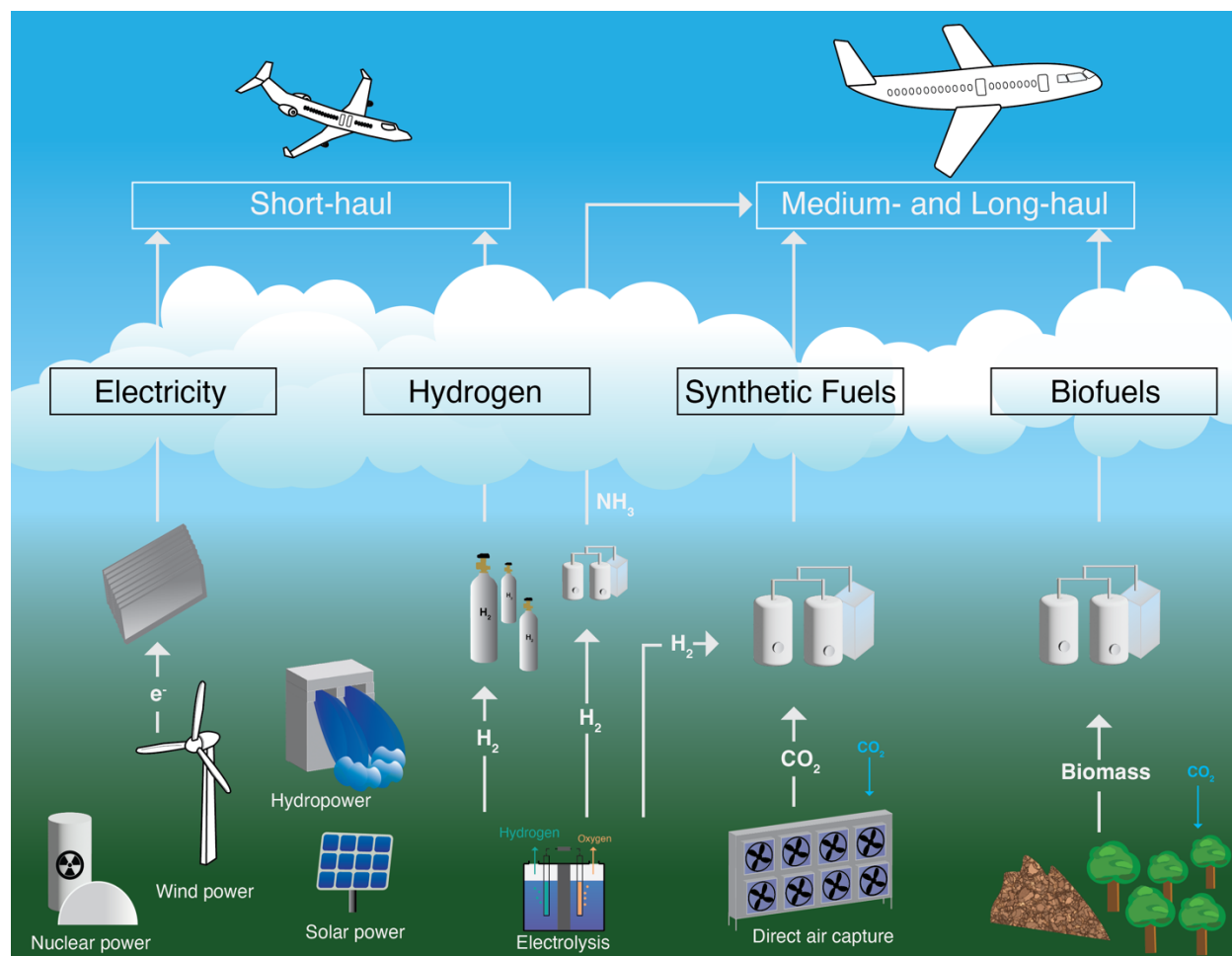
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Supplementary Figure 1 | (a) Global gross domestic product per capita compared to passenger-kilometers per capita. GDP per capita data from the World Bank¹, PKM data from ICAO^{2,3}, global population data from the World Bank⁴. **(b)** Aviation demand by country based on passengers carried over country's population and GDP per capita with data from the World Bank^{1,4,5}. Income group classification is also with data from World Bank⁶. Panel **(b)** omits Ireland (GDP per capita of \$80,886 and passengers carried per capita of 34.5). All data from panel **(b)** is for 2019, except for Aruba (2018 values), Jamaica (2018 values), Gabon (2016 values), Eritrea (2015 values), Yemen (2018 values) because of data availability.



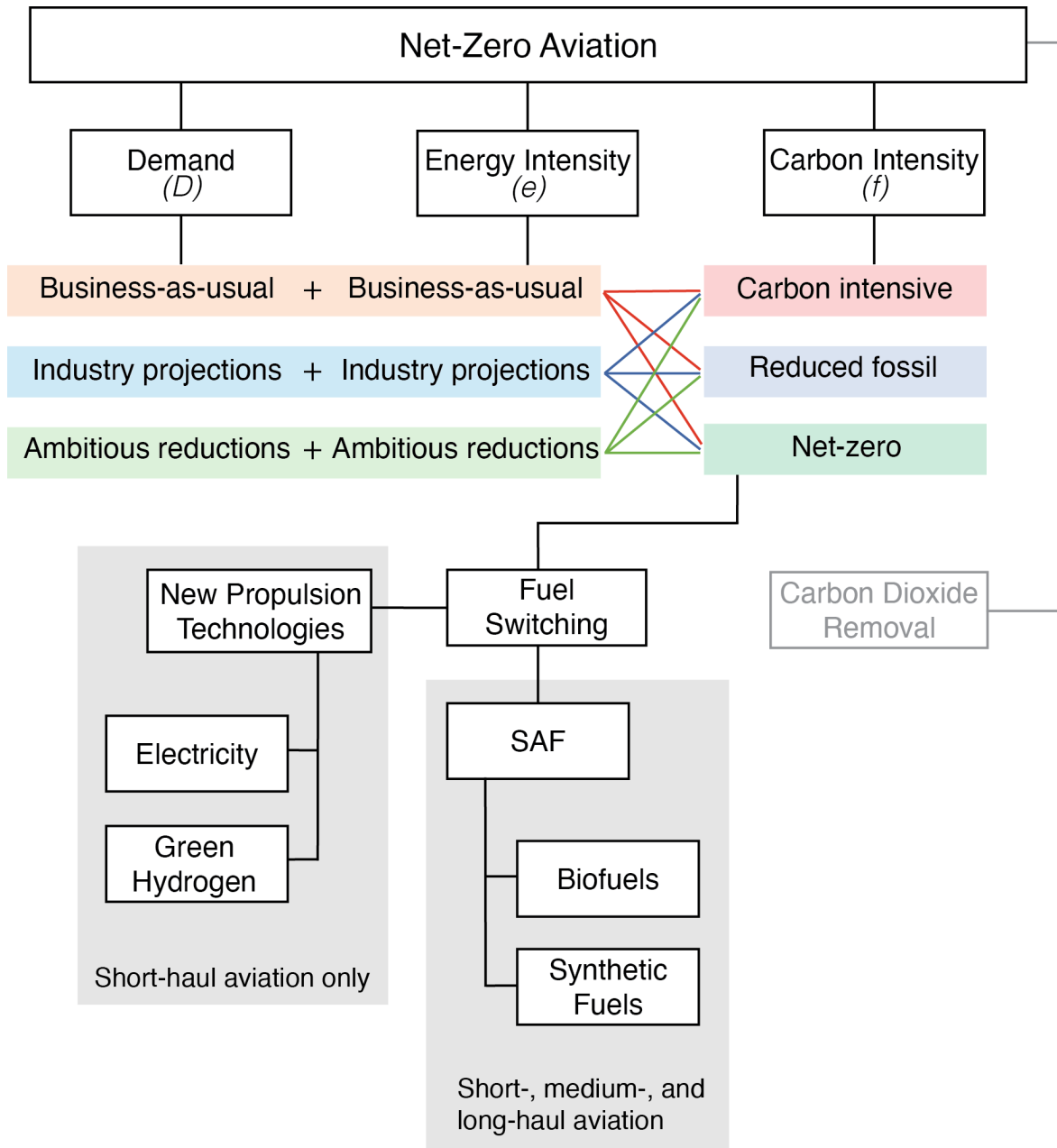
Supplementary Figure 2 | Schematic with different decarbonization options for aviation based on flight time: short-haul (<3 hours), medium-haul (3-6 hours), and long-haul (>6 hours)⁷. Decarbonizing aviation will be challenging, however, there are different technologies that could help achieve a net-zero sector^{8–10}. Four main energy sources are considered: electricity^{11–13}, hydrogen^{12–14}, synthetic fuels^{12,13,15–17}, and biofuels^{12–14,18–22}. We have also added a potential ammonia (NH₃) pathway¹⁴. The categories are not exclusive and are meant to depict a simple representation of decarbonizing aviation. Note that, though not depicted here for simplification, synthetic fuels and biofuels could also power short-haul aviation. Electricity and hydrogen are not expected to power medium- and long-haul aviation (see Supplementary Figure 6)^{12,22,23}.

		Demand & Energy Intensity (De)		
		Business-as-usual	Industry Projections	Ambitious reductions
Carbon Intensity (f)	Carbon Intensive	Historical demand	Industry-based demand	Low demand scenario
		Historical energy intensity	Industry commitment for energy intensity	High energy intensity reductions
		Fossil jet fuel	Fossil jet fuel	Fossil jet fuel
	Reduced Fossil	Historical demand	Industry-based demand	Low demand scenario
		Historical energy intensity	Industry commitment for energy intensity	High energy intensity reductions
		Medium biofuel & low alternative technology deployment	Medium biofuel & low alternative technology deployment	Medium biofuel & low alternative technology deployment
	Net-Zero	Historical demand	Industry-based demand	Low demand scenario
		Historical energy intensity	Industry commitment for energy intensity	High energy intensity reductions
		High biofuel & medium alternative technology deployment	High biofuel & medium alternative technology deployment	High biofuel & medium alternative technology deployment

Decreasing aviation demand & energy intensity of aircraft →

Decreasing carbon intensity of energy ↓

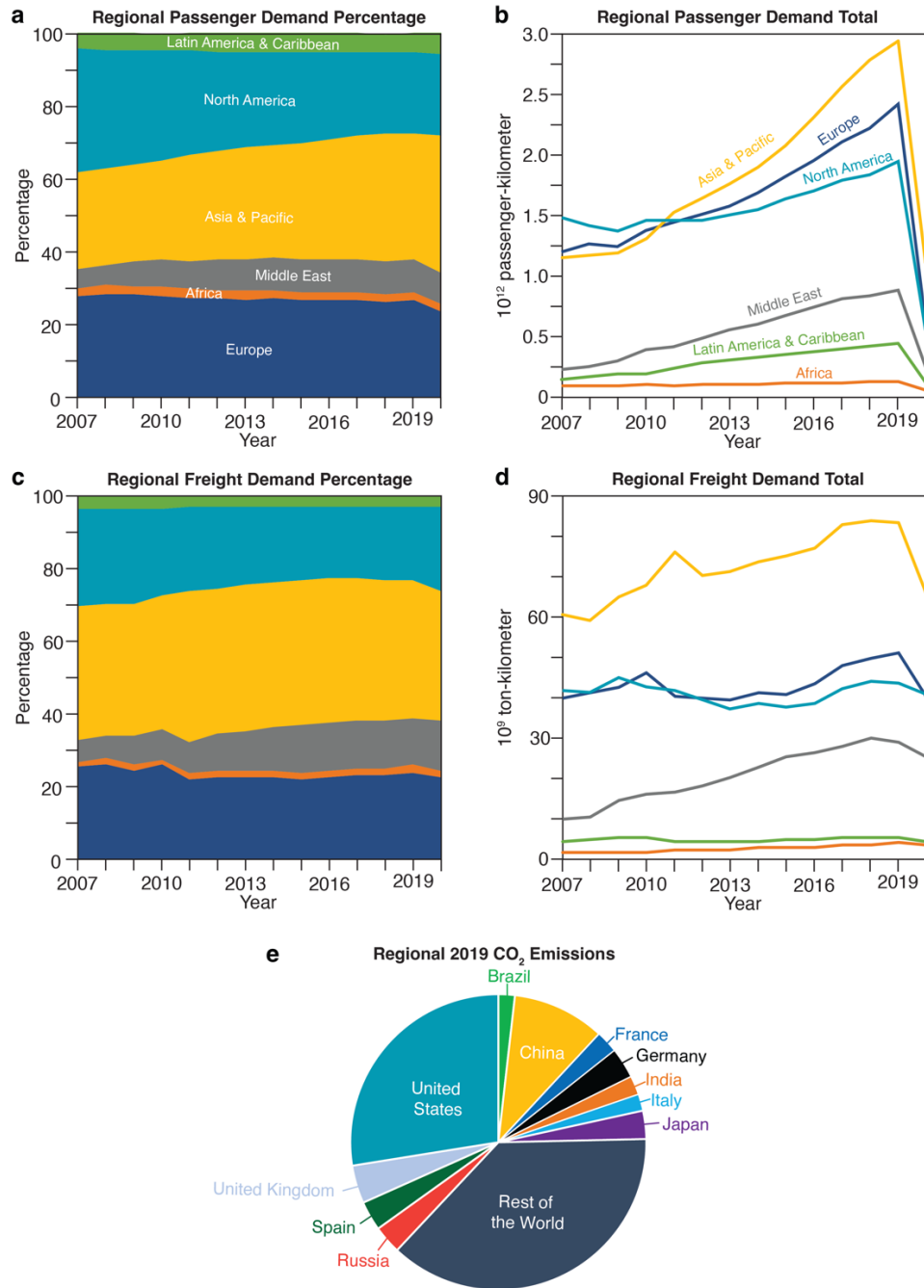
Supplementary Figure 3 | Nine scenarios for future global aviation emissions based on the Kaya identity. More details in Supplementary Table 1.



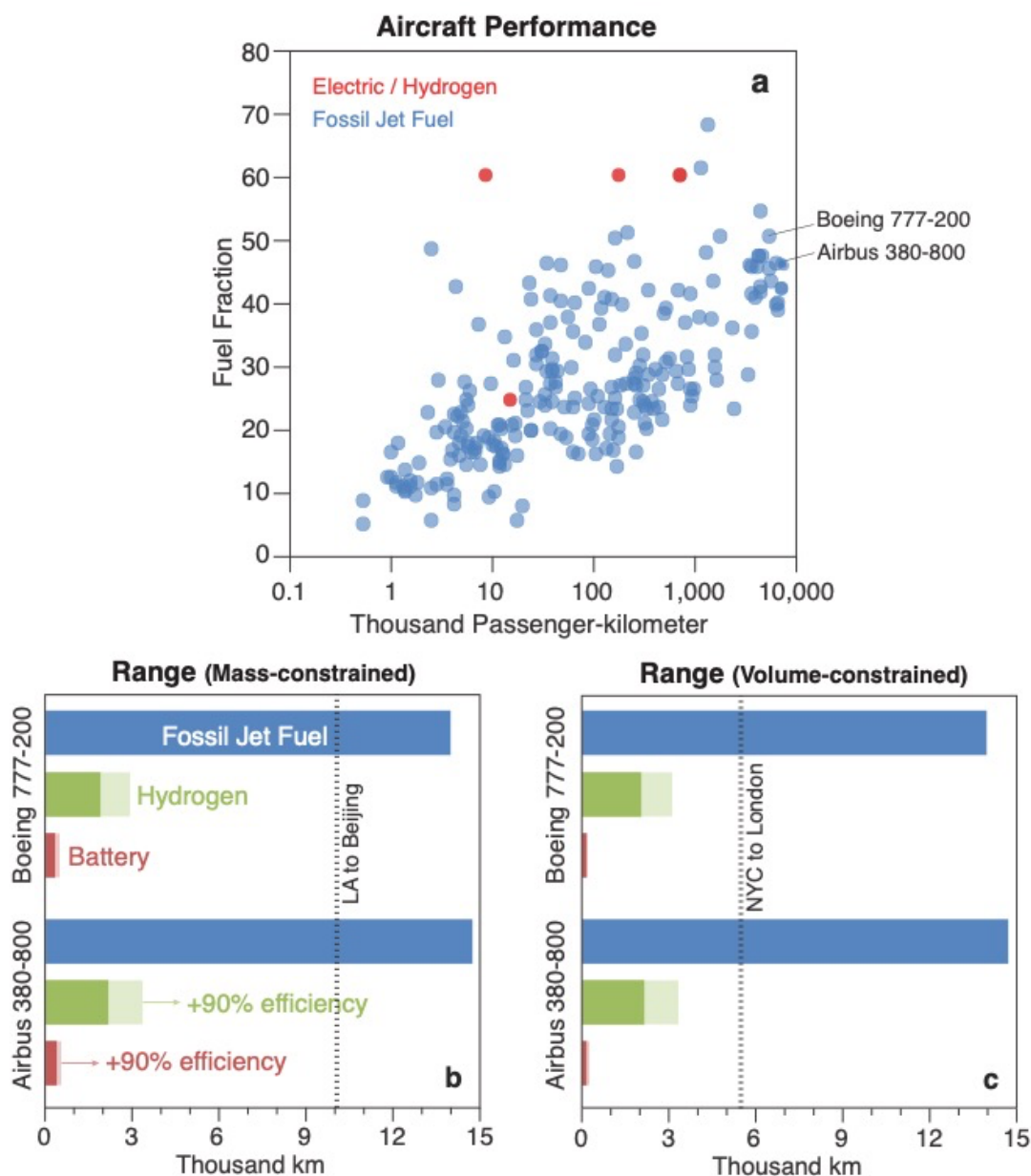
Supplementary Figure 4 | Schematic for Kaya properties in net-zero aviation and our scenario design. We pair demand (D) and energy intensity (e) assumptions with different carbon intensities (f), resulting in nine scenarios. Net-zero technologies are included based on flight duration (short-, medium-, and long-haul)⁷. Carbon dioxide removals are analyzed as a resource to achieve net-zero emissions per scenario. We highlight two fuel switching options: sustainable aviation fuels (SAFs) that could power any aircraft and new propulsion technologies which could only power short-haul aviation.

Supplementary Table 1 | The Kaya Identity Sources and Explanations

	Emissions (<i>F</i>)	Demand (<i>D</i>)	Energy intensity (<i>e</i> = <i>E/D</i>)	Carbon intensity (<i>f</i> = <i>F/E</i>)
	<i>Gt CO₂</i>	<i>tkm_e</i> and <i>pkm_e</i>	<i>MJ/tkm_e</i> and <i>MJ/pkm_e</i>	<i>gCO₂/MJ</i> and <i>gCO₂eq/MJ</i>
Historical	Historical emissions (1990-2020) from IEA ²⁴ . 2021 emissions from CMP and adjusted by previous year difference between CMP and IEA (13%) ²⁵ .	Passenger demand from ICAO (1990-2020)^{2,3}. 2021 values were estimated based on emissions²⁵. Freight demand from 1990-2020 from the World Bank Data²⁶. For 2021 we assume that cargo demand grew 7.9% in 2021 compared to 2019 based on IATA's estimates²⁷. Passenger demand was converted from "passenger-km" to "ton-km-equivalent" assuming 90 kg by passenger on average, consistent with IEA²⁸.	Energy intensity was calculated for 1990-2021 based on total aviation demand (passenger and freight) ^{2,3,26} and total aviation fuel consumption from IEA's World Energy Statistics and Balances ²⁹ .	We consider tank-to-wake emissions only, which excludes fuel production and includes only carbon combustion emissions for all fuels with values from ¹⁹ , which are 73.5 gCO ₂ /MJ (124.9 gCO ₂ eq/MJ) for fossil jet fuel. Assumed carbon intensity is 0 gCO ₂ /MJ (51.4 gCO ₂ eq/MJ) for biofuels and synthetic fuels (GWP100). Alternative technologies (EV-powered planes and green hydrogen) are assumed to be 0 gCO ₂ /MJ (0 gCO ₂ eq/MJ).
Projections	Future emissions projected based on different parameters from the Kaya identity.	Future demand scenarios follow three pathways: 1. Business-as-usual scenario following historical GDP growth of 4% per year, which represents the 1980-2019 average³⁰ with industry-based³¹ passenger recovery of returning to 2019 levels by 2024. 2. Industry projections scenario low-growth projection of 2.9% per year for passenger demand and 2.6% yearly increase for freight³¹, with industry-based³¹ passenger recovery of returning to 2019 levels by 2024. 3. An Ambitious reductions scenario where demand remains nearly flat, increasing by 12% by 2050 compared to 2019, consistent with the assumptions from the IEA's Net-zero scenario³⁵. No recovery.	Future energy intensity scenarios follow three pathways: 1. Business-as-usual scenario following 1% yearly energy intensity improvements continue into the future³². 2. Industry projections scenario commitment of achieving 2% increases per year³³. 3. An Ambitious reductions scenario where energy intensities improve at an average 4% per year, consistent with the IEA's Net-zero scenario¹³, which we extend to 2050.	Future carbon intensity scenarios follow three trajectories: 1. Carbon Intensive scenario where fossil jet fuel continues to power 100% of planes to 2050 (Supplementary Table 2). 2. A Reduced fossil scenario that follows a pathway with 65% of medium and long-haul aviation powered by sustainable aviation fuels and 13% of short-haul planes powered by non-emitting propulsion systems (electric planes or hydrogen) by 2050, following IATA's net zero emissions plan³⁴ (Supplementary Table 3). 3. A Net-Zero scenario where biofuels power 100% of medium- and long-haul aviation by 2050, and non-emitting propulsion systems power 50% of short-haul flights, with the remainder being powered by biofuels (Supplementary Table 4).



Supplementary Figure 5 | Regional aviation demand for passenger (**a** and **b**) and for freight (**c** and **d**) following ICAO's regions^{36–49}. Regional 2019 carbon dioxide emissions by countries and the rest of the world (**e**)²⁵. Note the different units in **b** (passenger-kilometer) and **d** (ton-kilometer). In order to convert to ton-kilometer-equivalent (consistent with Figure 1 from manuscript) we multiplied each passenger-km by 90 kg, and convert them to metric tons (consistent with IEA)²⁸.



Supplementary Figure 6 | The role of different fuels powering aviation. Panel (a) shows aircraft performance for different planes based on fuel fraction and thousand passenger-kilometer, with data from ICAO⁵⁰. Blue dots represent fossil jet fuel powered planes, and red dots represent planes powered by electricity or hydrogen. Total range for two types of long-haul planes are shown in terms of mass (b) and volume (c). Blue represents the maximum possible distance to fly in thousand km for each type of plane powered by fossil jet fuel, while green represents hydrogen and red battery powered. The lighter shades assume up to 90% higher efficiency based on Epstein et al.¹¹. There are two reference flights added as a dashed line in panels (b) and (c): from Los Angeles (LAX) to Beijing (PEK), and from New York City (JFK) to London (LHR). For total range based on mass (b) we assume 60% maximum fuel fraction (remainder allocated to passengers, seats, cargo, etc.), for the battery weight we assume 260 Wh/kg of a 18650 Li-ion cell, and for hydrogen weight 1500 kWh/t⁵¹. For total range based on volume (c) we assume that the volume of batteries and hydrogen is 1.5 times the volume of fossil jet fuel, and that the volume of batteries is 0.0785 kWh/L of 18650 Li-ion cell, and 1 kWh/L for hydrogen.

Supplementary Table 2 | Energy Consumption Fraction and Carbon Intensity for Carbon Intensive Scenarios*

	Long-, medium-, & short-haul				
Year	Fossil Jet fuel	SAF (biofuels/ synfuels)	Non-emitting propulsion (hydrogen/ electric)	Carbon Intensity gCO ₂ /MJ	Carbon Intensity gCO ₂ eq/MJ
2022	1.00	0.00	0.00	73.5	124.9
2025	1.00	0.00	0.00	73.5	124.9
2030	1.00	0.00	0.00	73.5	124.9
2035	1.00	0.00	0.00	73.5	124.9
2040	1.00	0.00	0.00	73.5	124.9
2045	1.00	0.00	0.00	73.5	124.9
2050	1.00	0.00	0.00	73.5	124.9

*Carbon intensive scenarios use only fossil jet fuel. Supplementary table 2 includes both short-haul and medium- and long-haul flights, and there is no distinction between the three since all flights use fossil jet fuel. Carbon intensity is calculated based on the percentage of long- and medium, and short-haul flights, and the percentage and carbon intensity of the energy source.

Supplementary Table 3 | Energy Consumption Fraction and Carbon Intensity for Reduced Fossil Scenarios*

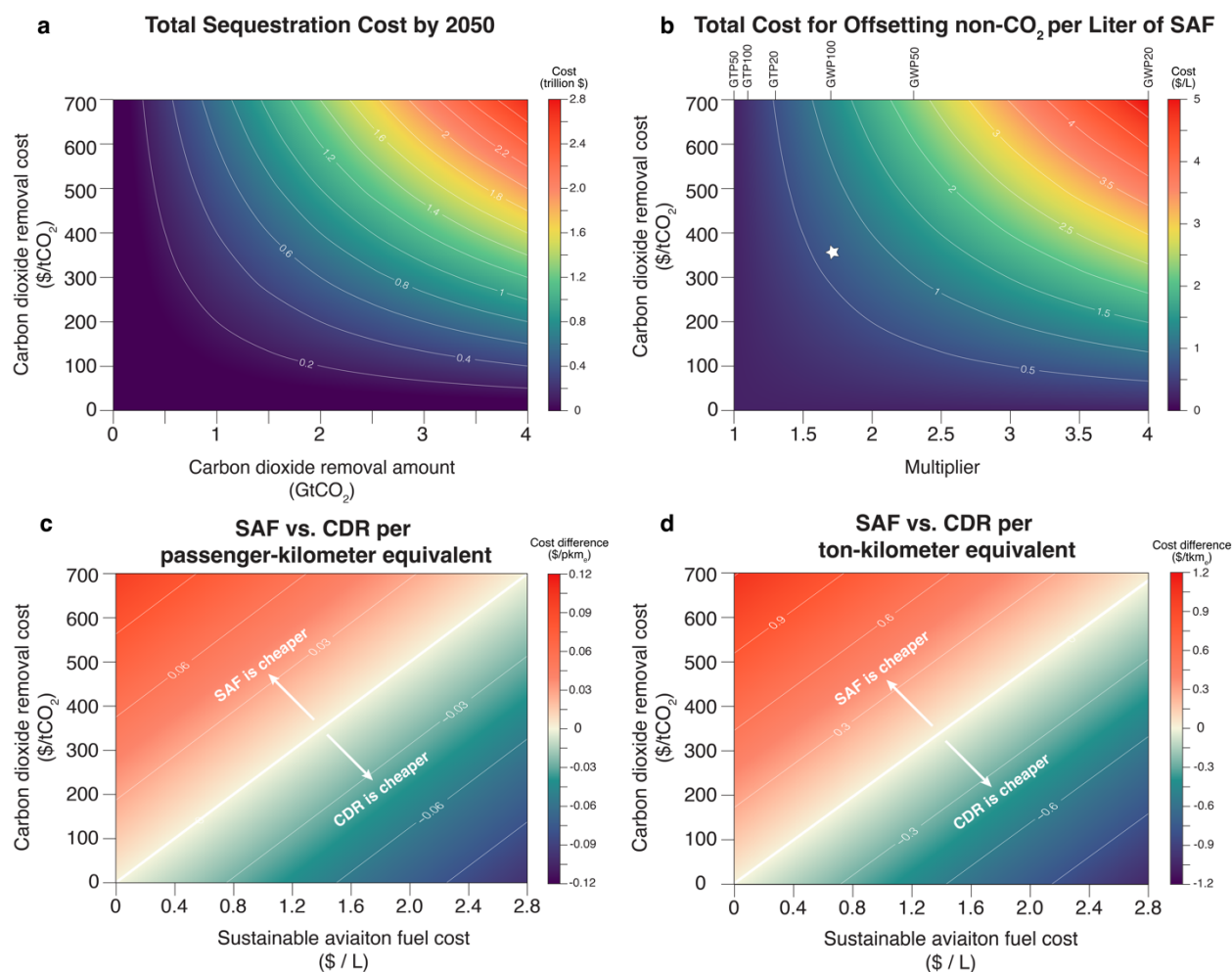
	Long- & Medium-haul		Short-haul				
Year	Fossil Jet fuel	SAF	Fossil Jet fuel	SAF	Non- emitting propulsion	Carbon Intensity gCO ₂ /MJ	Carbon Intensity gCO ₂ eq/MJ
2022	1.00	0.00	1.00	0.00	0.00	73.5	124.9
2025	0.98	0.02	0.98	0.02	0.01	71.8	123.1
2030	0.95	0.05	0.92	0.05	0.03	68.5	119.1
2035	0.83	0.17	0.78	0.16	0.06	59.2	109.1
2040	0.61	0.39	0.56	0.36	0.08	42.9	92.1
2045	0.46	0.54	0.41	0.48	0.11	31.9	80.4
2050	0.35	0.65	0.30	0.57	0.13	23.9	71.7

*Based on distance flown by plane, the split is 54% short-haul, 25% medium-haul and 21% long-haul⁵². We are assuming that this split remains constant into the future. We group medium- and long-haul and differ them from short-haul aviation since we assume that longer flights cannot use non-emitting propulsion systems (hydrogen and electricity). Carbon intensity is calculated based on the percentage of long- and medium, and short-haul flights, and the percentage and carbon intensity of the energy source. Values may not add up to 1 because of rounding errors.

Supplementary Table 4 | Energy Consumption Fraction and Carbon Intensity for Net-zero Scenarios*

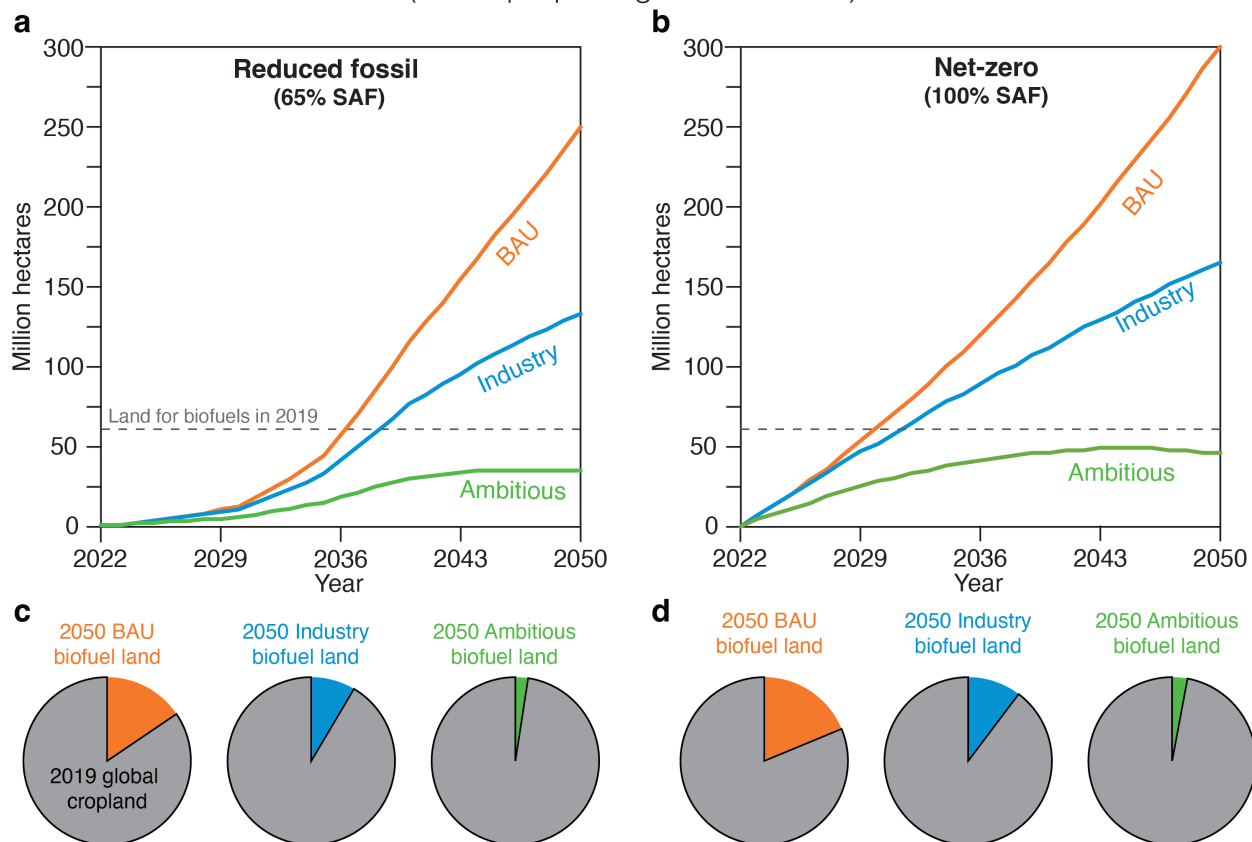
	Long- & Medium-haul		Short-haul			Carbon Intensity gCO ₂ /MJ	Carbon Intensity gCO ₂ eq/MJ
Year	Fossil Jet fuel	SAF	Fossil Jet fuel	SAF	Non-emitting propulsion		
2022	1.00	0.00	1.00	0.00	0.00	73.5	124.9
2025	0.89	0.11	0.88	0.11	0.02	64.9	115.8
2030	0.71	0.29	0.63	0.25	0.12	49.2	97.4
2035	0.54	0.46	0.42	0.37	0.21	34.9	80.4
2040	0.36	0.64	0.25	0.45	0.31	21.9	64.8
2045	0.18	0.82	0.11	0.49	0.40	10.3	50.5
2050	0.00	1.00	0.00	0.50	0.50	0.00	37.6

*Based on distance flown by plane, the split is 54% short-haul, 25% medium-haul and 21% long-haul⁵². We are assuming that this split remains constant into the future. We group medium- and long-haul and differ them from short-haul aviation since we assume that longer flights cannot use non-emitting propulsion systems (hydrogen and electricity). Carbon intensity is calculated based on the percentage of long- and medium, and short-haul flights, and the percentage and carbon intensity of the energy source.



Supplementary Figure 7 I (a) Total sequestration cost by 2050 in trillion US dollars based on the amount of carbon removed related to our scenarios and the carbon sequestration cost following the cost ranges of Fuss et al.⁵³ and the IEA⁵⁴. If carbon credits are less expensive than SAFs, airlines may seek to offset rather than reduce their combustion emissions⁵⁵. (b) Total cost for offsetting the non-CO₂ emissions embodied in 1 liter of SAF based on different carbon dioxide removal costs and multipliers from Lee et al.⁵⁶. The white star represents the assumptions used in Figure 4: a multiplier of 1.7 for a GWP100 and \$350/tCO₂ cost. (c) and (d) represent the cost difference between using SAFs vs. CDR to mitigate the climate impacts (both CO₂ and non-CO₂) of aviation per passenger-kilometer and ton-kilometer, respectively. Anything above the thick white line (orange and red colors) represents ranges where it is cheaper to mitigate aviation's emissions with SAFs compared to CDR, whereas everything below the thick white line (turquoise and blue colors) represents ranges where it is cheaper to mitigate with CDR as opposed to SAFs. For example, if the costs of SAF were \$2.8/L and CDR costs about \$300/tCO₂, then it would be about \$0.06 cheaper per pkm_e (or \$0.65 per tkm_e) to use fossil jet fuel and then remove equivalent emissions with CDR, than to pay for SAFs. If, on the other hand, the costs of SAF were about \$0.8/L and CDR costs were about \$700/tCO₂, then it would be about \$0.08 cheaper per pkm_e (or \$0.85 per tkm_e) to avoid emissions by using SAFs than using fossil jet fuel and mitigating emissions with CDR.

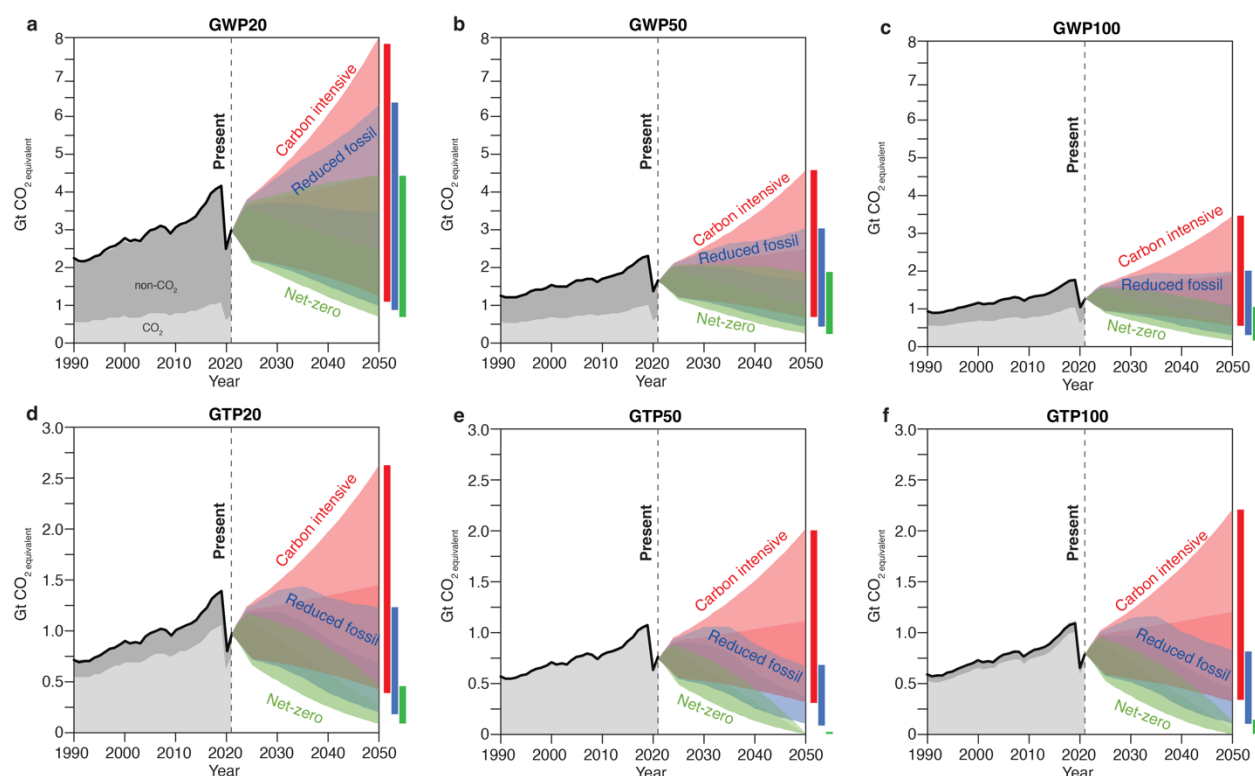
Total Land Required (100% purpose-grown biomass)



Supplementary Figure 8 I Panels (a) and (b) show the amount of land in million hectares required to grow the biofuels needed per scenario assuming that 100% of the SAF demand is met by purpose-grown biomass and assuming that 15,075,617.68 hectares are needed per EJ, from Rulli et al.⁵⁷. The higher the growth in aviation demand and lower the improvements in energy intensity (BAU lines), the higher the need for SAF to decarbonize aviation, and the more land is needed for growing biofuels (assuming that the SAF demand is 100% biofuels). Panels (c) and (d) show the percentage of land needed to grow biofuels by 2050 compared to the land allocated in 2019 for growing crops based on FAOSTAT⁵⁸. The horizontal line represents the estimated amount of land allocated to growing biofuels based on global biofuel production in 2019 from IEA⁵⁹ and the assumed amount of land needed per EJ of biofuels from Rulli et al.⁵⁷.

Supplementary Table 5 | Total CO₂eq/CO₂ Emissions from Lee et al.⁵⁶

GWP20	GWP50	GWP100	GTP20	GTP50	GTP100
4	2.3	1.7	1.3	1	1.1



Supplementary Figure 9 | Total emissions in our nine scenarios based on Business-as-usual, Industry projections and Ambitious projections for demand and energy intensity (De) paired with Carbon intensive, Reduced fossil and Net-zero carbon intensities (f). Each panel represents one global warming potential (a, b, and c) or global temperature potential (d, e, and f) and time horizon (20, 50 or 100 years). Values are based on projections of CO₂ emissions from our scenarios and Lee et al.⁵⁶ multipliers introduced on Supplementary Table 5.

Supplementary Table 6 | Synthetic Fuel Costs in USD/liter

		Hydrogen Unit Cost (USD/kg H ₂)							
		0	1	2	3	4	5	6	7
Carbon Unit Cost (USD/kg CO ₂)	0	0.00	0.40	0.80	1.20	1.60	2.00	2.40	2.80
	0.1	0.31	0.71	1.11	1.51	1.91	2.31	2.71	3.11
	0.2	0.63	1.03	1.43	1.83	2.23	2.63	3.03	3.43
	0.3	0.94	1.34	1.74	2.14	2.54	2.94	3.34	3.74
	0.4	1.26	1.66	2.06	2.46	2.86	3.26	3.66	4.06
	0.5	1.57	1.97	2.37	2.77	3.17	3.57	3.97	4.37
	0.6	1.88	2.28	2.68	3.08	3.48	3.88	4.28	4.68
	0.7	2.20	2.60	3.00	3.40	3.80	4.20	4.60	5.00

Supplementary Table 7 | Synthetic Fuel Costs in USD/liter + CDR Cost*

		Hydrogen Unit Cost (USD/kg H ₂)							
		0	1	2	3	4	5	6	7
Carbon Unit Cost (USD/kg CO ₂)	0	0.62	1.02	1.42	1.82	2.22	2.62	3.02	3.42
	0.1	0.93	1.33	1.73	2.13	2.53	2.93	3.33	3.73
	0.2	1.25	1.65	2.05	2.45	2.85	3.25	3.65	4.05
	0.3	1.56	1.96	2.36	2.76	3.16	3.56	3.96	4.36
	0.4	1.88	2.28	2.68	3.08	3.48	3.88	4.28	4.68
	0.5	2.19	2.59	2.99	3.39	3.79	4.19	4.59	4.99
	0.6	2.50	2.90	3.30	3.70	4.10	4.50	4.90	5.30
	0.7	2.82	3.22	3.62	4.02	4.42	4.82	5.22	5.62

*Assuming a GWP100 years and a carbon removal cost of \$350/tCO₂

Supplementary Table 8 | FT Fuel Costs in USD/liter

		Inversed Efficiency (kg biomass / kg fuel)				
		0	1	2	3	4
Feedstock Cost (USD/kg biomass)	0	0.00	0.17	0.33	0.50	0.67
	0.1	0.00	0.26	0.51	0.77	1.02
	0.2	0.00	0.34	0.69	1.03	1.37
	0.3	0.00	0.43	0.86	1.29	1.72
	0.4	0.00	0.52	1.04	1.56	2.08
	0.5	0.00	0.61	1.21	1.82	2.43
	0.6	0.00	0.70	1.39	2.09	2.78
	0.7	0.00	0.78	1.57	2.35	3.13

Supplementary Table 9 | FT Fuel Costs in USD/liter + CDR Cost*

		Inversed Efficiency (kg biomass / kg fuel)				
		0	1	2	3	4
Feedstock Cost (USD/kg biomass)	0	0.68	0.85	1.02	1.18	1.35
	0.1	0.68	0.94	1.19	1.45	1.70
	0.2	0.68	1.02	1.37	1.71	2.05
	0.3	0.68	1.11	1.54	1.97	2.41
	0.4	0.68	1.20	1.72	2.24	2.76
	0.5	0.68	1.29	1.90	2.50	3.11
	0.6	0.68	1.38	2.07	2.77	3.46
	0.7	0.68	1.46	2.25	3.03	3.81

*Assuming a GWP100 years and a carbon removal cost of \$350/tCO₂

Supplementary Table 10 | HEFA Fuel Costs in USD/liter

		Inversed Efficiency (kg biomass / kg fuel)				
		0	0.5	1	1.5	2
Feedstock Cost (USD/kg biomass)	0	0.00	0.22	0.45	0.67	0.90
	0.2	0.00	0.31	0.62	0.94	1.25
	0.4	0.00	0.40	0.80	1.20	1.60
	0.6	0.00	0.49	0.98	1.47	1.95
	0.8	0.00	0.58	1.15	1.73	2.31
	1.0	0.00	0.66	1.33	1.99	2.66

Supplementary Table 11 | HEFA Fuel Costs in USD/liter + CDR Cost*

		Inversed Efficiency (kg biomass / kg fuel)				
		0	0.5	1	1.5	2
Feedstock Cost (USD/kg biomass)	0	0.68	0.91	1.13	1.35	1.58
	0.2	0.68	0.99	1.31	1.62	1.93
	0.4	0.68	1.08	1.48	1.88	2.28
	0.6	0.68	1.17	1.66	2.15	2.63
	0.8	0.68	1.26	1.83	2.41	2.99
	1.0	0.68	1.35	2.01	2.67	3.34

*Assuming a GWP100 years and a carbon removal cost of \$350/tCO₂

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