Goldman Sachs | Research

June 23, 2021 | 9:50PM BST

Carbonomics

Introducing the GS net zero carbon models and sector frameworks

We present our modeling of the paths to net zero carbon, with two global models of de-carbonization by sector and technology, leveraging our Carbonomics cost curve. We present a scenario consistent with the Paris Agreement's goal to keep global warming well below 2°C (**GS <2.0°**), and a more aspirational path, aiming for global net zero by 2050, consistent with limiting global warming to 1.5°C (**GS 1.5°**). We expect a cumulative **US$56 tn of green infrastructure investments to net zero**, reaching >2% of GDP by 2032 in the GS 1.5° scenario. Renewable power is at the heart of the energy transformation, supporting the abatement of c.50% of global CO_2 emissions, leading **global power demand to triple by 2050.** However, a broader ecosystem of technologies will be needed: we estimate that the **hydrogen market could increase 7-fold** by 2050, to >500 Mtpa, while **carbon capture** grows from c.40 $MtCO_2$ currently to >7,000 $MtCO_2$ pa, and carbon offsets (mostly natural sinks, but also Direct Air Carbon Capture) contribute c.15% of de-carbonization for the harder-to-abate sectors. Both scenarios imply **peak oil demand by 2025**, but **we still see the need for new oil mega-project start-ups until 2030 or 2035** on GS 1.5° and GS <2.0°, because of decline rates. Gas demand peaks in 2030 in the GS 1.5° scenario, but has a critical role as a transition fuel in the GS <2.0° path, with growing demand until 2037. We translate our global net zero models into **pathways for emission intensity reduction for 30 key emitting corporate industries**, providing a **framework for gauging corporate emission reduction targets.**

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Carbonomics

Story in Numbers

We have modeled two global paths to net zero carbon: an aspirational path that aims for global net zero by 2050, consistent with limiting global warming to 1.5°C (GS 1.5°) and a budget of c.500 $GtCO_2$ remaining net cumulative CO_2 emissions from 2020...

...and a path consistent with the Paris Agreement's aim to keep global warming well below 2°C (GS <2.0°), with a cumulative remaining carbon budget of c.750 $GtCO_2$ and global net zero by 2060.

GS 1.5° calls for a net reduction in CO_2 emissions of 18%/40%/89% by 2025/30/40 respectively, compared with 11%/23%/60% for GS <2.0°

We expect a cumulative US$56 tn of green infrastructure investments to global net zero carbon, reaching >2% of GDP by 2032 in the 1.5° scenario

Power generation is at the heart of the energy transformation, with renewable power supporting the abatement of c.50% of global CO_2 emissions...

...leading global power demand to triple by 2050, and surpass 70,000 TWh.

Electrification and hydrogen transform road transportation, with full penetration of new energy vehicles (NEVs) by 2035 for light vehicle sales, and 2040 for heavy-duty, requiring c.US$4 tn of investment in charging infrastructure.

We estimate that the market for hydrogen could increase 7x by 2050 to >500 Mtpa, driven by the decarbonisation of industry, heavy transport and buildings.

Carbon capture grows into a major industry, from c. 40 $MtCO_2$ currently to >7,000 $MtCO_2$ pa by 2050 in the GS 1.5° scenario.

Carbon offsets in the form of natural sinks and DACCS are also critical for the path to global net zero, contributing to c.15% of de-carbonization for the harder-to-abate sectors by 2050.

The role of fossil fuels: Oil demand peaks by 2025, but we still need new greenfield start-ups until 2030 and 2035 in the two scenarios...

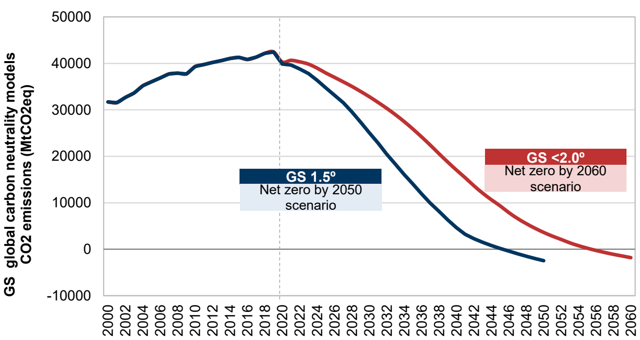
...while gas demand peaks in 2030 in the GS 1.5° scenario, and has a critical role as a transition fuel in the GS <2.0° path, with growing demand until 2037.

Natural resources sit at the heart of electrification, driving c.10Mt of incremental annual global copper demand to 2050 (a c.40% uplift from 2019 demand), c. 25 Mt for aluminium (a c.40% uplift from 2019 demand) and multi-fold increases for lithium and nickel.

We translate our global net zero models into pathways for emission intensity reduction for 30 key emitting corporate industries.

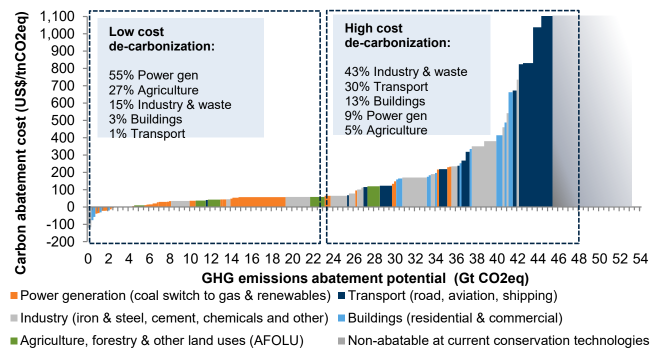
Carbonomics; the path to net zero, thesis in charts

Exhibit 1: We have constructed two global carbon neutrality scenarios: one aspirational scenario consistent with 1.5°C and one consistent with <2.0°C global warming
GS net zero global models, CO2 emissions (incl. AFOLU)



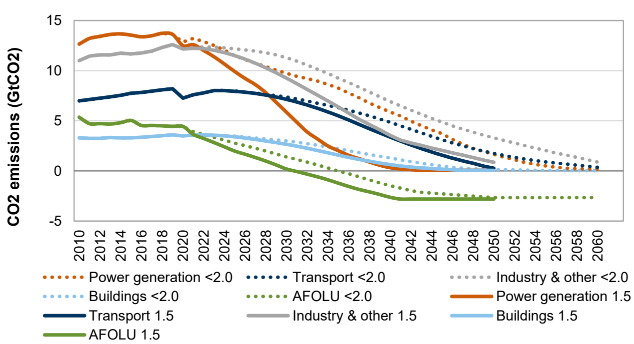
Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 2: Low cost de-carbonization is dominated by power generation today, while transport and industry are challenging...
2020 conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and current costs



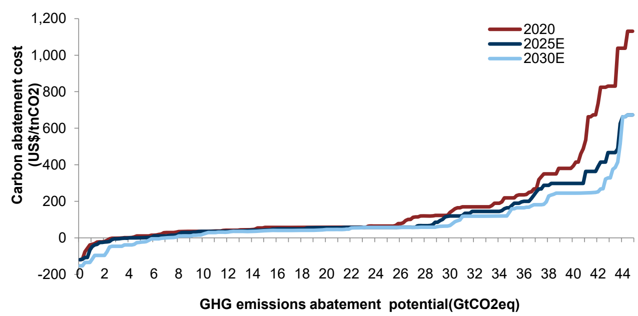
Source: Goldman Sachs Global Investment Research

Exhibit 3: ...leading power generation to take the brunt of carbon reduction in the 1.5 scenario, but a more balanced split in the <2.0 scenario...
GS 1.5 vs. GS <2.0 CO2 emissions by sector (GtCO2)



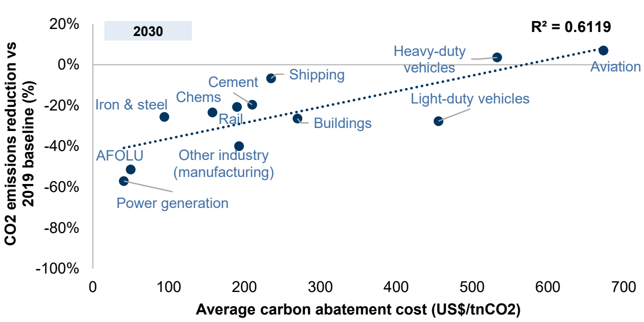
Source: Goldman Sachs Global Investment Research

Exhibit 4: ...as we expect the cost curve to transform this decade, driven by cost deflation, mostly in energy storage
Carbon abatement cost curve for de-carbonization of anthropogenic GHG emissions, based on current technologies



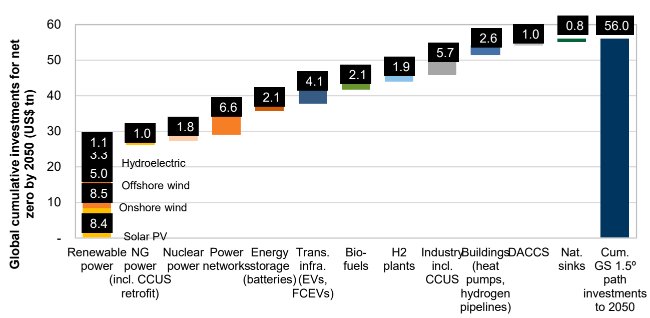
Source: Goldman Sachs Global Investment Research

Exhibit 5: Positioning on the cost curve drives the pace of de-carbonization by sector
2030 CO2 emissions reduction vs. 2019 by sub-sector vs. average current carbon abatement cost



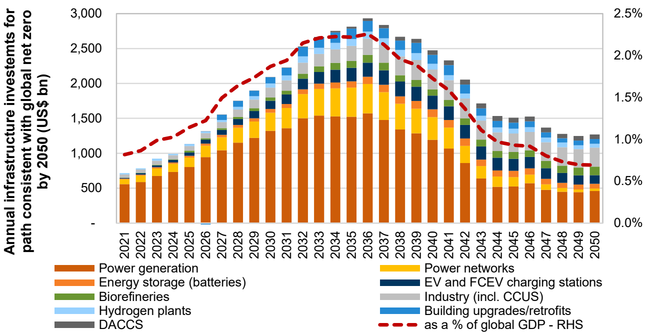
Source: Goldman Sachs Global Investment Research

Exhibit 6: We expect US$56 tn of infrastructure investments to global Net Zero carbon...
Cumulative infrastructure investment opportunity for our GS 1.5° global net zero by 2050 model (US$ tn)



Source: Goldman Sachs Global Investment Research

Exhibit 7: ...reaching >2% of GDP by 2032 in the 1.5° scenario
Annual infrastructure investments for net zero by 2050 (US$ tn)



Source: Goldman Sachs Global Investment Research

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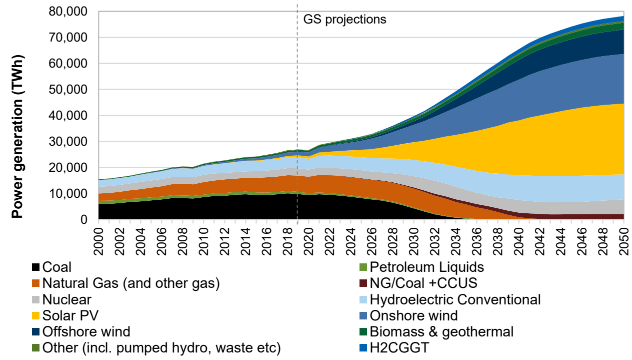
Global power generation (TWh)



Source: BP Statistical Review, Goldman Sachs Global Investment Research

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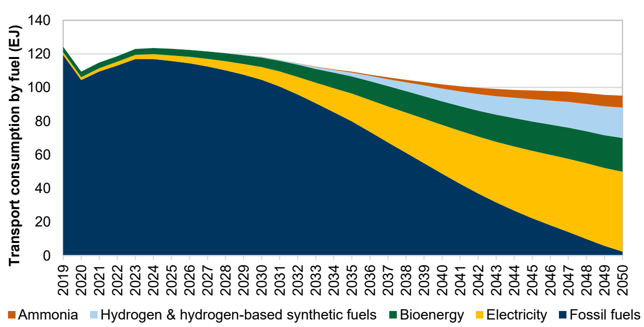
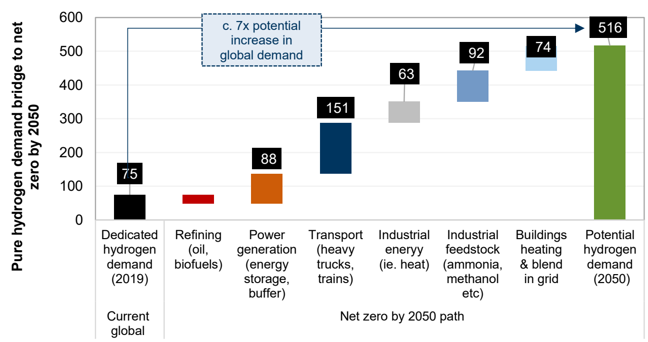


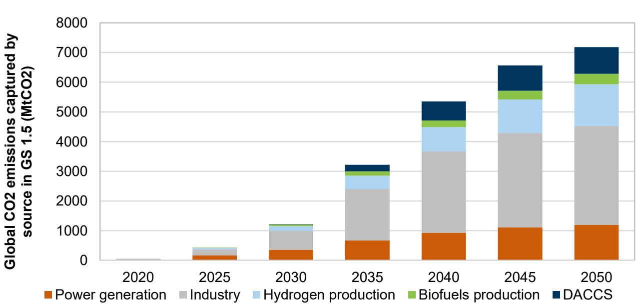
Source: Goldman Sachs Global Investment Research

Exhibit 10: We expect hydrogen demand to increase 7-fold on the path to Net Zero...
Hydrogen demand bridge to 2050E on our global net zero path



Source: Goldman Sachs Global Investment Research

Exhibit 11: ...while carbon capture, utilization and storage (CCUS) becomes a major industry
Global CO2 emissions captured by source (MtCO2)



Source: Goldman Sachs Global Investment Research

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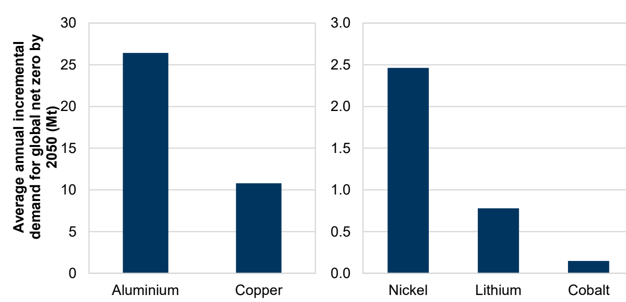
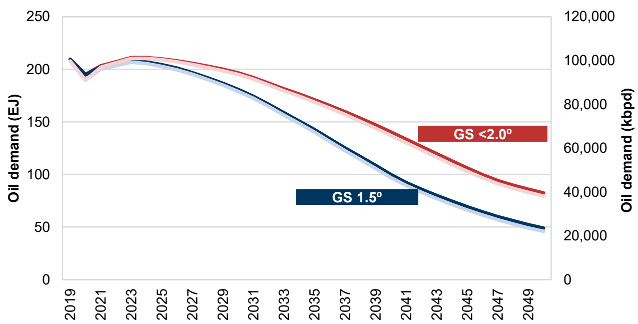
Average annual incremenal demand for global net zero by 2050 (Mt)



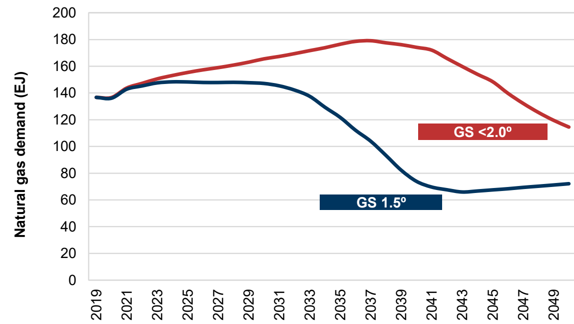
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 13: Hydrocarbons: Oil demand peaks in the mid-2020s in both scenarios...
Oil demand (EJ and kbpd)



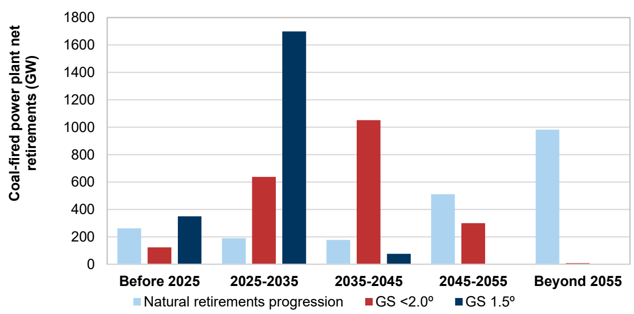
Source: Goldman Sachs Global Investment Research

Exhibit 14: ..while the role of natural gas varies notably in the two scenarios, with a much more important role as a transition fuel in the the GS <2.0° scenario
Natural gas demand (EJ)



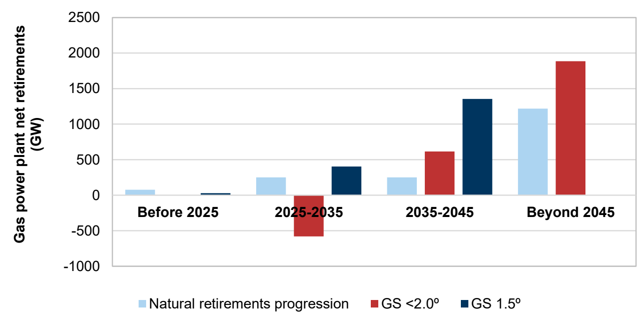
Source: Goldman Sachs Global Investment Research

Exhibit 15: Power plant retirements in coal have to take place by 2035 in the 1.5° scenario, 20 years before their natural end of life...
Coal-fired power plants net retirements (GW)



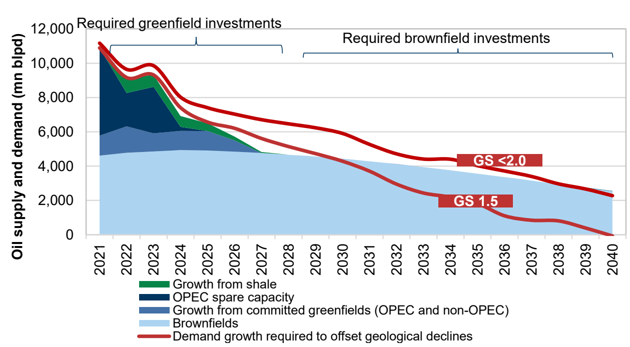
Source: IEA, Goldman Sachs Global Investment Research

Exhibit 16: ...while gas power plant retirements mostly take place by 2045
Natural gas power plants net retirements (GW)



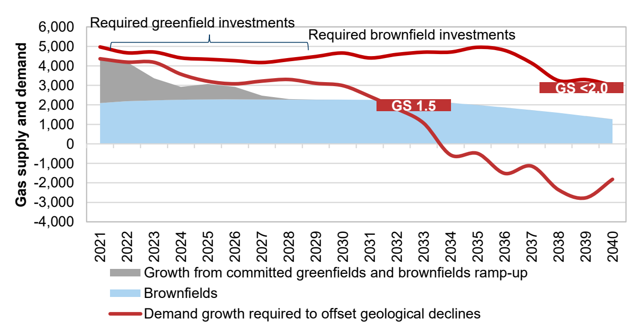
Source: IEA, Goldman Sachs Global Investment Research

Exhibit 17: Our analysis suggests the need for new oil greenfield projects until 2030 or 2035 in the two scenarios...
New production from greenfield and brownfield projects required to balance the oil market



Source: Goldman Sachs Global Investment Research

Exhibit 18: ..and 2030 or 2050 for gas, depending on the scenario
New production from greenfield and brownfield projects required to balance the gas market



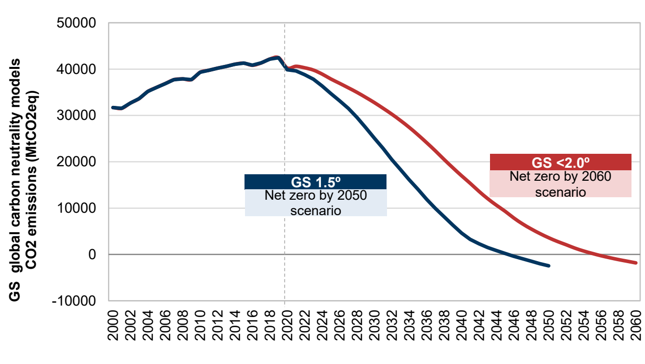
Source: Goldman Sachs Global Investment Research

PM Summary; the path to net zero

We have built two global paths to Net Zero carbon: one aspirational scenario consistent with a 1.5°C global temperature rise, and one consistent with a rise well below 2.0°C (the 'Paris Agreement scenario')

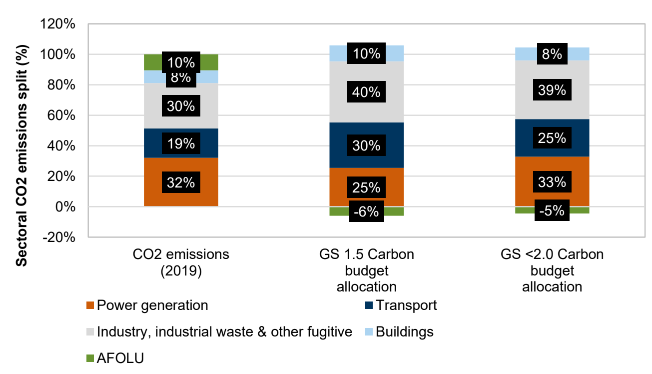
In this report, we introduce our emissions path for **global net zero carbon by 2050**, which would be **consistent with limiting global warming to 1.5°C,** with limited temperature overshoot **(GS 1.5°)**. For this scenario, we assume **a carbon budget for remaining net cumulative CO_2 emissions from all sources from 2020 to be c.500 $GtCO_2$**, consistent with the IPCC estimates in its Special Report on Global Warming of 1.5 °C (2018) - 580 $GtCO_2$ from the 2018 base as the IPCC SR1.5 report indicates, consistent with around a 50% probability of limiting warming to 1.5 °C by 2100. **We also introduce** a less aspirational, but also likely more achievable **global net zero model, which is consistent with the Paris Agreement's aim to keep global warming well below 2°C (GS <2.0°)** and achieving global net zero around 2060. For the purpose of this analysis, we define the carbon budget for our GS <2.0° model to be near the mid-point of the range of IPCC's RCP2.6 scenario, **implying a cumulative remaining carbon budget of around 750 $GtCO_2$ from 2020**. For our global net zero carbon scenarios we adopt a **sectoral approach**, **leveraging our Carbonomics de-carbonization cost curve,** and **allocating the available carbon budget across different emitting industries on the basis of cost positioning and technological readiness.**

Exhibit 19: We have constructed two global carbon neutrality scenarios: one aspirational scenario, consistent with 1.5°C of global warming, and one consistent with <2.0°C...
GS net zero global models, CO2 emissions (incl. AFOLU)



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 20: ...adopting a sectoral carbon budget allocation approach which is largely dependent on the technological readiness and carbon abatement cost of clean de-carbonization technologies in each sector, as addressed by our Carbonomics cost curve
Sectoral CO2 emissions split (%)



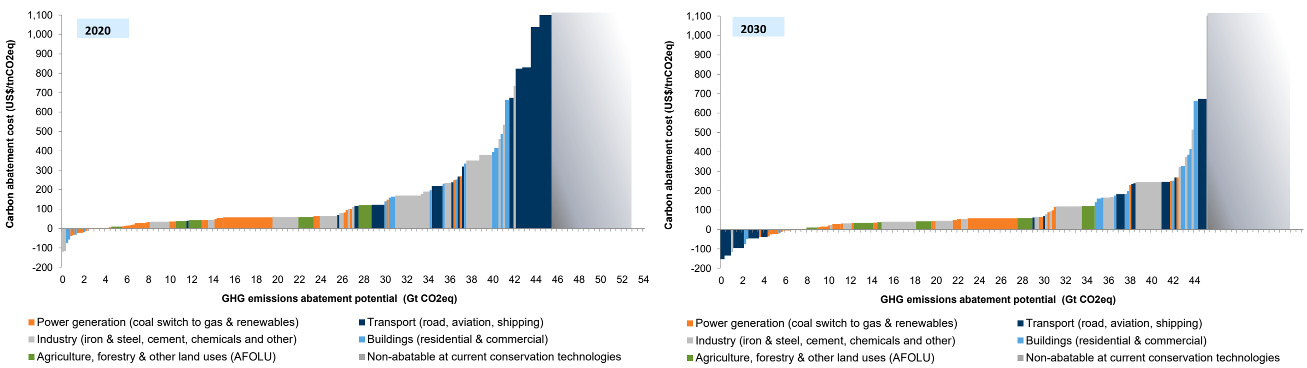
Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

We expect the Carbonomics cost curve to transform this decade, driven by cost deflation, mostly in energy storage (batteries and clean hydrogen)

The additional carbon budget flexibility offered by the <2° scenario effectively provides an extra decade to achieve global net zero. This would provide more time for three key technologies driving the de-carbonization of transport and industry (batteries, clean hydrogen and carbon capture) to move lower on the Carbonomics cost curve, before being rolled out on a giant scale worldwide. **We estimate that the upper half of the cost curve can fall by 22%/30% respectively by 2025/2030, driven by technological innovation and the benefits of scale**, mostly in energy storage and carbon capture technologies. **In the GS 1.5° path, power generation needs to de-carbonize by 57% by the end of this decade**, implying retirement of coal power plants by 2035 (two decades before the end of their useful life) and of gas power plants by 2045 (one decade before). This potentially disruptive and abrupt change in the power generation sector is a result of the tight carbon budget and the immaturity of de-carbonization technologies in transport and industry to be deployed at giant scale this decade. However, **under the less strict GS <2.0° path, the de-carbonization technologies in transport and industry have more time to evolve (we estimate 83% lower carbon abatement costs for the de-carbonization of transport by 2030, compared to today) and need a smaller relative allocation of the carbon budget** (25% to transport, compared to 30% in the GS 1.5° path). **This allows power generation to de-carbonize at a more reasonable pace (-28% de-carbonization by 2030), avoiding the mass retirement of young power generation assets**, with a more gradual transition **and a greater role for natural gas**.

Exhibit 21: We estimate that the upper half of the cost curve can fall by c.30% by 2030, driven by technological innovation and the benefits of scale, mostly in energy storage and carbon capture technologies

2020/30E conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies



Source: Goldman Sachs Global Investment Research

We expect US$56 tn pa of infrastructure investments to global Net Zero carbon, reaching >2% of GDP by 2033 in the 1.5° scenario

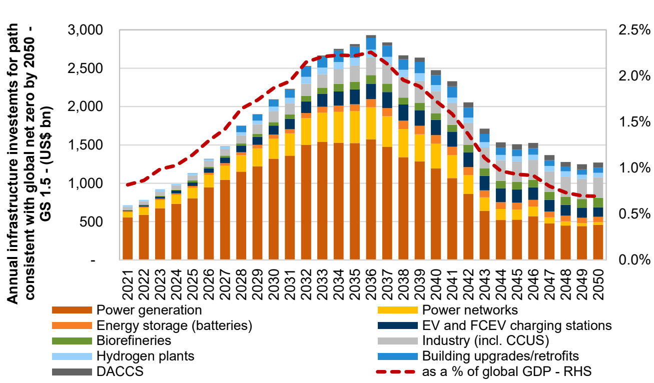
In aggregate, we estimate a total investment opportunity in clean tech infrastructure of US$56 tn by 2050 in the GS 1.5° path. This figure focuses solely on **incremental infrastructure investments** and does not include maintenance and other end-use capex. Overall, the average annual investments in de-carbonization that we estimate over 2021-50 are c.US$1.9 tn, with the peak in the 2036 (US$2.9 tn) representing 2.3% of global GDP (vs. US$1.6 tn pa with a peak of US$2.5 tn in 2041 in the GS <2.0° scenario). We estimate that **c.50% of de-carbonization is reliant on access to clean power generation**, including electrification of transport and various industrial processes, electricity used for heating and more. Overall, we expect **total demand for power generation** in a global net zero scenario by 2050 to **increase three-fold (vs. that of 2019) and surpass 70,000 TWh as the de-carbonization**

process unfolds. Based on our GS 1.5° model, power generation almost entirely de-carbonizes **by 2040** (2055 under the GS <2.0° scenario).

The de-carbonization of transport, buildings and industry will require a complex ecosystem of low carbon technologies, including energy storage (both batteries and clean hydrogen) and carbon capture alongside the supply of clean power. For light duty vehicles (LDVs) transport (primarily constituting passenger vehicles, commercial vehicles and short/medium-haul trucks), we consider **electrification the key de-carbonization technology.** For **long-haul heavy trucks**, we **consider clean hydrogen a competitive option**, owing to its faster refueling time, lower weight and high energy content. Sustainable aviation fuels (SAFs), synthetic fuels and improved aircraft efficiency are in our view all key parts of the solution to lower carbon aviation, while LNG and ammonia drive the de-carbonization of shipping, and hydrogen addresses rail.

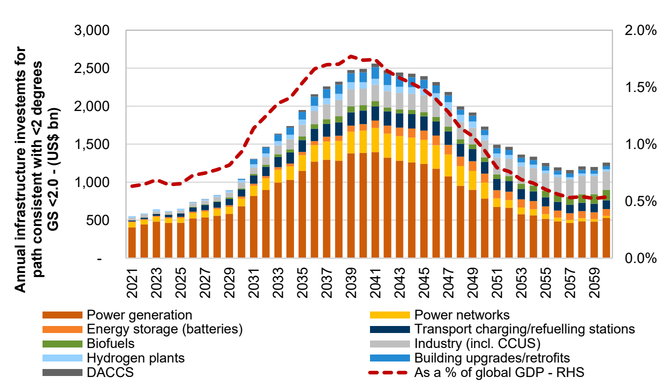
Fuel switch and efficiency govern emissions reduction in buildings, while clean hydrogen, CCUS, efficiency, circular economy and electrification set the scene for a new industrial technology revolution. We estimate that clean hydrogen can contribute to c.20% of global de-carbonization with its **addressable market growing 7-fold from c.75 Mt in 2019 to c.520 Mtpa on the path to global net zero by 2050.** We have incorporated carbon capture technologies in our GS 1.5° path for carbon neutrality by 2050, **with CCUS across sectors contributing to annual CO_2 abatement of c.7.2 $GtCO_2$ by 2050. Electrification and clean energy is likely to have an impact on total demand for natural resources, and in particular base metals** such as aluminium, copper, lithium and nickel, driven by renewables (solar panel, wind turbines manufacturing), power network infrastructure, charging infrastructure, electric vehicles and battery manufacturing. We attempt to quantify the potential impact that the path to net zero will have on the demand for each of these metals. We find that annual **green copper demand in a global net zero path by 2050 will rise by c.10 Mtpa, a c.40% increase from global copper demand in 2019.** Similarly, **the global average incremental annual green aluminum demand is estimated to be around 25Mtpa to 2050, c.40% of total global aluminium demand in 2019.**

Exhibit 22: In aggregate, we estimate a total investment opportunity in clean tech infrastructure of US$56 tn by 2050 in the GS 1.5° path, representing c.2.3% of global GDP at peak in 2036...
Annual infrastructure investments for GS 1.5 path to net zero by 2050 (US$ tn)



Source: Goldman Sachs Global Investment Research

Exhibit 23: ...and c.1.8% of GDP at its peak in 2040 for the GS<2.0° path
Annual infrastructure investments for GS <2.0 path to net zero by 2060 (US$ tn)

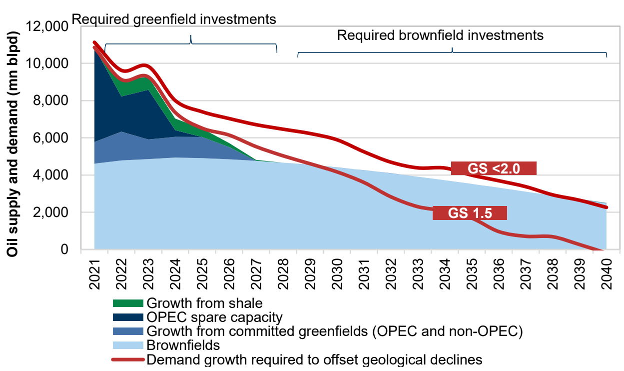


Source: Goldman Sachs Global Investment Research

Hydrocarbons and stranded assets: Our analysis suggests the need for new oil greenfield projects until 2030 or 2040 in the two net zero scenarios

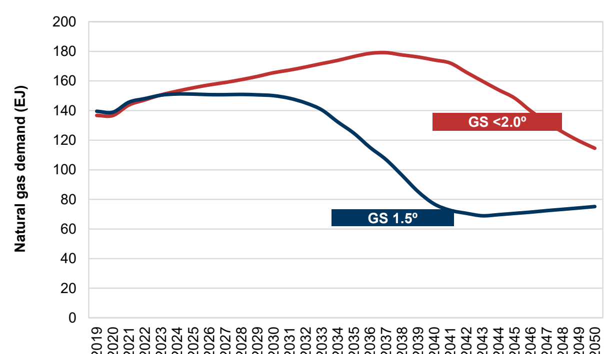
Both net zero scenarios show oil demand peaking in the middle of this decade, before starting a gradual decline that accelerates from 2030, driven by the improved affordability of EVs and better charging infrastructures. **The use of natural gas is materially different in our two scenarios. Natural gas has a critical role as a transition fuel for industry and power generation in the GS <2.0° path**, given the larger carbon budget and the extra available decade to achieve global net zero, while the tight budget of the 1.5° path forces a quicker (and more expensive) transition towards renewables and hydrogen. **Our GS <2.0° scenario has gas demand peaking in 2037, vs. 2030 in the GS 1.5° scenario**. We have leveraged on our Top Projects work, where we model in detail the oil & gas industry's decline rates and new developments, to estimate the required investments in new brownfield and greenfield oil & gas developments under both net zero scenarios. **In the GS 1.5° scenario, we estimate that we would need new greenfield start-ups in oil and in gas until 2030, and that we need brownfield capex until 2040 in oil and 2035 in gas. In the GS <2.0° scenario, we estimate that we would need new greenfield start-ups in oil until 2035, and in gas beyond 2040, and that we would need brownfield capex until 2050 in oil and beyond 2050 in gas.** We estimate that tightening financing conditions for new hydrocarbon developments are already bringing an end to non-OPEC growth, a steepening of the cost curve and shrinking reserves: oil reserve life has shrunk to c.25 years, a 50% reduction from 2014, as the industry stops exploring for new resources. We outline these supply dynamics in detail in our annual oil & gas industry deep dive report *Top Projects*. This comes at a time when the focus on fossil fuel consumers does not match the intensified focus on producers.

Exhibit 24: Our analysis suggests the need for new oil greenfield projects until 2030 or 2040 in the two scenarios...
New production from greenfield and brownfield projects required to balance the oil market



Source: Goldman Sachs Global Investment Research

Exhibit 25: ...with the role of natural gas varying notably in the two scenarios, with a much more important role as a transition fuel in the the GS <2.0° scenario
Natural gas demand (EJ)



Source: Goldman Sachs Global Investment Research

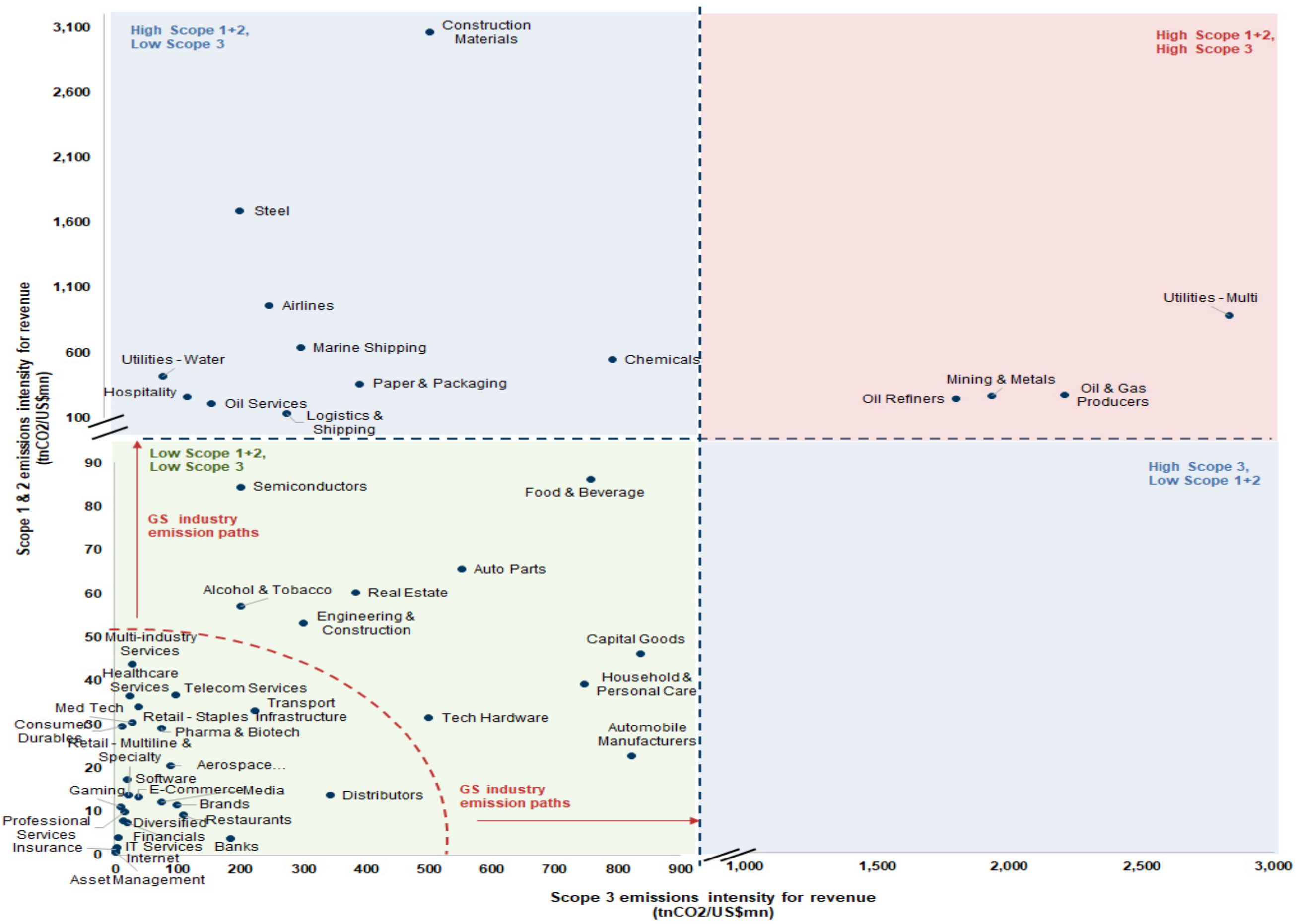
We have mapped the carbon intensity reduction of 30 corporate industries in both our global net zero scenarios (GS 1.5° above, GS <2.0° below)

We have applied our GS 1.5° net zero by 2050 and GS 2.0° net zero by 2060 scenarios to **construct corporate emission reduction paths by industry for the highest-emitting industries globally on Scope 1 and 2 but also on Scope 3 for sectors where Scope**

3 emissions are material. This provides a tool to screen corporates against the aspirational/less aspirational net zero by 2050/2060 paths, and to assess their current emissions intensity reduction targets. We primarily formulate these corporate paths for a **carbon intensity measure,** rather than absolute emissions (to adjust for market share movements). We have mapped 30 industries with **high relative Scope 1 & 2 revenue emissions intensity and/or high Scope 3 revenue emissions intensity. For homogeneous industries with a defined unit of production, we show both the percentage reduction in emissions intensity, and the actual intensity per unit of output (e.g. ton/MWh) For heterogeneous industries, which do not have a consistent output metric, instead of an absolute carbon intensity measure we have built an index for emissions reduction, based on the current emissions split and emissions sourcing of key corporates in each sector.** Carbon offsets in the form of natural sinks and DACCS are also critical for the path to global net zero, especially for harder-to-abate sectors, in the absence of further technological innovation. We estimate that natural sinks and DACCS' contribution to the de-carbonization of harder-to-abate sector emissions (defined as the CO_2 emissions with a carbon abatement cost above US$100/tn$CO_2$ in our cost curve) is around 15% by 2050.

Exhibit 26: We contruct emission reduction pathways for 30 corporate industries with high Scope 1 &2 and/or high Scope 3 emissions intensity per revenue

Scope 1 & 2 emissions intensity for revenue (y-axis) vs. Scope 3 emissions intensity for revenue (x-axis) for corporates listed in Europe



Source: Bloomberg, MSCI, Thomson Reuters Eikon, Company data, Goldman Sachs Global Investment Research

Exhibit 27: We have mapped the carbon intensity reduction by corporate industry in both our global net zero scenarios (GS 1.5° above, GS <2.0° below)

Sector	Industry	Carbon intensity measure	Activity indicator	Scopes coverage	% Reduction in carbon intensity vs 2019 base						Carbon intensity value (stated units)						
					2025	2030	2035	2040	2045	2050	2019	2025	2030	2035	2040	2045	2050
Energy	Oil & Gas Integrated producers	gCO2/MJ	energy sold	Scope 1,2,3	-8%	-20%	-41%	-71%	-85%	-93%	70.2	64.8	56.1	41.3	20.3	10.2	5.1
	Oil refiners	gCO2/MJ	energy sold	Scope 1,2,3	-8%	-24%	-46%	-71%	-87%	-97%	74.8	68.5	57.0	40.2	22.0	9.9	2.4
	Gas producers	gCO2/MJ	energy sold	Scope 1,2,3	-6%	-13%	-32%	-73%	-83%	-83%	63.2	59.4	54.7	43.0	17.2	10.7	10.6
	Electric Utilities	kgCO2/MWh	energy produced	Scope 1,2	-38%	-71%	-92%	-99%	-100%	-100%	504.3	310.4	147.1	38.8	5.0	0.8	0.8
Transportation	Airlines	gCO2/pkm	fleet	Scope 1,2	-14%	-29%	-50%	-68%	-82%	-94%	110.4	95.3	78.2	55.1	35.1	20.0	6.8
	Aerospace & defence	gCO2/pkm	aircrafts sold	Scope 1,2,3	-13%	-29%	-50%	-68%	-82%	-94%	67.6	58.5	48.0	33.9	21.6	12.3	4.2
	Automotive manufacturers - LDV	gCO2/km	vehicles sold	Scope 1,2,3	-14%	-45%	-84%	-99%	-100%	-100%	175.6	151.5	96.1	28.4	1.7	0.3	0.3
	Automotive manufacturers - HDV	gCO2/km	vehicles sold	Scope 1,2,3	-9%	-30%	-76%	-98%	-99%	-99%	631.3	577.1	440.8	151.9	9.5	6.5	6.0
	Maritime Shipping	gCO2/tkm	fleet	Scope 1,2	-17%	-35%	-51%	-68%	-86%	-97%	6.9	5.7	4.5	3.4	2.2	1.0	0.2
	Logistics & Shipping	Index		Scope 1,2,3	-15%	-31%	-52%	-71%	-85%	-96%							
Basic materials	Copper	tnCO2/tn	tonnes refined	Scope 1,2	-30%	-58%	-78%	-88%	-93%	-96%	4.0	2.8	1.7	0.9	0.5	0.3	0.2
	Steel	tnCO2/tn	tonnes produced	Scope 1,2	-17%	-37%	-58%	-76%	-91%	-97%	1.77	1.47	1.11	0.74	0.42	0.17	0.05
	Cement (Construction materials)	tnCO2/tn	tonnes produced	Scope 1,2	-11%	-22%	-40%	-56%	-72%	-91%	0.62	0.55	0.49	0.38	0.27	0.17	0.05
	Aluminium (all)	tnCO2/tn	tonnes produced	Scope 1,2	-27%	-58%	-75%	-80%	-83%	-87%	8.6	6.3	3.7	2.1	1.7	1.5	1.1
	Aluminium primary	tnCO2/tn	tonnes produced	Scope 1,2	-28%	-57%	-74%	-78%	-80%	-81%	12.8	9.2	5.5	3.3	2.8	2.6	2.4
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2	-16%	-46%	-73%	-95%	-98%	-98%	0.0105	0.0089	0.0057	0.0028	0.0005	0.0002	0.0002
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2,3	-17%	-37%	-58%	-77%	-91%	-97%	1.21	1.00	0.76	0.50	0.28	0.11	0.03
	Coal mining	tnCO2/tn	tonnes produced	Scope 1,2	-18%	-40%	-56%	-72%	-84%	-90%	0.061	0.050	0.037	0.027	0.017	0.010	0.006
	Nickel	tnCO2/tn	tonnes produced	Scope 1,2	-23%	-44%	-59%	-68%	-76%	-81%	11.20	8.65	6.27	4.54	3.57	2.73	2.11
	Diversified metals & mining	Index		Scope 1,2	-24%	-51%	-70%	-81%	-87%	-91%							
	Diversified metals & mining	Index		Scope 3	-15%	-34%	-55%	-71%	-84%	-92%							
	Paper & packaging	tnCO2/tn	tonnes produced	Scope 1,2	-33%	-64%	-87%	-95%	-97%	-98%	0.8	0.5	0.3	0.1	0.0	0.0	0.0
Chemicals	Chemicals- ammonia	tnCO2/tn	tonnes produced	Scope 1	-7%	-21%	-44%	-63%	-79%	-94%	2.3	2.1	1.8	1.3	0.8	0.5	0.1
	Chemicals- methanol	tnCO2/tn	tonnes produced	Scope 1	-8%	-22%	-41%	-61%	-81%	-97%	2.1	1.9	1.6	1.2	0.8	0.4	0.1
	Chemicals- HVCs	tnCO2/tn	tonnes produced	Scope 1	-19%	-35%	-52%	-68%	-82%	-87%	0.98	0.80	0.63	0.48	0.32	0.18	0.13
	Diversified chemicals	Index		Scope 1,2	-27%	-50%	-68%	-80%	-89%	-92%							
	Diversified chemicals	Index		Scope 3	-13%	-32%	-49%	-67%	-81%	-89%							
Other	Real estate	tnCO2/m2	square meter	Scope 1,2	-33%	-59%	-82%	-95%	-99%	-100%	0.039	0.027	0.016	0.007	0.002	0.000	0.000
	Real estate	tnCO2/m2	square meter	Scope 1	-16%	-40%	-67%	-88%	-97%	-99%	0.015	0.012	0.009	0.005	0.002	0.000	0.000
	Semiconductors	Index		Scope 1,2	-30%	-62%	-86%	-98%	-99%	-99%							
	Hospitality	Index		Scope 1,2	-32%	-62%	-85%	-96%	-99%	-100%							
	Household & Personal Care	Index		Scope 1,2	-22%	-53%	-79%	-96%	-98%	-98%							
	Household & Personal Care	Index		Scope 3	-16%	-38%	-62%	-81%	-93%	-96%							
	Food & beverage	Index		Scope 1,2	-24%	-55%	-80%	-97%	-99%	-99%							
	Food & beverage	Index		Scope 3	-7%	-18%	-30%	-45%	-55%	-61%							
	Food retail	Index		Scope 1,2	-26%	-58%	-82%	-97%	-99%	-99%							
	Food retail	Index		Scope 3	-8%	-19%	-33%	-48%	-58%	-65%							
	Tobacco	Index		Scope 1,2	-25%	-56%	-81%	-97%	-99%	-99%							
	Tobacco	Index		Scope 3	-10%	-22%	-36%	-52%	-61%	-68%							
	Capital goods	Index		Scope 1,2	-25%	-56%	-81%	-96%	-98%	-99%							
	Capital goods	Index		Scope 3	-15%	-33%	-54%	-72%	-85%	-93%							

Sector	Industry	Carbon intensity measure	Activity indicator	Scopes coverage	% Reduction in carbon intensity vs 2019 base						Carbon intensity value (stated units)						
					2025	2030	2035	2040	2045	2050	2019	2025	2030	2035	2040	2045	2050
Energy	Oil & Gas Integrated producers	gCO2/MJ	energy sold	Scope 1,2,3	-7%	-14%	-25%	-40%	-58%	-75%	70.0	65.3	60.4	52.8	41.7	29.3	17.7
	Oil refiners	gCO2/MJ	energy sold	Scope 1,2,3	-6%	-15%	-29%	-48%	-68%	-83%	74.4	69.6	63.4	52.8	38.7	24.0	12.8
	Gas producers	gCO2/MJ	energy sold	Scope 1,2,3	-6%	-11%	-16%	-28%	-42%	-59%	63.2	59.3	56.3	52.8	45.4	36.4	25.7
	Electric Utilities	kgCO2/MWh	energy produced	Scope 1,2	-26%	-44%	-63%	-79%	-89%	-96%	504.3	370.7	280.2	186.7	103.6	53.6	21.4
Transportation	Airlines	gCO2/pkm	fleet	Scope 1,2	-11%	-23%	-37%	-53%	-64%	-74%	110.4	98.2	85.1	70.0	51.7	39.4	28.5
	Aerospace & defence	gCO2/pkm	aircrafts sold	Scope 1,2,3	-11%	-23%	-36%	-53%	-64%	-74%	67.6	60.2	52.3	43.0	31.8	24.2	17.5
	Automotive manufacturers - LDV	gCO2/km	vehicles sold	Scope 1,2,3	-11%	-29%	-55%	-76%	-88%	-96%	175.6	156.5	124.3	78.9	42.2	20.4	7.3
	Automotive manufacturers - HDV	gCO2/km	vehicles sold	Scope 1,2,3	-8%	-18%	-36%	-68%	-94%	-97%	631.3	580.8	516.1	406.1	202.0	36.1	17.5
	Maritime Shipping	gCO2/tkm	fleet	Scope 1,2	-17%	-34%	-49%	-63%	-80%	-89%	6.9	5.7	4.6	3.5	2.6	1.4	0.7
	Logistics & Shipping	Index		Scope 1,2,3	-13%	-27%	-42%	-59%	-71%	-81%							
Basic materials	Copper	tnCO2/tn	tonnes refined	Scope 1,2	-22%	-40%	-58%	-75%	-86%	-93%	4.0	3.1	2.4	1.7	1.0	0.5	0.3
	Steel	tnCO2/tn	tonnes produced	Scope 1,2	-10%	-24%	-42%	-58%	-72%	-85%	1.77	1.59	1.35	1.04	0.74	0.50	0.27
	Cement (Construction materials)	tnCO2/tn	tonnes produced	Scope 1,2	-10%	-19%	-27%	-42%	-57%	-73%	0.62	0.56	0.51	0.45	0.36	0.27	0.17
	Aluminium (all)	tnCO2/tn	tonnes produced	Scope 1,2	-21%	-39%	-56%	-70%	-78%	-83%	8.6	6.8	5.2	3.8	2.6	1.9	1.5
	Aluminium primary	tnCO2/tn	tonnes produced	Scope 1,2	-22%	-39%	-55%	-68%	-76%	-80%	12.8	10.0	7.9	5.8	4.1	3.1	2.6
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2	-7%	-17%	-40%	-61%	-78%	-88%	0.0105	0.0098	0.0087	0.0063	0.0041	0.0023	0.0012
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2,3	-10%	-24%	-42%	-58%	-72%	-85%	1.21	1.09	0.92	0.71	0.50	0.34	0.19
	Coal mining	tnCO2/tn	tonnes produced	Scope 1,2	-16%	-34%	-50%	-68%	-81%	-89%	0.061	0.051	0.040	0.030	0.020	0.011	0.006
	Nickel	tnCO2/tn	tonnes produced	Scope 1,2	-17%	-30%	-44%	-58%	-70%	-79%	11.20	9.34	7.81	6.25	4.71	3.34	2.35
	Diversified metals & mining	Index		Scope 1,2	-18%	-35%	-53%	-69%	-81%	-87%							
	Diversified metals & mining	Index		Scope 3	-9%	-21%	-37%	-53%	-67%	-79%							
	Paper & packaging	tnCO2/tn	tonnes produced	Scope 1,2	-22%	-39%	-58%	-75%	-86%	-93%	0.8	0.6	0.5	0.3	0.2	0.1	0.1
Chemicals	Chemicals- ammonia	tnCO2/tn	tonnes produced	Scope 1	-3%	-9%	-22%	-40%	-53%	-64%	2.3	2.2	2.1	1.8	1.4	1.1	0.8
	Chemicals- methanol	tnCO2/tn	tonnes produced	Scope 1	-7%	-16%	-28%	-42%	-58%	-74%	2.1	1.9	1.8	1.5	1.2	0.9	0.5
	Chemicals- HVCs	tnCO2/tn	tonnes produced	Scope 1	-11%	-23%	-35%	-47%	-60%	-71%	0.98	0.87	0.75	0.63	0.51	0.39	0.29
	Diversified chemicals	Index		Scope 1,2	-17%	-32%	-46%	-60%	-72%	-81%							
	Diversified chemicals	Index		Scope 3	-13%	-31%	-47%	-65%	-80%	-89%							
Other	Real estate	tnCO2/m2	square meter	Scope 1,2	-26%	-44%	-60%	-77%	-89%	-96%	0.039	0.029	0.022	0.016	0.009	0.004	0.001
	Real estate	tnCO2/m2	square meter	Scope 1	-15%	-33%	-54%	-75%	-92%	-98%	0.015	0.013	0.010	0.007	0.004	0.001	0.000
	Semiconductors	Index		Scope 1,2	-19%	-35%	-55%	-73%	-86%	-93%							
	Hospitality	Index		Scope 1,2	-24%	-42%	-61%	-79%	-90%	-96%							
	Household & Personal Care	Index		Scope 1,2	-12%	-25%	-47%	-66%	-82%	-90%							
	Household & Personal Care	Index		Scope 3	-14%	-30%	-48%	-67%	-83%	-91%							
	Food & beverage	Index		Scope 1,2	-14%	-27%	-48%	-67%	-82%	-91%							
	Food & beverage	Index		Scope 3	-6%	-13%	-24%	-37%	-49%	-57%							
	Food retail	Index		Scope 1,2	-16%	-30%	-51%	-70%	-84%	-92%							
	Food retail	Index		Scope 3	-5%	-12%	-23%	-36%	-49%	-59%							
	Tobacco	Index		Scope 1,2	-15%	-28%	-50%	-69%	-83%	-91%							
	Tobacco	Index		Scope 3	-9%	-17%	-29%	-41%	-53%	-62%							
	Capital goods	Index		Scope 1,2	-15%	-29%	-51%	-69%	-83%	-92%							
	Capital goods	Index		Scope 3	-9%	-21%	-37%	-53%	-68%	-80%							

Source: Goldman Sachs Global Investment Research

Laying out the path to global net zero carbon: A sectoral approach consistent with limiting global warming to 1.5 °C and <2.0°C

In this report, we introduce our emissions paths for global net zero. The first path aims for **global net zero carbon by 2050 (GS 1.5°)**, which would be **consistent with limiting global warming to 1.5°C** with limited temperature overshoot. Such a scenario would involve a complete overhaul of the energy sector, and require transformative changes across all key emitting industries globally: we address this in detail in the sections of the report that follow. The total cumulative CO_2 emissions (carbon budget) associated our GS 1.5° path is in line with the one the IPCC specifies as potentially consistent with limiting global warming to 1.5°C with low or limited temperature overshoot, as assessed by the IPCC in its Special Report on Global Warming of 1.5 °C. The carbon budget implies that remaining total cumulative CO_2 emissions from all sources from 2020 would be around c.500 $GtCO_2$ (580 $GtCO_2$ from the 2018 base as the IPCC SR1.5 report indicates, consistent with around a 50% probability of limiting warming to 1.5 °C by 2100). For our global zero carbon scenario we adopt a **sectoral approach**, **leveraging our Carbonomics de-carbonization cost curve,** and **allocating the available carbon budget across different emitting industries on the basis of current cost and technological readiness.** This implies that sectors currently found lower on the Carbonomics cost curve and with greater technological readiness will likely be the first to de-carbonize, resulting in their respective carbon budget allocation. We note that this path outlines one of the many possible routes for global net zero by 2050, and is, similar to our Carbonomics de-carbonization cost curve, reliant on currently existing de-carbonization technologies (assuming economies of scale for technologies in pilot phase).

Exhibit 28: We introduce our GS 1.5°, a scenario consistent with global net zero carbon emissions by 2050 and limiting global warming to 1.5°C with limited overshoot

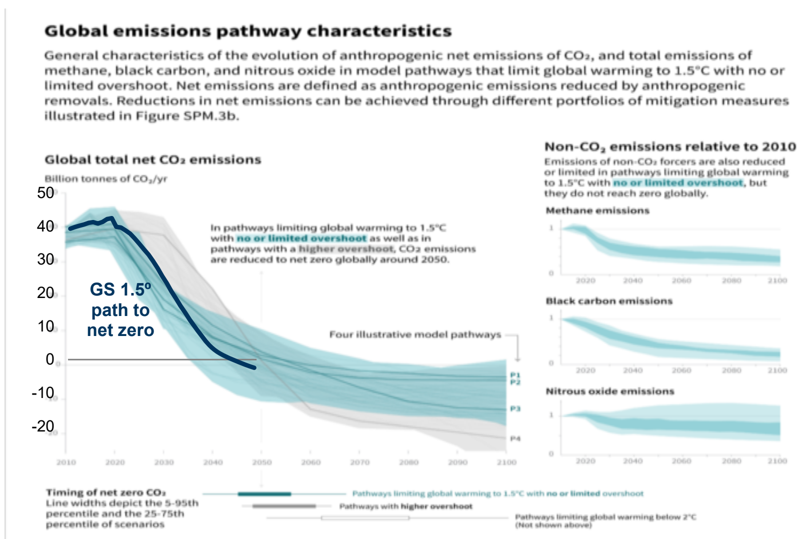
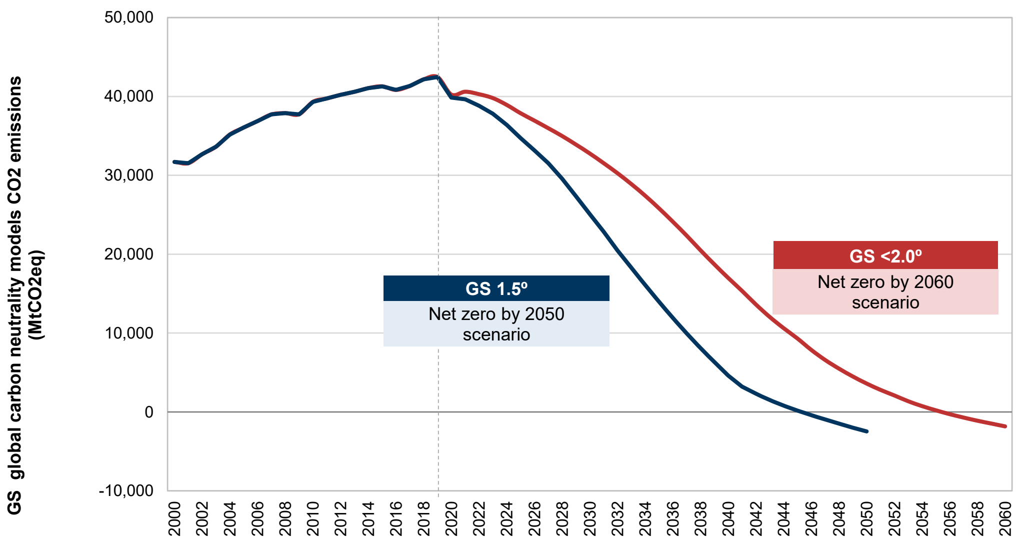


Figure SPM.3a from IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, 32 pp.

Source: IPCC Special Report of Global Warming of 1.5, Goldman Sachs Global Investment Research

As part of this report we also introduce our less aspirational, but also perhaps more realistically achievable, global net zero model which is consistent with the Paris agreement's aim to keep global warming well below 2°C (GS <2.0°) and achieving global net zero around 2060. Exhibit 29 shows the comparison between the two emission paths, GS 1.5° and GS <2.0°. The carbon budget for the GS <2.0° scenario is higher than the GS 1.5° scenario, yet with a very wide range of carbon budget uncertainty found in literature across different scientific scenarios. For the purpose of this analysis, we define the carbon budget for our GS <2.0° model to be within the range of IPCC's RCP2.6 scenario (a wide range is provided, we chose a budget close to the mid-point) implying a cumulative remaining carbon budget of around 750 $GtCO_2$ from 2020.

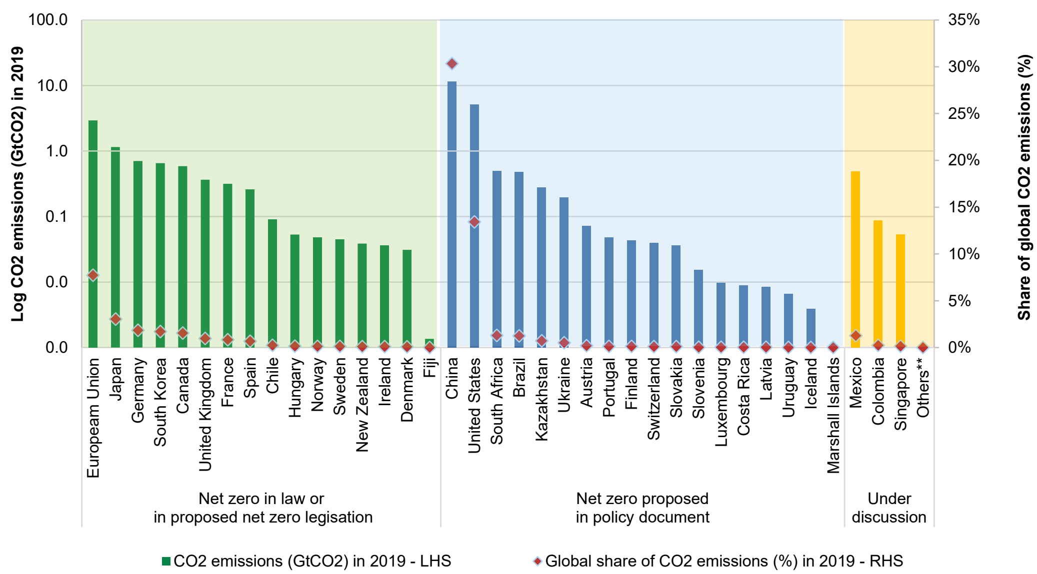
Exhibit 29: We have constructed two global carbon neutrality scenarios, one aspirational scenario consistent with 1.5°C global warming by 2100, and one consistent with well below 2.0°C global warming, in line with the Paris agreement ambition
GS Global net zero carbon models CO2 emissions (MtCO2)



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

While a **net zero by 2050 scenario, consistent with GS 1.5°, represents an aspirational scenario** that would require transformational changes across all key parts of the global energy ecosystem and broader economy, with, in our view, a **limited probability of occurring under the current economic and policy frameworks globally** (China, the world's largest emitter's ambition is to achieve net zero emissions by 2060, a decade later than the net zero by 2050 model requires), over the past two years we have seen a rapid acceleration in the number of national net zero pledges made by national jurisdictions globally, as well as by corporates embedding a net zero by 2050 target. By year-end 2020, we estimate that c.60% of global CO_2 emissions were covered by national net zero pledges (including those in law, in proposed legislation and in policy documents), with the additions of China and the United States the most notable examples. Around half of the emissions covered by these national pledges are embedded in net zero targets for 2050 or earlier, implying c.30% of global CO_2 emissions are currently embedded in a pledge for carbon neutrality by 2050. Similarly, we have seen a rapid acceleration of net zero by 2050 pledges across listed corporates, making it potentially a path against which corporate targets could be compared. **For the purpose of the analysis presented in this report, we primarily focus on outlining in detail our sectoral approach for our global net zero by 2050 scenario - GS 1.5°. Nonetheless, we do provide a scenario comparison between GS 1.5°and GS <2.0°, to showcase some of the key technological and financial differences between the two scenarios.**

Exhibit 30: The rapidly rising number of national net pledges worldwide by YE2020 covered c.60% of the global CO2 emissions, of which around half have a timeline for net zero by 2050 or sooner (the key exception being China)



** Others under consideration includes many countries and regions (list not exhaustive)

Source: Energy & Climate Intelligence Unit, Goldman Sachs Global Investment Research

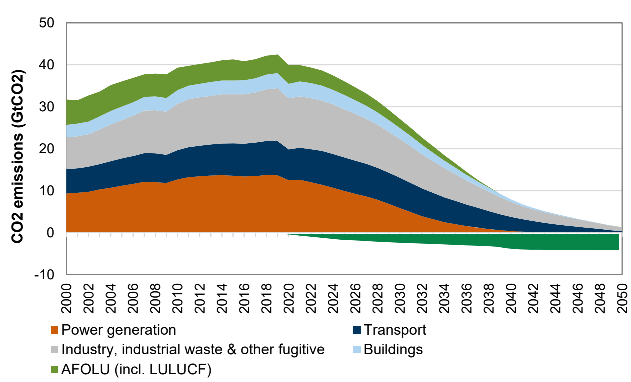
A sectoral carbon budget allocation approach that incorporates the cost and readiness of available de-carbonization technologies, as assessed by our Carbonomics cost curve

Our path to net zero addresses all the key emitting sectors: **power generation, transport** (light and heavy-duty road transport, aviation, shipping, rail), **industry** (including industrial combustion, industrial processes, fuel extraction, other fugitive and waste), **buildings** (residential and commercial) and **agriculture, forestry and other land uses (AFOLU)**. In our deep-dive de-carbonization report, Carbonomics: Innovation, Deflation and Affordable De-carbonization, we introduce in detail our Carbonomics carbon abatement cost curve. The Carbonomics cost curve shows the reduction potential and carbon abatement cost for anthropogenic GHG emissions through >100 different applications of GHG conservation technologies across all key emitting sectors globally.

Overall, we expect all the key technologies addressed in our de-carbonization cost curve to play a role in facilitating the path to net zero, each in their respective sector. **The speed of de-carbonization in each sector is largely dependent on the current carbon abatement cost and state of readiness of the available clean technologies presented in our Carbonomics cost curve**. As such, in our modes for global net zero, different sectors de-carbonize at different speeds and have a different carbon budget allocation, depending on their relative cost positioning and readiness on our de-carbonization cost curve. We note that our Carbonomics cost curve of de-carbonization **is not static, and is expected to evolve over time as the costs of existing technologies continue to change and as technological innovation leads to the addition of further de-carbonization technologies across sectors.** As such, **our GS global net zero models are also dynamic, and are expected to evolve over time** as technological innovation and focus on de-carbonization continues.

Exhibit 31: As part of this report, we introduce the GS 1.5° path for global carbon neutrality by 2050 consistent with 1.5°C global warming...

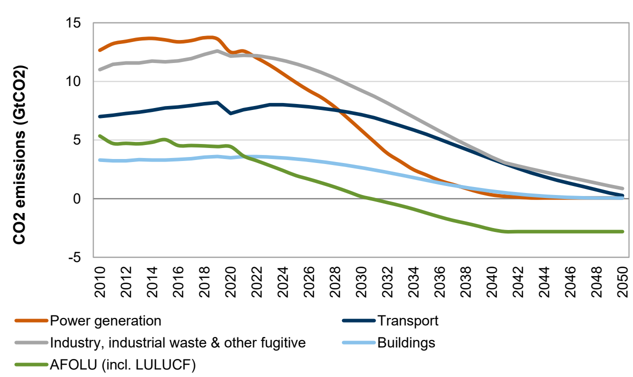
Global CO2 emissions by major emitting sector (GtCO2), including AFOLU



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 32: ...adopting a sectoral approach, modelling the emissions across all key emitting sectors

Global CO2 emissions by major emitting sector (GtCO2), including AFOLU

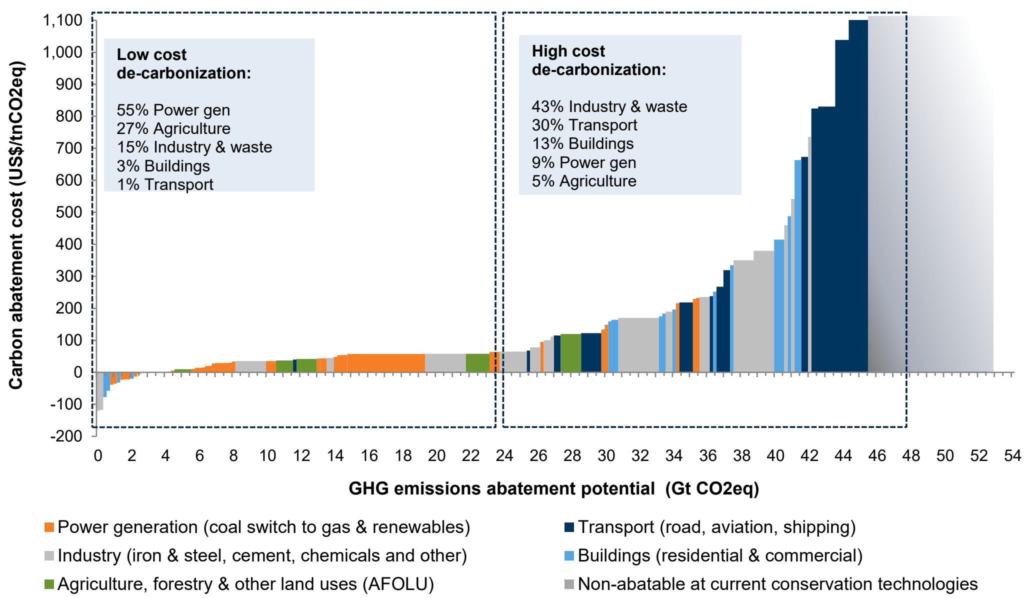


Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

As shown in our Carbonomics cost curve (Exhibit 33), the current carbon abatement cost and readiness of available de-carbonization technologies varies across different sectors and sub-sectors. Overall, power generation dominates the low end of the carbon abatement cost spectrum we present in the curve, with renewable power technologies already developed at scale with costs that have fallen rapidly over the past decade. Improved agricultural land and crop management practices, buildings' energy efficiency and energy and material efficiency in industry are some of the other technologies that can be found on the lower end of the cost curve. The high-cost end of the cost curve is mostly dominated by heavy industry de-carbonization (and in particular industrial process emissions, high temperature heat processes) and transportation (aviation, shipping, road transport).

Exhibit 33: Our GS global net zero models include a de-carbonization path across sectors that is largely dependent on the carbon abatement cost and readiness of the available de-carbonization technologies, as shown in our Carbonomics cost curve

2020 conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase

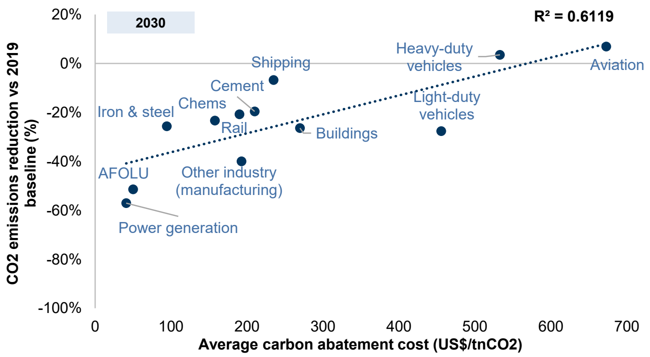


Source: Goldman Sachs Global Investment Research

As mentioned previously, the pace of de-carbonization varies by sector and sub-sector, depending on the carbon abatement cost and technological readiness, as addressed by our Carbonomics cost curve shown above. Exhibit 34 and Exhibit 35 show that **the pace of de-carbonization to 2030/40/50 for each sub-sector in our GS 1.5° scenario is correlated with the sub-sector's current average carbon abatement cost, as described previously, with the sectoral carbon budget allocation following a similar trend.** Harder-to-abate sectors such as aviation, heavy-duty transport, shipping with a higher carbon abatement cost de-carbonize slower, compared to sectors such as power generation, buildings and efficiency measures, which are associated with a lower carbon abatement cost.

Exhibit 34: The pace of de-carbonization in each sector and sub-sector is correlated to the average carbon abatement price of the available clean technologies in that sector...

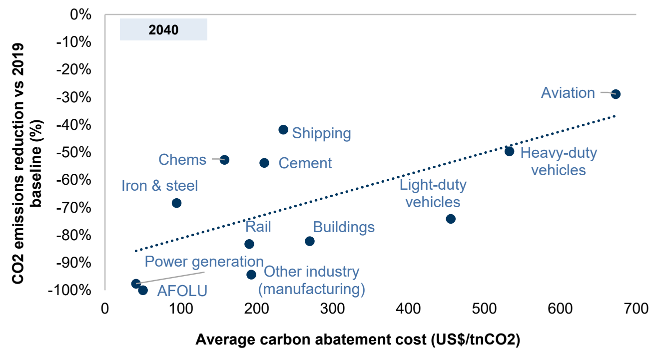
CO_2 emissions reduction vs. 2019 by sub-sector vs. average carbon abatement cost



Source: Goldman Sachs Global Investment Research

Exhibit 35: ...as shown in these exhibits for both 2030 and 2040

CO_2 emissions reduction vs. 2019 by sub-sector vs. average carbon abatement cost



Source: Goldman Sachs Global Investment Research

Comparing our GS 1.5°C and GS <2.0°C global carbon neutrality scenarios

As mentioned in the beginning of this report, we have constructed **two global emission paths** for **carbon neutrality:**

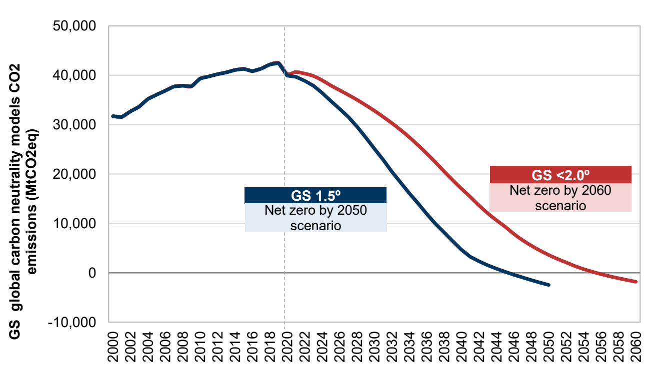
- **GS 1.5°:** An aspirational path that aims for **global net zero by 2050** with a carbon budget which would be **consistent with limiting global warming to 1.5°C with limited overshoot.**
- **GS <2.0°:** A path consistent with **global net zero by 2060** and in line with **maintaining global warming well below 2.0°C,** consistent with the Paris Agreement ambitions.

Whilst we primarily focused on introducing in detail our global net zero by 2050 path (GS 1.5°) in the later sections of this report, in this section we aim to draw some comparisons across the two models.

1) Comparison of sectoral carbon budgets allocation: Under the current economic and policy framework, power generation and industry transform at a slower and more achievable pace under the GS <2.0° scenario

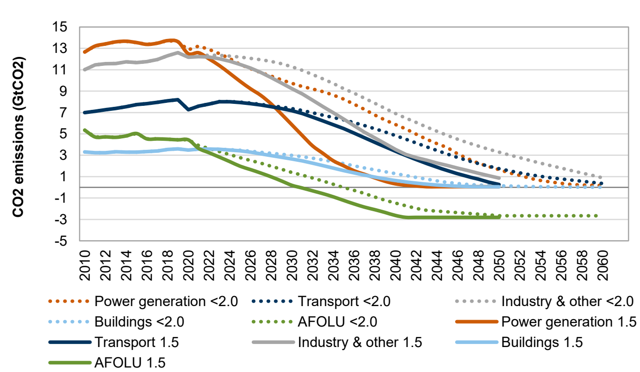
We adopted the **same methodology and sectoral hybrid approach for the construction of both scenarios**, leveraging our Carbonomics de-carbonization cost curve, and allocating the available carbon budget across different emitting industries on the basis of the current cost and technological readiness. The more aspirational GS 1.5° path has a very strict carbon budget and as such calls for a complete and immediate overhaul of the energy sector that requires transformative changes across all key emitting industries globally. It also aims to achieve global net zero by 2050, whilst the GS <2.0° path aims to achieve global carbon neutrality by 2060 (a decade later and in line with the ambitions laid out by the world's largest emitter, China).

Exhibit 36: In this section of the report we focus on drawing comparisons between our two global net zero scenarios consistent with 1.5 and <2.0 degrees of global wamring respectively (GS 1.5 and GS <2.0)...
GS global carbon neutrality models CO2 emission (MtCO2)



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 37: ..with the two paths showing different sectoral carbon emission allocations
GS 1.5 vs GS <2.0 CO2 emissions by sector (GtCO2)



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

In Exhibit 36 and Exhibit 37 above we show the comparison of the emission paths under the two scenarios, both on aggregate and by sector. It is evident that all sectors de-carbonize at a faster pace under the GS 1.5° model compared to the <2.0° model given the lower available carbon budget and the additional decade to reach net zero. Yet, the most evident changes are the pace of de-carbonization of power generation and industry. Under the more aspirational GS 1.5° path power generation becomes the first sector to de-carbonize, and does so at a very fast pace. This is attributed to the fact that power generation remains the sole key sector where the available clean de-carbonization technologies have been developed at scale and are economic under the current policy framework. On the contrary, under the less strict GS <2.0° path, power generation de-carbonizes at a slower pace enabling for a greater role for natural gas as a transition fuel. A similar situation is observed in industry, with a more gradual transition and a greater role for natural gas. Notably, the pace of de-carbonization of transport is not too dissimilar under the two scenarios, implying that given the larger carbon budget under the GS <2.0 path, transportation has a relatively lower carbon budget contribution, leaving further space for power generation and industry to de-carbonize.

Exhibit 38: The overall carbon budget and the sectoral carbon budget allocations differ between our two global carbon neutrality scenarios





	GS 1.5° path				GS <2.0° path			
Sectoral approach emissions analysis	Further sectoral emissions analysis breakdown	Carbon budget allocation (GtCO2, % of total budget)			Further sectoral emissions analysis breakdown	Carbon budget allocation (GtCO2, % of total budget)		
Power Generation	Power Generation	129	25%	25%	Power Generation	246	33%	33%
Transportation	Aviation	22	4%	30%	Aviation	34	4%	25%
	Shipping	17	3%		Shipping	20	3%	
	Rail	2	<1%		Rail	2	<1%	
	Light-duty road transport	59	12%		Light-duty road transport	64	8%	
	Heavy-duty road transport	51	10%		Heavy-duty road transport	66	9%	
Buildings	Residential buildings	37	7%	10%	Residential buildings	45	6%	9%
	Commercial buildings	16	3%		Commercial buildings	19	3%	
Industry (combustion & process), fugitive & waste	Iron & Steel	43	8%	40%	Iron & Steel	56	7%	39%
	Cement	46	9%		Cement	56	8%	
	Aluminium*	8	1%		Aluminium*	10	1%	
	Chemicals & petrochemicals, incl. ammonia, methanol, HVCs	31	6%		Chemicals & petrochemicals, incl. ammonia, methanol, HVCs	47	6%	
	Pulp, paper & packaging	3	1%		Pulp, paper & packaging	4	1%	
	Food & tobacco processing	10	2%		Food & tobacco processing	13	2%	
	Other industry incl. fuel extraction/ processing and waste	63	12%		Other industry incl. fuel extraction/ processing and waste	103	14%	
AFOLU (Agriculture, forestry, other land use)	Agriculture and land use change	44	9%	-6%	Agriculture and land use change	61	8%	-5%
	Natural sinks, DACCS	-74	-14%		Natural sinks, DACCS	-95	-5%	
	Total carbon budget GS 1.5	507	100%		Total carbon budget GS <2.0	750	100%	

* Direct emissions

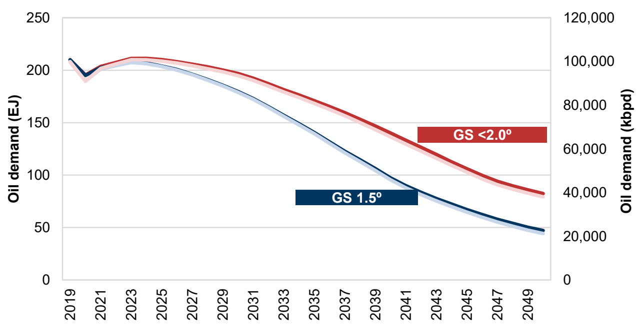
Source: Goldman Sachs Global Investment Research

2) The role of fossil fuels: The role of natural gas as an important transition fuel for power generation and industry is more prominent in the GS <2.0° path compared to the GS 1.5° path

In the exhibits that follow we present the total oil and natural gas demand under the two paths we constructed. In the case of oil, the overall path shown in Exhibit 39 looks similar under the two scenarios, with the GS <2.0° allowing the flexibility for a slower demand decline compared to the GS 1.5° scenario. The case of natural gas on the other hand is different, with the fossil fuel having a critical role as a transition fuel in the GS <2.0° path given both the larger carbon budget and the extra available decade to achieve global net zero that enables a smoother and less abrupt transition compared to the GS 1.5° path. Such a transition will more likely be realistically achievable under the current economic and policy frameworks globally, compared to the GS 1.5°.

Exhibit 39: Oil demand shows a similar path under the two scenarios, with the key difference being the pace of demand decline for combustable oil...

Oil demand (EJ and kbpd) under our two paths

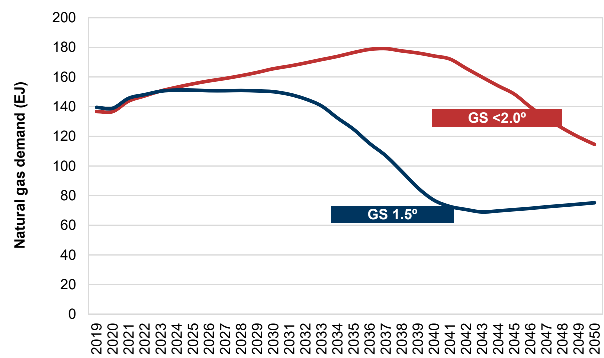


* We use the crude oil energy conversion to find the total energy in EJ without distinguishing between the different oil products

Source: Goldman Sachs Global Investment Research

Exhibit 40: ..while on the contrary, the role of natural gas varies notably under the two scenarios, with the GS <2.0 scenario incorproating natural gas as a key transition fuel in power generation and industry, a flexibility that is not available under the more constrained GS 1.5 path

Natural gas demand (EJ)



Source: Goldman Sachs Global Investment Research

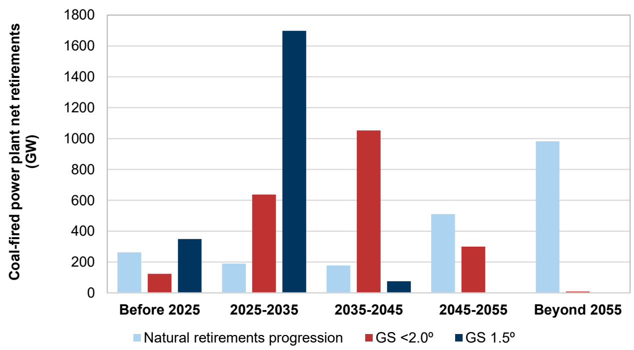
3) Fossil fuel asset retirements: The GS <2.0° path allows more flexibility for a smoother path of retirements for coal-fired power plants and close to the natural pace of retirement for gas power plants reducing the risk of stranded assets

Given the difference in the pace of transition of power generation between the two scenarios, as described above, the pace of retirements of fossil fuel based power plants also differs between the two scenarios. Exhibit 41 shows the coal power plant retirements by decade on the path to global net zero under three distinct cases: (a) the natural retirements progression of the existing coal power plants capacity based on the current age distribution of existing plants, (b) the net retirements of coal power plants in the GS <2.0° path and (c) the net retirement of coal power plants in the stricter, more aspirational GS 1.5° path. As can be seen in the exhibit, both de-carbonization scenarios call for a faster pace of coal power plant retirements than the natural progression would suggest (given the relatively young coal power plant fleet in Asia, with the majority being <20 years old in age), yet the GS <2.0° path shows a smoother retirements profile, contrary to GS 1.5° which requires the vast majority of coal power plants to be retired by

2035. The average operational lifetime of a coal-fired power plant in this analysis is assumed to be around 45 years.

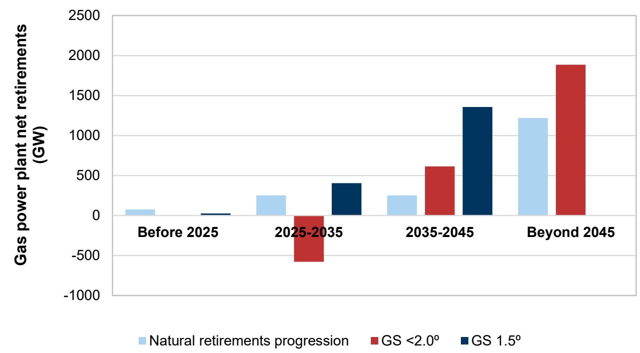
Exhibit 42 shows a similar analysis done for natural gas power plants. The aspirational GS 1.5° path calls for the retirement of all natural gas fired plants by 2045, whilst on the contrary the GS <2.0° path in fact calls for net capacity additions over 2025-35, with natural gas being a key transition fuel particularly in emerging markets, and a more gradual pace of retirements which is not too dissimilar from the natural progression of retirements based on the current age distribution of global gas power plants. The operational lifetime of a gas power plant in this analysis is assumed to be around 35 years, the average operating life of gas plants today.

Exhibit 41: Whilst both of our global net zero scenarios call for a phase out of coal power plants, the coal-fired plants retirement profile under GS <2.0 path is smoother...
Coal-fired power plant net retirements (GW)



Source: IEA, Goldman Sachs Global Investment Research

Exhibit 42: ..whilst for natural gas, the GS <2.0 scenario in fact calls for capacity additions in 2025-35 and a pace of gas power plant retirements that is not too disimilar from the one sugested by the natural retirements progression
Gas power plant net retirements (GW)



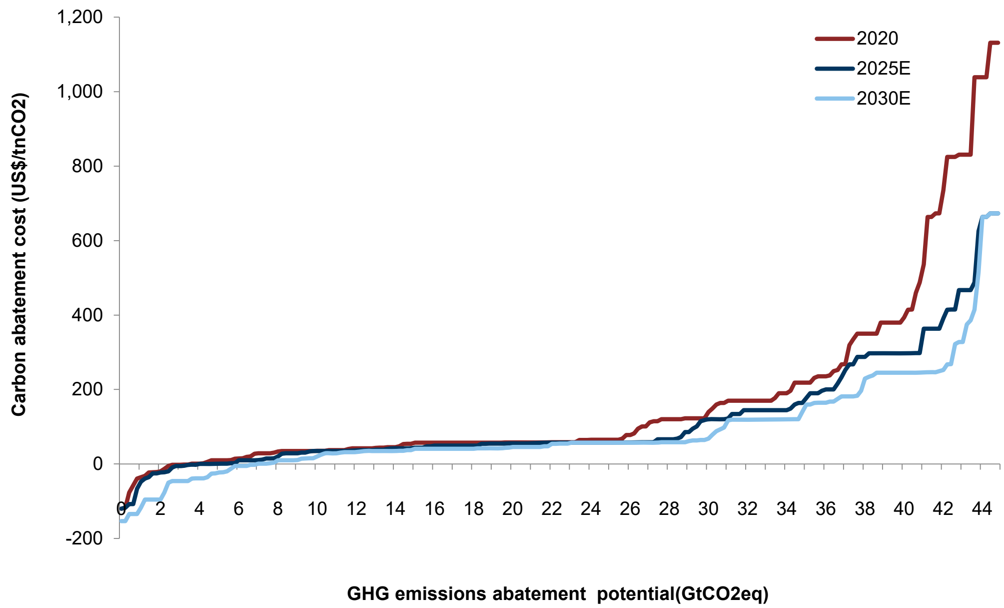
Source: IEA, Goldman Sachs Global Investment Research

4) The evolution of the cost curve: GS <2.0° path allows for an extra decade of cost deflation and technological innovation, during which the cost curve of de-carbonization has the potential to substantially evolve reducing the overall cost to net zero

The additional carbon budget flexibility offered by the <2° scenario effectively provides an extra decade for global net zero, achieving it by 2060 as opposed to by 2050 required by the 1.5° scenario. During this time we expect a number of technologies to move lower on the carbonomics cost curve, benefiting from ongoing cost deflation, economies of scale and further technological innovation. We identified earlier in this report the four key transformation technologies on the path to net zero: power generation, batteries, carbon sequestration and clean hydrogen. As shown in Exhibit 43 an additional decade can meaningfully change the cost curve of de-carbonization. For the purpose of this analysis we primarily focus on the potential deflation of battery energy storage (applied to transport and power generation) and clean hydrogen (applied to transport, industry and buildings). The major shift in the Carbonomics cost curve (even when only considering these two technologies) clearly indicates that a decade can have a critical impact on the cost of de-carbonization, making the <2° scenario more economically affordable.

Exhibit 43: The additional carbon budget flexibility provided by the GS <2.0 scenario compared to the GS 1.5 enables global net zero to be achieved almost a decade later, resulting in a lower overall cost of de-carbonization given the major shift in the Carbonomics cost curve that can be achieved in a decade as a result of cost deflation, economies of scale and further technological innovation.

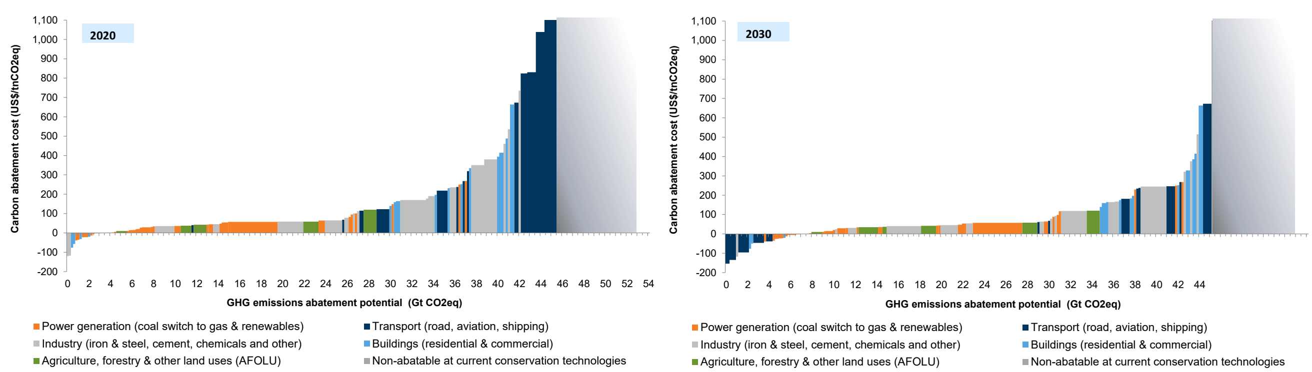
Conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies, assuming economies of scale for technologies in the pilot phase



Source: Goldman Sachs Global Investment Research

Exhibit 44: Cost deflation in battery energy storage and clean hydrogen alone is sufficient to marterially change the Carbonomics cost curve during the course of a decade

Conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies, assuming economies of scale for technologies in the pilot phase



Source: Goldman Sachs Global Investment Research

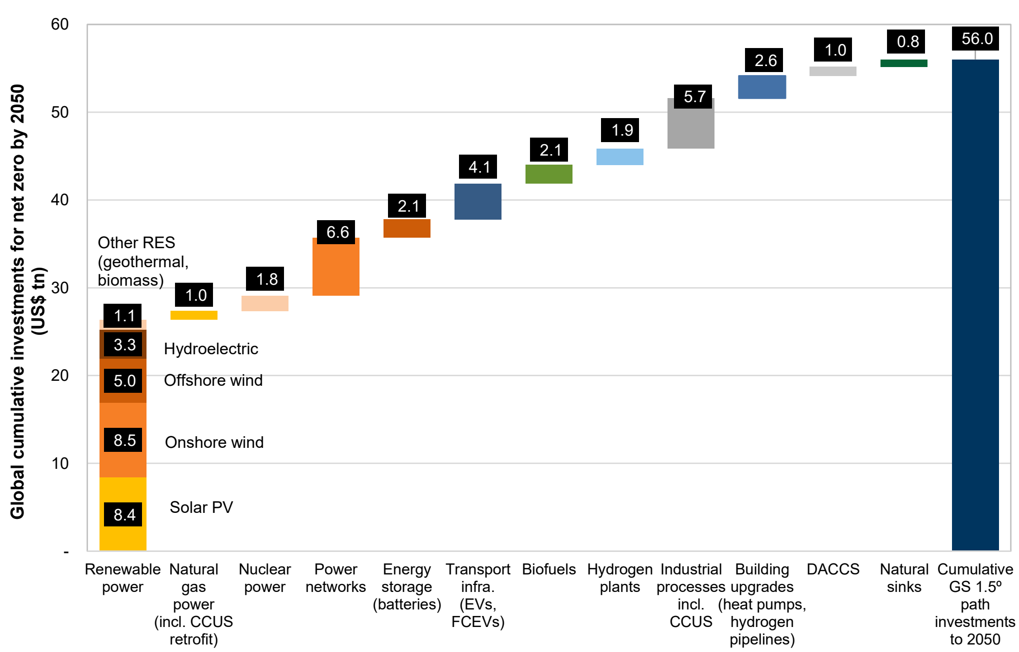
The investment path: US$50-60 tn infrastructure investment opportunity on the path to carbon neutrality

A global path to net zero by 2050 (GS 1.5°) has the potential to transform not only the global energy ecosystems but also the economy and society's standard of living. Exhibit 45 shows the wide range of investment opportunities associated with what we believe are the key infrastructure milestones required to achieve net zero emissions by 2050. These include, among others, the increasing uptake of renewable energy, bioenergy, an increasing focus on infrastructure investments for networks and charging stations that will enable a new era of electrification, an upgrade and/or retrofit of industrial plants (the cleanest available alternative technology), retrofitting of buildings and other existing heating infrastructure enabling greater uptake of cleaner fuels such as electrification and/or clean hydrogen, and finally a greater focus on carbon sequestration (natural sinks and carbon capture).

In aggregate, we estimate a total investment opportunity around US$56 tn by 2050 in a scenario consistent with the path to net zero we have outlined above, which **implies an average annual green infrastructure investment opportunity of c.US$1.5-2 tn.** We note that this figure focuses solely on **incremental infrastructure investments** and does not include maintenance and other end-use capex.

Exhibit 45: We estimate that there exists in aggregate a c.US$56 tn investment opportunity across sectors on the path to global net zero by 2050

Cumulative investment opportunity across sectors for our GS 1.5° global net zero by 2050 model (US$ tn)

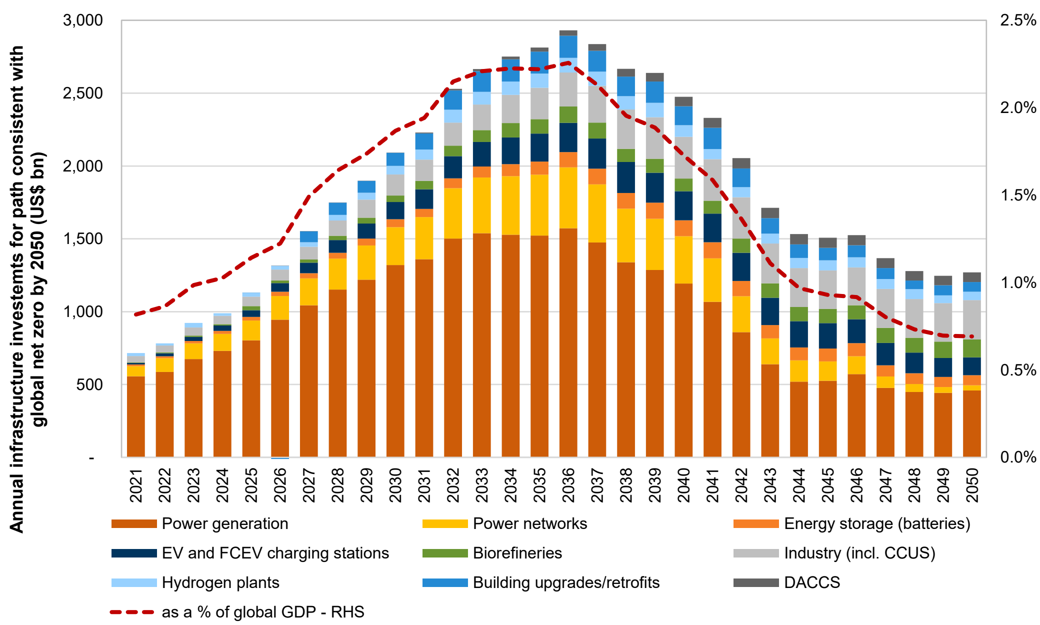


Source: Goldman Sachs Global Investment Research

The global path to net zero by 2050 requires, on our estimates, US$1.5-2 tn pa of infrastructure investments, representing c.2% of global GDP

As highlighted in Exhibit 45, we estimate a total investment opportunity of c.US$50-60 tn by 2050 in a scenario consistent with the path to net zero and 1.5°C global warming, but we would not expect this to be evenly distributed annually to 2050. Instead, we anticipate an annual de-carbonization investment profile similar to that shown in Exhibit 46, with an acceleration of investments to 2035-40, the years when we expect investments to peak, driven largely by the initial infrastructure expansion required for power networks, charging networks, the massive expansion of renewable power, buildings upgrades and heating pipeline infrastructure to accelerate the penetration of electrification and clean hydrogen, and fuel substitution in transport and industry. Overall, the average annual investments in de-carbonization that we estimate over 2021-50 are c.US$1.9 tn (compared with <US$1 tn spent on power generation in 2019), with the peak in the 2030s (c.US$2.9 tn) representing >2% of global GDP.

Exhibit 46: We expect an annual investment profile similar to the one presented here, for a path consistent with global net zero by 2050, with investments peaking in the mid 2030s, representing up to c.2% of global GDP (US$ 2010 PPP)



Source: Goldman Sachs Global Investment Research

Laying out the path to global net zero carbon by 2050: Defining sectoral carbon budgets

Our GS 1.5° path to global net zero by 2050 addresses all the key emitting sectors: power generation, transport, industry and waste, buildings and AFOLU including agriculture, forestry and other land uses emissions. As mentioned in the sections previously, the pace of de-carbonization in each sector and sub-sector included in our path is expected to vary, depending on the carbon abatement cost and readiness of the available de-carbonization technologies. Consequently, the sectoral and sub-sectoral allocation of the carbon budget required to limit global warming within 1.5°C is expected to be different from the current share of emissions contribution of each sector. The sectoral and sub-sector allocation of the remaining carbon budget to 2050 are shown in Exhibit 47. Industry and transport are the two key sectors with the largest carbon budget allocation to 2050, c.40% and 30% respectively, given they are responsible for some of the hardest-to-abate emissions, with the clean technology alternatives relatively costly and in several cases largely undeveloped. Among these are heavy industries (iron & steel, cement, high temperature heat) as well as long-haul heavy transport including shipping, aviation and trucks.

Exhibit 47: Sectoral coverage of CO2 emissions under our GS 1.5° path and sectoral carbon budget allocation to 2050

		GS 1.5° path			
	Sectoral approach emissions analysis	Further sectoral emissions analysis breakdown	Carbon budget allocation (GtCO2, % of total budget)		
	Power Generation	Power Generation	129	25%	25%
	Transportation	Aviation	22	4%	30%
		Shipping	17	3%	
		Rail	2	<1%	
		Light-duty road transport	59	12%	
		Heavy-duty road transport	51	10%	
	Buildings	Residential buildings	37	7%	10%
		Commercial buildings	16	3%	
	Industry (combustion & process), fugitive & waste	Iron & Steel	43	8%	40%
		Cement	46	9%	
		Aluminium*	8	1%	
		Chemicals & petrochemicals, incl. ammonia, methanol, HVCs	31	6%	
		Pulp, paper & packaging	3	1%	
		Food & tobacco processing	10	2%	
		Other industry incl. fuel extraction/ processing and waste	63	12%	
	AFOLU (Agriculture, forestry, other land use)	Agriculture and land use change	44	9%	-6%
		Natural sinks, DACCS	-74	-14%	
		Total carbon budget GS 1.5	507	100%	

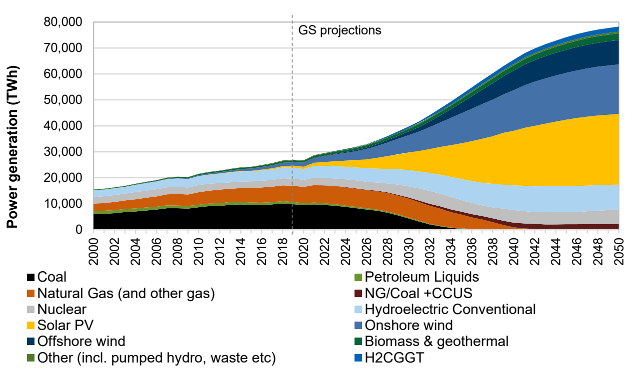
Source: Goldman Sachs Global Investment Research

Power generation: The critical piece to the global carbon neutrality jigsaw

Power generation is the most vital component for any net zero scenario, with the sector contributing to c.32% of global anthropogenic CO_2 emissions (incl. AFOLU), making it the most critical area of focus to tackle the net zero challenge. The role of power generation is, in our view, only likely to increase in the coming decades, as the penetration and pace of electrification is rapidly increasing across sectors as these progressively follow their own de-carbonization path (including amongst others road transport, building heating, industrial manufacturing processes and low-temperature industrial heat). Overall, we expect total demand for power generation in a global net zero scenario by 2050 to **increase three-fold (vs. that of 2019) and surpass 70,000 TWh as the de-carbonization process unfolds.**

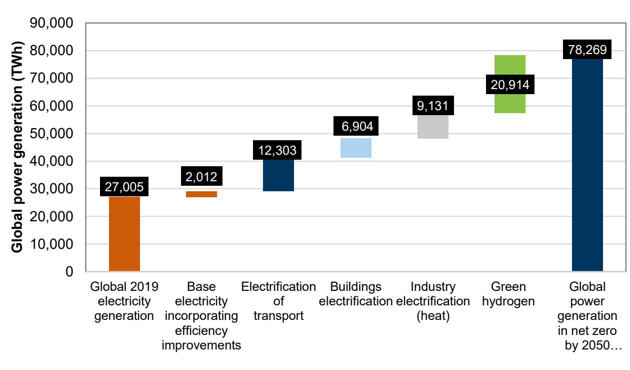
Based on our Carbonomics cost curve analysis, power generation currently dominates the low end of the carbon abatement cost spectrum, with renewable power technologies already developed at scale and costs that have fallen rapidly over the past decade making them competitive with fossil fuel power generation technologies in many regions globally. As such, we believe that **power generation will likely be the first sector to de-carbonize in our GS 1.5° path, reaching carbon neutrality earlier than other harder-to-abate sectors.** Based on our GS 1.5° model, power generation reaches **net zero around 2040** with non-fossil fuel energy share (including nuclear) reaching c.96% in that timeframe. The total carbon budget allocation to the sector is 129Gt, representing 25% of the total carbon budget to 2050, a portion that is smaller than its current emission share. Moreover, the rapid acceleration of power demand leads to a critical need to achieve carbon-free generation as early as possible, in order to meet a carbon budget consistent with 1.5°C global warming, which would otherwise have been hard to achieve without a notable overshoot.

Exhibit 48: Based on our global net zero by 2050 path, power generation demand increases three-fold to 2050...
Global electricity generation (TWh)



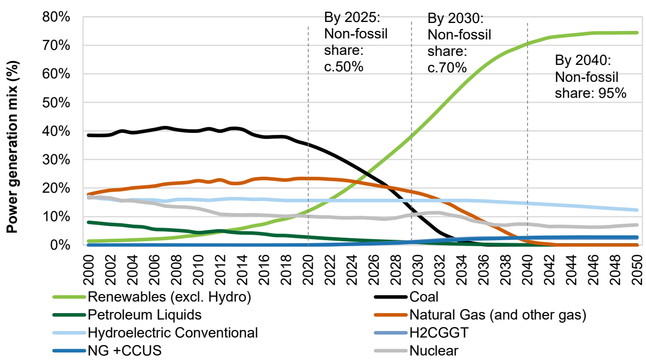
Source: BP Statistical Review, Goldman Sachs Global Investment Research

Exhibit 49: ...as it forms a critical part of the de-carbonization route for other sectors such as the electrification of transport, buildings, heat in industry, production of green hydrogen and more
Glpbal electricity generation bridge to 2050E (TWh)



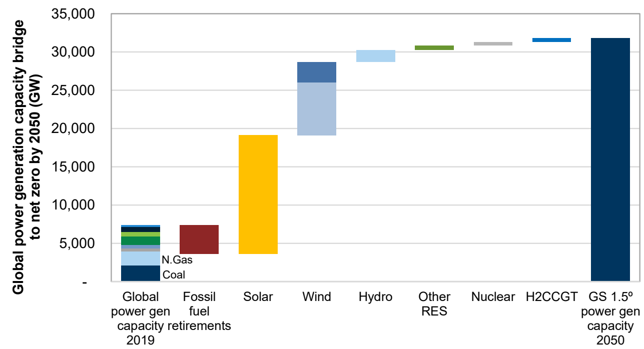
Source: Goldman Sachs Global Investment Research

Exhibit 50: A path consistent with net zero by 2050 requires transformation changes to the global power generation mix, with the non-fossil fuel share in our GLOS path rising from c.36% currently to >95% by 2050...
Global power generation fuel mix (%)



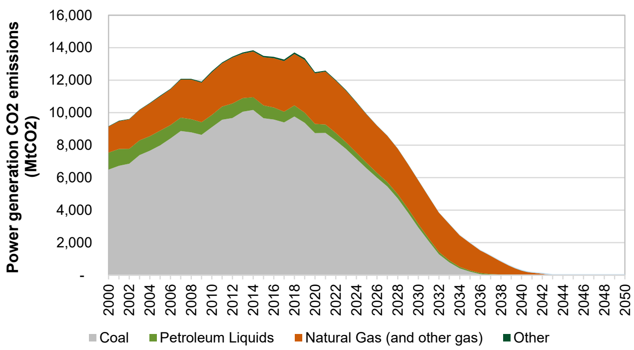
Source: BP Statistical Review, Goldman Sachs Global Investment Research

Exhibit 51: ...leading to >15,000 GW of solar and 10,000 GW of wind net power generation capacity additions to 2050
Global net power generation capacity bridge to 2050 (GW)



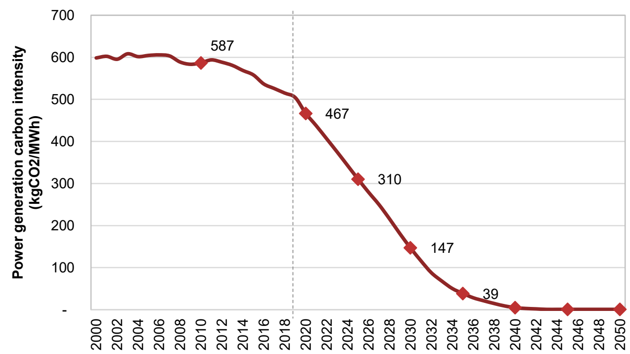
Source: Goldman Sachs Global Investment Research

Exhibit 52: Given the technological readiness and cost deflation of available from de-carbonization technologies, we expect power generation to be the first sector to achieve carbon neutrality...
Power generation CO2 emissions (MtCO2)



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 53: ...achieving net zero carbon emissions by 2040 and helping to facilitate de-carbonization across other sectors through the uptick of electrification
Power generstion carbon intensity (kgCO2/MWh)



Source: BP Statistical Review, Goldman Sachs Global Investment Research

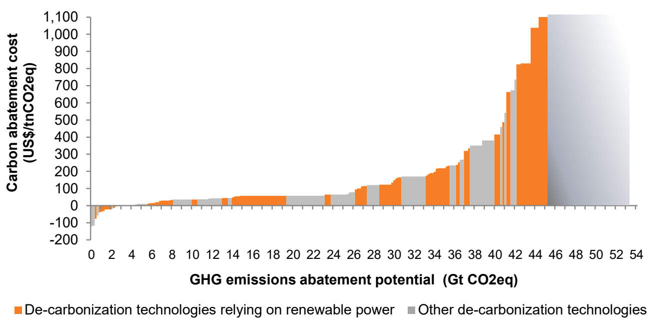
Renewable power: The low-carbon technology dominating 'low-cost de-carbonization', benefiting from economies of scale and a bifurcation in the cost of capital for high- vs. low-carbon energy

Renewable power is the key technology that is envisaged to transform the landscape of the energy industry. It represents one of the most economically attractive opportunities on our de-carbonization cost curve, on the back of lower technology costs as the industry benefits from economies of scale and a lower cost of capital. We estimate that **c.50% of the de-carbonization of global anthropogenic GHG emissions is reliant on access to clean power generation** (as shown in Exhibit 54), including electrification of transport and various industrial processes, electricity used for heating and more.

Renewable power costs have fallen >70% in aggregate across technologies over the past decade, and we note that along with the operational cost reduction that renewable energy has enjoyed over the past decade, owing to economies of scale, the ongoing downward trajectory in the cost of capital, as we highlight in our report *Carbonomics: Innovation, Deflation and Affordable De-carbonization*, for these low-carbon developments has also made a meaningful contribution to the overall affordability and competitiveness of clean energy. We show in Exhibit 56 how the reduction in the cost of capital has contributed to one-third of the reduction in LCOEs of renewable technologies since 2010. In contrast, financial conditions keep tightening for long-term hydrocarbon developments, creating higher barriers to entry, lower activity, and ultimately lower oil & gas supply, in our view. This has created an unprecedented divergence in the cost of capital for the supply of energy, as we show in Exhibit 57, with the continuing shift in allocation away from hydrocarbon investments leading to hurdle rates of 10%-20% for long-cycle oil & gas developments compared with c.3%-5% for the regulated investments in Europe.

Exhibit 54: Access to renewable power is the most critical component, being broadly vital for the de-carbonization of c.50% of the current global antrhopogenic emissions abatement across sectors...

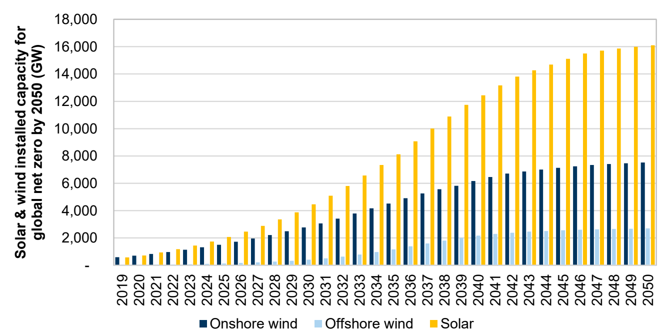
Global anthropogenic GHG emissions de-carbonization cost curve with orange indicating technologies reliant on access to renewable power



Source: Goldman Sachs Global Investment Research

Exhibit 55: ...and as such we expect stellar growth in renewable capacity, in particular for wind and solar, for our GS GLOS path, consistent with global net zero by 2050

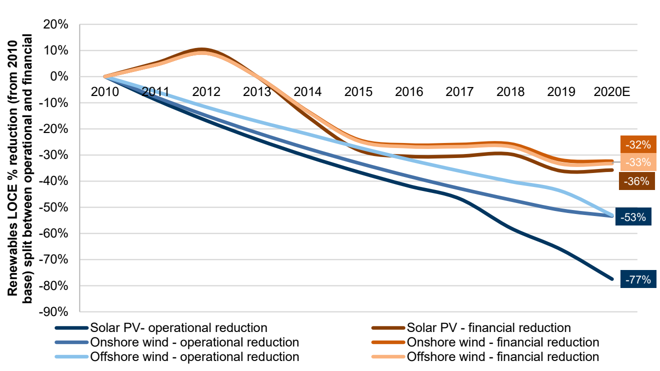
Solar and wind total installed capacity for global net zero (TW)



Source: Goldman Sachs Global Investment Research

Exhibit 56: Renewable power LCOEs have decreased by >70% in aggregate across technologies, benefiting from a reduction in the cost of capital for these clean energy developments, contributing c.1/3 of the cost reduction since 2010

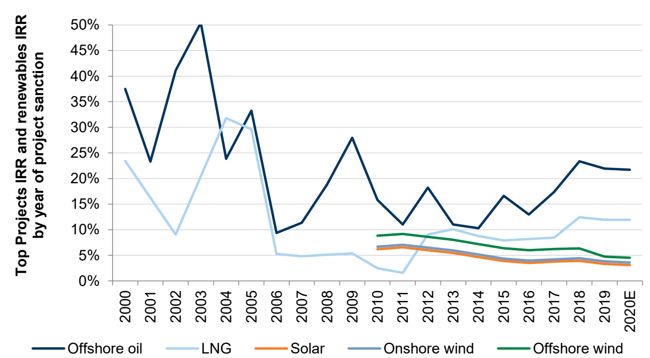
LCOE for solar PV, wind onshore and wind offshore for select regions % reduction split by operational and financial



Source: Goldman Sachs Global Investment Research

Exhibit 57: The bifurcation in the cost of capital for hydrocarbons vs. renewable energy developments is widening, on the back on investor pressure for de-carbonization

Top Projects IRR for oil & gas and renewable projects by year of project sanction



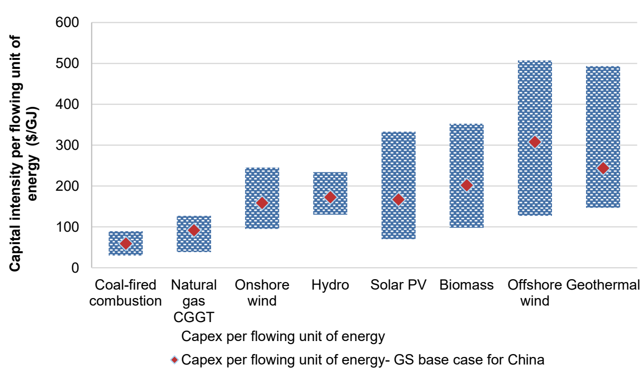
Source: Goldman Sachs Global Investment Research

The power generation investment opportunity: Higher capital intensity of renewable power and the rising importance of energy storage and networks infrastructure pave the way for a c.US$37 tn investment opportunity

Earlier in this report, we highlighted the substantial potential investment creation opportunity associated with a path consistent with net zero emissions by 2050. Renewable power generation acts as a major contributor to this infrastructure investment opportunity (Exhibit 45). This is mainly attributed to the higher capital intensity of these technologies and their associated infrastructure, compared with traditional fossil fuel energy developments. In the exhibits that follow, we present the capital intensity (capex) per unit of output energy for each type of power generation technology. We present the results both in units of capex per flowing unit of energy (US$/GJ of peak energy capacity) and per unit of energy over the life of the asset (US$/GJ). This shows higher capital intensity per unit of energy as we move to cleaner alternatives for power generation. However, this does not necessarily translate into higher costs for the consumer, thanks to the availability of very cheap financing (under an attractive and stable long-term regulatory framework) and lower opex, compared with traditional hydrocarbon developments.

Exhibit 58: Renewable clean technologies in power generation have higher capital intensity compared with traditional fossil fuel sources, based on per flowing unit of energy...

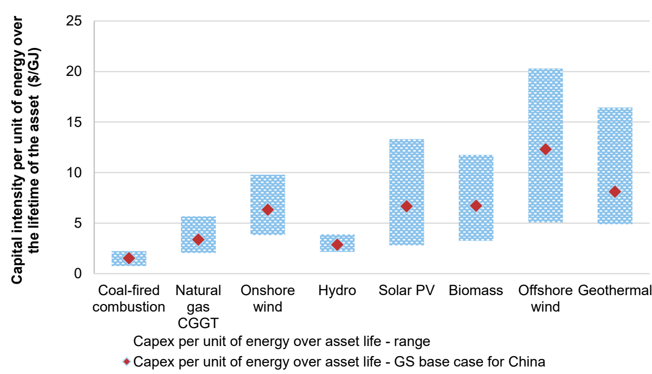
Capex per flowing unit of energy (US$/GJ)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 59: ...and over the lifetime of the asset

Capex per unit of energy over the life of the asset (US$/GJ) for each technology

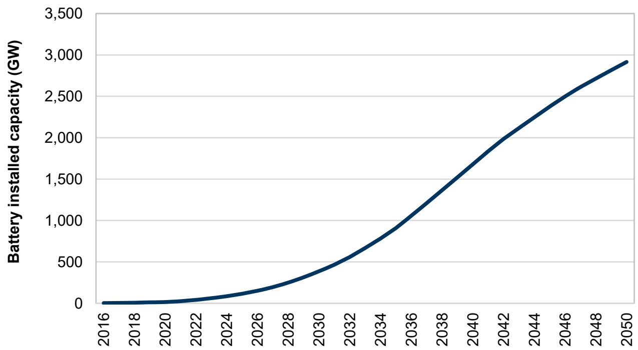


Source: Company data, Goldman Sachs Global Investment Research

As the growth in renewable power accelerates, intraday and seasonal variability has to be addressed through energy storage solutions. To reach full de-carbonization of power markets, we believe two key technologies will likely contribute to solving the energy storage challenge: **utility-scale batteries and hydrogen**, each having a complementary role. We incorporate both of these technologies in our path to net zero and expect utility scale batteries for energy storage to reach c.3,000 GW by 2050 (Exhibit 60, while clean hydrogen-run CGGTs reach c.2.5% in the electricity generation mix in a similar timeframe). **Energy storage and the need for extensive network infrastructure** is a particularly **important consideration as demand for power generation growth accelerates, to ensure a resilient global energy ecosystem.**

Exhibit 60: Our GS 1.5° path incorporates a large acceleration of utility battery energy storage, expected to reach c.3,000 GW by 2050...

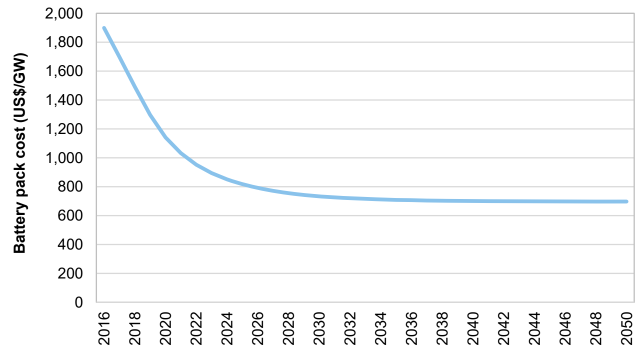
Power generation battery energy storage (GW)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 61: ...and benefiting from cost deflation in utility scale batteries

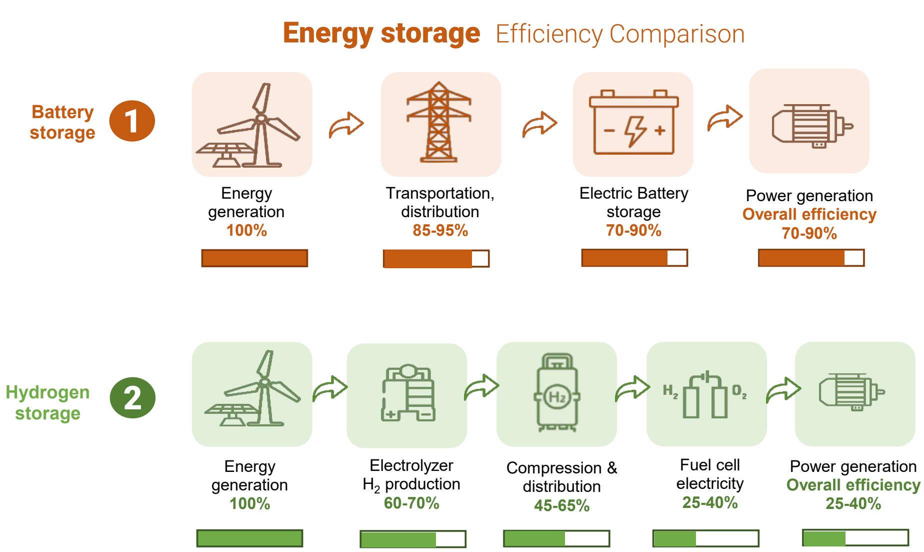
Battery pack cost for power generation energy storage (US$/GW)



Source: Goldman Sachs Global Investment Research

While batteries are currently the most developed technology for intraday power generation storage, we consider hydrogen as a more relevant technology for seasonal storage, implying the need for innovation and development of both technologies. Batteries, for instance, are particularly suited to sunny climates, where solar PV production is largely stable throughout the year and can be stored for evening usage. Hydrogen on the other hand, and the process of storing energy in chemical form and reconverting it to power through fuel cells, could be used to offset the seasonal mismatch between power demand and renewable output. Yet, with fuel cells overall currently having efficiencies that vary between 50% and 65%, the overall efficiency of energy storage becomes a weak point for hydrogen, where we estimate the life-cycle of energy storage efficiency to be in the range of c.25%-40% overall, compared with c.70%-90% for batteries, as shown in Exhibit 62

Exhibit 62: We see utility scale batteries and hydrogen as the two key complementary technologies to address the energy storage challenge



Source: Company data, Goldman Sachs Global Investment Research.

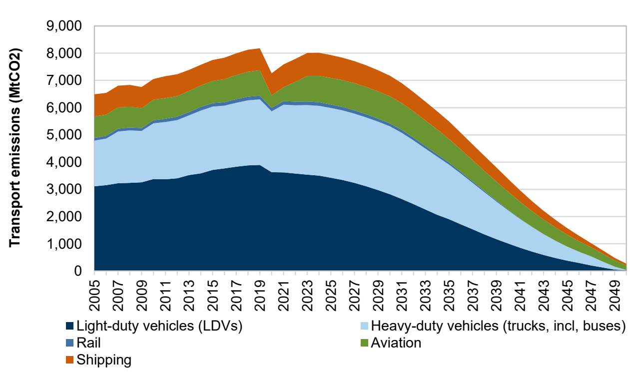
Transportation: The rise of NEVs and alternative fuels with different technologies across transport modes

Transportation, in contrast to power generation, mostly sits in the 'high-cost' area of the de-carbonization cost curve, with the sector responsible for c.22% of the global anthropogenic CO_2 emissions (2019, incl. AFOLU). As part of our analysis, we lay out the path to net zero emissions for transportation, as shown in Exhibit 63, addressing all key transportation modes: short and medium-haul road transport, heavy long-haul transport, rail, aviation and shipping. The speed of de-carbonization varies depending on the transport mode, as shown in Exhibit 64, largely driven by the difference in costs and technological readiness of the available clean alternatives required for each sub-sector. Light-duty vehicles and rail (which is already largely de-carbonized through electrification) are the two transport modes with a faster relative de-carbonization, given the readiness and notable cost deflation of clean technologies for both (electrification). Conversely, aviation and shipping de-carbonize at a slower pace, given the still largely undeveloped or early stage development de-carbonization alternatives in both (sustainable aviation fuels, synthetic fuels, clean hydrogen and ammonia), which we expect to enjoy a large uptake in adoption and account for a notable part of the fleet only post 2030.

We further address how the fuel mix of the energy consumption of transport evolves over time in our GS 1.5 scenario and present the results both in aggregate and by key transport mode in Exhibit 65 and Exhibit 66. Overall, electricity increases its share in total transport energy consumption to c.50% by 2050, whilst fossil fuel share declines from >95% at present to just 3%. Bioenergy, clean hydrogen & synthetic fuels, and ammonia all emerge as important energy sources for transportation, accounting for c.21%/ 19%/8% respectively.

Exhibit 63: We model the emissions in the transport sector by mode in our GS 1.5°path to global net zero by 2050...

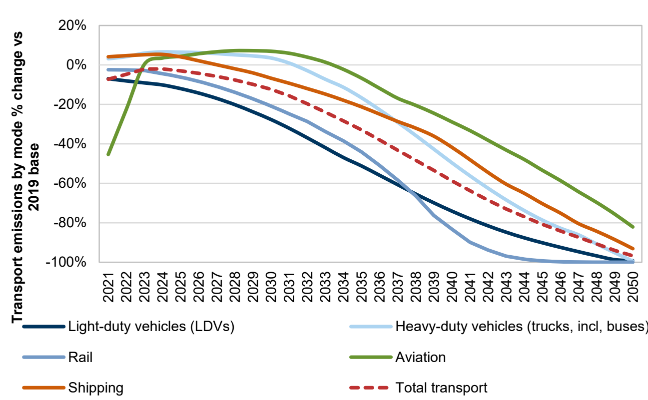
Transport sector emissions (MtCO2) split by key transport mode



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

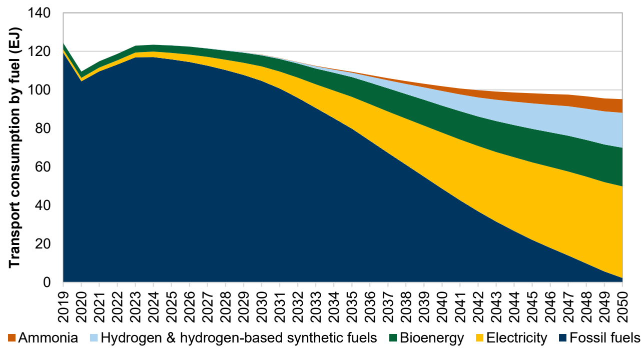
Exhibit 64: ...with the speed of de-carbonization varying across modes depending on the cost and readiness of the respective clean technologies

Transport emissions by mode % change vs. 2019 base



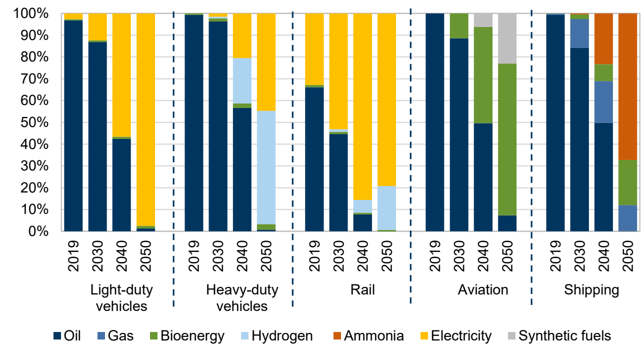
Source: Goldman Sachs Global Investment Research

Exhibit 65: The energy mix of the transport sector is expected to evolve dramatically over time for a path consistent with net zero...
Transport energy consumption by fuel (EJ)



Source: Goldman Sachs Global Investment Research

Exhibit 66: ...with electrification, bioenergy, synthetic fuels, clean hydrogen and ammonia all playing key roles in the transition
Fuel mix of energy consumption in transport by transport mode (%)



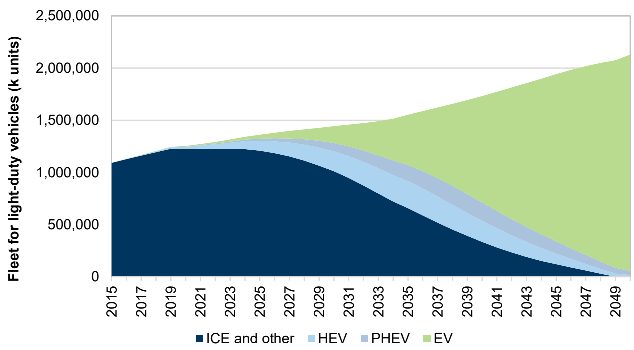
Source: Goldman Sachs Global Investment Research

Light-duty road transport vehicles: Electrification at the heart of the transport evolution

We believe road transport is at the start of its most significant technological change in a century, with electrification, autonomous driving and clean hydrogen at the core of the de-carbonization challenge. For light duty vehicles (LDVs) transport (primarily constituting passenger vehicles, commercial vehicles and short/medium-haul trucks), we consider **electrification the key de-carbonization technology.** For **long-haul heavy trucks**, we **consider clean hydrogen a competitive option**, owing to its faster refueling time, lower weight and high energy content. Overall, we estimate that the total LDVs road fleet (including passenger vehicles, short and medium-haul trucks) will increase almost two-fold to 2050 (from a 2019 base), with new energy vehicles – NEVs (including all of BEVs, PHEVs and FCEVs) reaching almost 100% penetration in the road transport fleet as shown in Exhibit 68, for a path consistent with net zero emissions globally by 2050 and peak emissions before 2030.

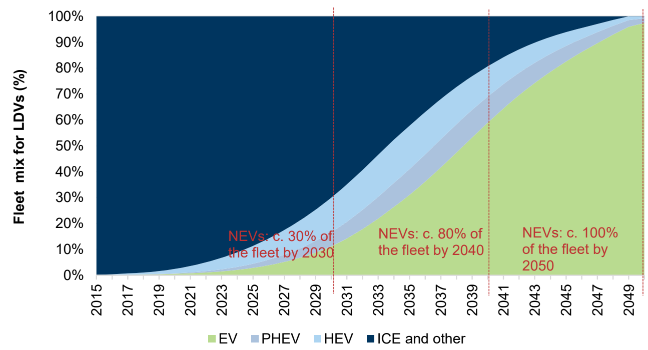
While we project considerable growth in pure battery vehicles, the ultimate de-carbonization solution for light road transport (essential for a net zero path), we expect multi-energy powertrain to also play a role in the facilitation of this transition, accounting for a considerable portion of sales and the fleet over the next 20 years. Multi-energy vehicles include plug-in hybrid EV (PHEVs), range-extended EVs, and light emission hybrid cars (HEVs). Overall, considering all NEV types, our net zero path requires a NEV penetration in the light-duty road transport fleet to reach 30% by 2030, close to 80% by 2040, and almost 100% by 2050. NEVs sales make up c.38%/70%/>95% and 100% of total LDV sales by 2025/30/35/40E respectively, effectively reaching zero carbon intensity in LDV sales by 2035-36, as shown in Exhibit 70. We primarily focus on the evolution of the fleet for the purpose of emission accounting in this analysis, with the fleet evolution reliant on both vehicles sales and retirements, as it is ultimately the penetration in the fleet that directly translates into transport emissions.

Exhibit 67: Our GS 1.5 path assumes a major shift in the mix of the fleet of LDVs to 2050...
Light-duty vehicles fleet (k units)



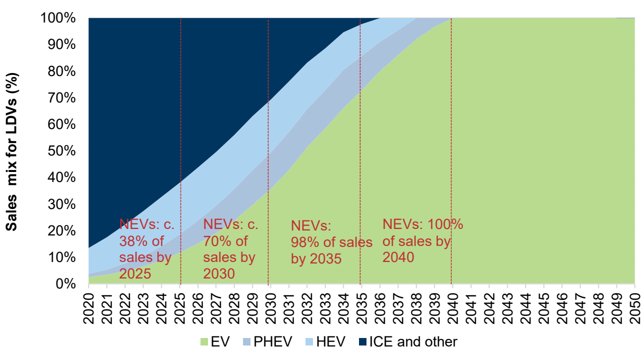
Source: BNEF, Goldman Sachs Global Investment Research

Exhibit 68: ...with NEVs (including BEVs, PHEVs and HEVs) making c.30%/80%/100% of the fleet by 2030/40/50E respectively
Light-duty vehicles fleet mix evolution over time (%)



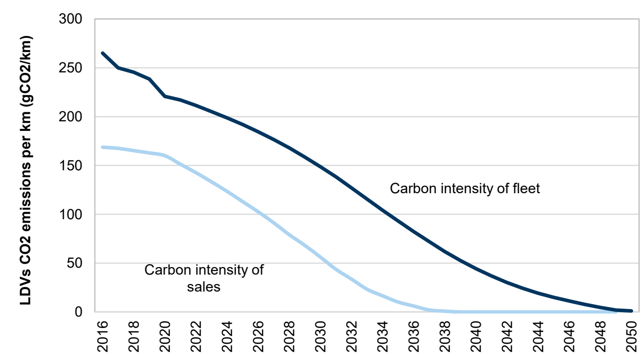
Source: Goldman Sachs Global Investment Research

Exhibit 69: To achieve an LDV fleet that is almost 100% NEVs by 2050, the share of ICE vehicle in total LDV sales must reach zero around 2035-40...
Light-duty vehicles sales mix (%)



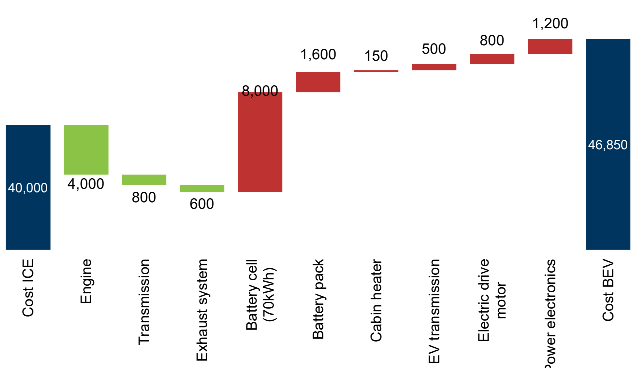
Source: Goldman Sachs Global Investment Research

Exhibit 70: ...with the carbon intensity of the fleet tracking the carbon intensity of sales, with a c.10-15 year delay
LDVs' CO2 carbon intensity per km travelled (gCO2/km)



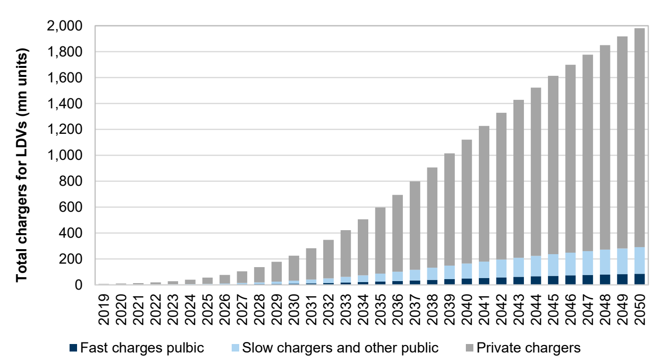
Source: Goldman Sachs Global Investment Research

Exhibit 71: A mid-size EV costs on average c.€6-7k more than a comparable ICE version on our estimates at present...
ICE to BEV walk (€) for passenger vehicles



Source: Goldman Sachs Global Investment Research

Exhibit 72: ...with a large charging infrastructure opportunity on the path to carbon neutrality
GS 1.5 total chargers for LDVs (mn units)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 73: BEVs appear to be the most attractive current de-carbonization alternative technology for short-haul passenger transport

Model	Tesla Model 3 SR	BMW 330i	Toyota Mirai
Model			
Type of vehicle	BEV	ICE	FCEV
Price ($, ex-subsidies)	$37,990	$41,250	$57,500
EPA range (km)	402 km	714 km	502 km
Curb weight	1726 kg	1614 kg	1850 kg
Energy source	50 kWh battery pack	60 litre fuel tank	Two hydrogen tanks (5kg, 700 bar)
Cost of refuelling (CA)	$6.5	$52.2	$83.2
Refuelling time	30 minutes (80% DC charge)	2 minutes	5 minutes
0-60 mph	5.3s	5.5s	9.0s
CO2 g/km	0 g/km	150 g/km	0 g/km

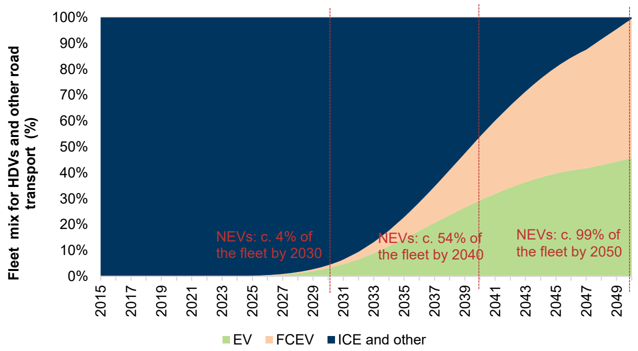
Source: Company data, Goldman Sachs Global Investment Research

Heavy-duty road transport and other vehicles: The rise of clean hydrogen and alternative clean fuels

While we believe that electric vehicles screen as the most attractive de-carbonization solution for LDV applications, including short and medium-haul transport, we believe that clean hydrogen could be a key competing technology when long-haul heavy transport is considered, given its high energy content per unit mass and faster refueling time. Although the FCEVs (fuel cell electric vehicles) global stock was estimated to be around 25,000 at the end of 2019, owing to a limited product offering, non-competitive price points and little infrastructure, we see the recent policy drive towards de-carbonization as a reason to reconsider the potential for FCEVs. Despite small absolute volumes, the growth of FCEVs could accelerate notably, particularly in heavy long-haul transport applications, buses and forklifts. Overall, our net zero path by 2050 (GS 1.5°) calls for a sales mix that evolves notably in the coming years, with FCEVs and EVs making up c.22%/100%% of total HDV sales by 2030/40E. For a deep dive on the future of trucking, please see our global autos team's published report and presentation.

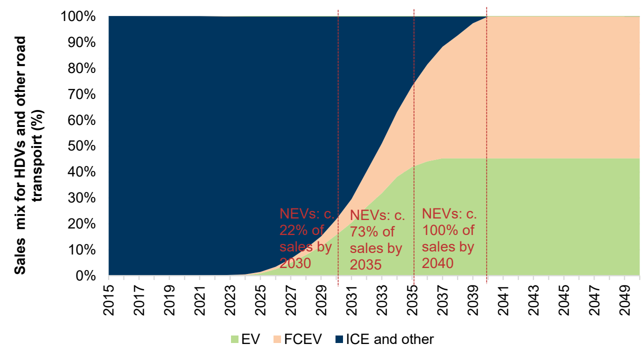
In our GS 1.5° scenario, we project considerable growth in both electric vehicles and FCEVs as the penetration of both overtakes internal combustion engine vehicles in the coming decades. However, the shift in the fleet mix for heavy-duty vehicles starts later than the transition in LDVs, given the lower product offering and the need for further technological innovation (in the case of long-haul large capacity batteries) and cost deflation (in the case of fuel cells).

Exhibit 74: Clean hydrogen and electrification are in our view the two key technologies to address long-haul havy-duty transport...
Fleet mix for heavy-duty vehicles and other road transport (%)



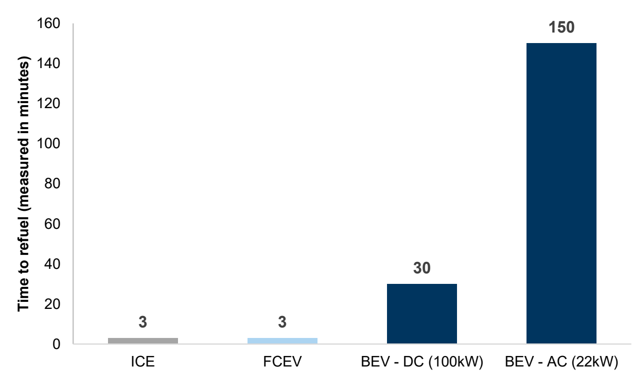
Source: Goldman Sachs Global Investment Research

Exhibit 75: ...with NEVs (FCEVs and EVs) accounting for c.100% of heavy-duty vehicle sales by 2040.
Sales mix for heavy-duty vehicles and other transport (%)



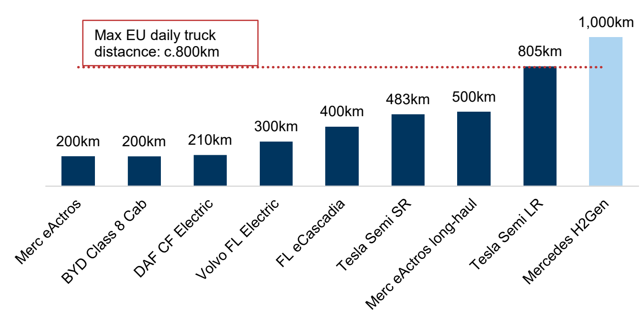
Source: Goldman Sachs Global Investment Research

Exhibit 76: Hydrogen outperforms significantly when we compare the refueling times of FCEVs versus BEVs at different kW charging ratings...
mins to refuel/recharge



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 77: ...and also provides a range advantage, particularly useful for long-haul truck applications
ZEV Class 8 trucks and range (km)

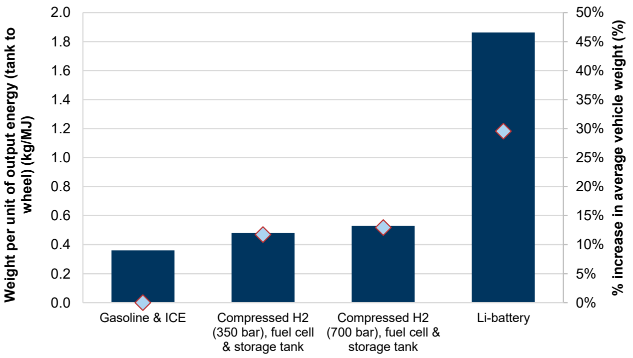


EU max daily driving time at 9 hours (assuming average speed of 90km/h)

Source: Transport & Environment, EU, Goldman Sachs Global Investment Research

Exhibit 78: FCEVs (average passenger vehicle) using compressed hydrogen screen attractively on a weight per unit of output energy basis when compared with Li-battery EVs

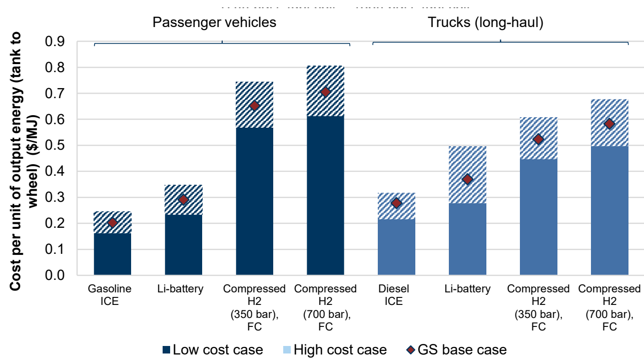
Weight per unit of output energy (tank-to-wheel basis, kg/MJ) for average passenger vehicle and % increase in average vehicle weight



Source: US Department of Energy, EIA, Goldman Sachs Global Investment Research

Exhibit 79: While FCEVs are not cost competitive for short-haul passenger vehicles, on our estimates they become more competitive in long-haul heavy transport

Cost per unit of output energy (tank-to-wheel, $/MJ)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 80: Looking at current prices, FCEV trucks are more expensive on a TCO basis, but with large cost reduction potential

Total cost of ownership of a Class 8 truck (15 years)

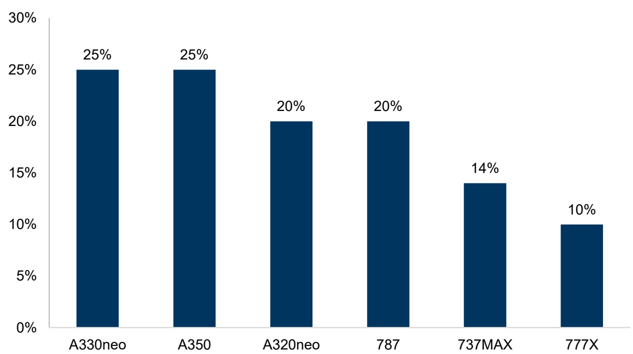
Model	Hydrogen truck		BEV truck		Diesel Truck
	2020	2025	2020	2025	2020
Model					
Cost of Truck	$250,000	$210,000	$250,000	$190,000	$120,000
Cost of fuel	$6 per kg/H2	$4.80 per kg/H2	0.10 $ per kWH	0.10 $ per kWH	$2.58 per gallon
Fuel consumption	7.5 miles per kg	7.5 miles per kg	0.4 miles per kWh	0.45 miles per kWh	8 MPG
Fuel cost over 15 years	$1,200,000	$960,000	$375,000	$333,333	$483,750
Maintenance costs	$259,500	$259,500	$242,400	$242,400	$311,800
Battery costs	$8,400	$5,688	$120,000	$81,262	$0
Payload losses	$0	$0	$266,667	$200,000	$0
Total cost	$1,717,900	$1,435,188	$1,254,067	$1,046,996	$915,550
$ per mile	$1.15	$0.96	$0.84	$0.70	$0.61
$ per mile (ex-payload)	$1.15	$0.96	$0.66	$0.56	$0.61

Source: Company data, Goldman Sachs Global Investment Research

Aviation: One of the harder-to-abate sectors, with new generation aircraft/fleet renewal, sustainable aviation fuels (SAFs) and other new propulsion technologies paving the way for technological transformation

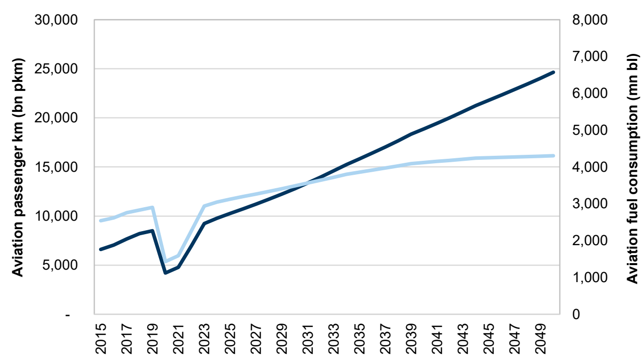
Aviation sits at the top of our Carbonomics cost curve, and is one of the toughest sectors to de-carbonize. Sustainable aviation fuels (SAFs), synthetic fuels and improved aircraft efficiency are in our view all key parts of the solution. In the near term, we view that new generation of aircraft and fleet renewal as likely to achieve the lowest-cost aviation emissions abatement. New generation aircraft, which can burn c.15%-20% less fuel than their predecessors, currently have limited penetration across the global fleet, yet as fuel costs typically account for c.25% of airline opex, simplistically assuming a unilateral switch to new gen aircraft could boost airline margins, all else equal. Although lower investment capacity amid weakened balance sheets post Covid is resulting in near-term aircraft deferrals, we do not expect medium and long-term fleet renewal plans to change.

Exhibit 81: The switch to more efficient aircraft has the potential to lead to c.15%-20% fuel burn improvement...
Fuel burn improvement vs. previous generation as per company data



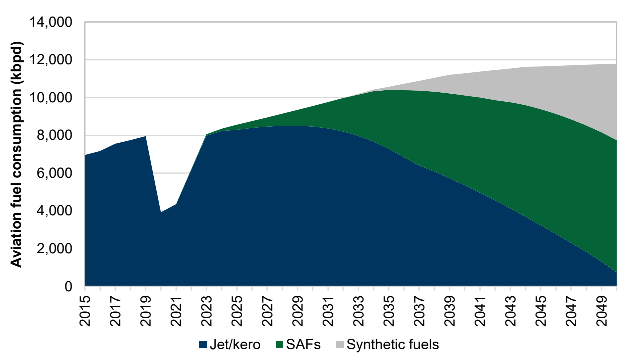
Source: Company data

Exhibit 82: ...and is the key tool in the near and medium term given the ongoing increase in activity we expect in the sector...
Aviation pkm and fuel consumption



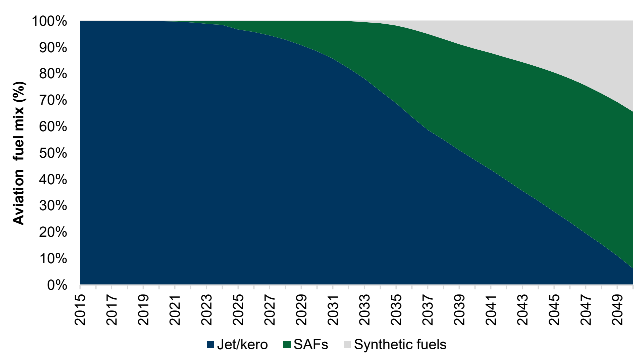
Source: IATA (historical), Goldman Sachs Global Investment Research

Exhibit 83: ...but ultimately, a fuel switch is necessary, with SAFs and syntehtic fuels paving the de-carbonization path in the medium and longer term...
Aviation fuel consumption (kbpd)



Source: IATA, Goldman Sachs Global Investment Research

Exhibit 84: ...accounting for c.60%/35% of the aviation fuel mix respectively by 2050
Aviation fuel mix (%)

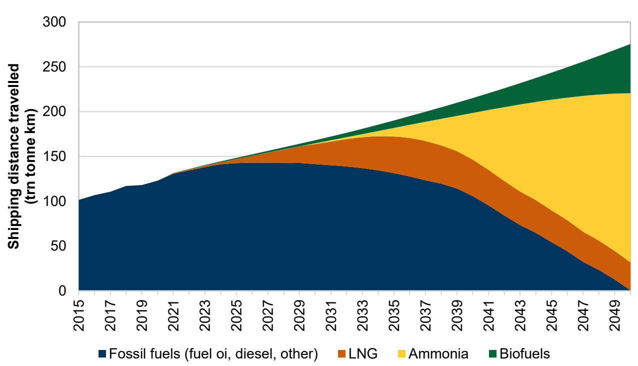


Source: Goldman Sachs Global Investment Research

Shipping: Alternative low-carbon fuels such as clean ammonia, bioenergy and LNG all have a role in the de-carbonization process of one of the most challenging areas from a carbon-abatement perspective

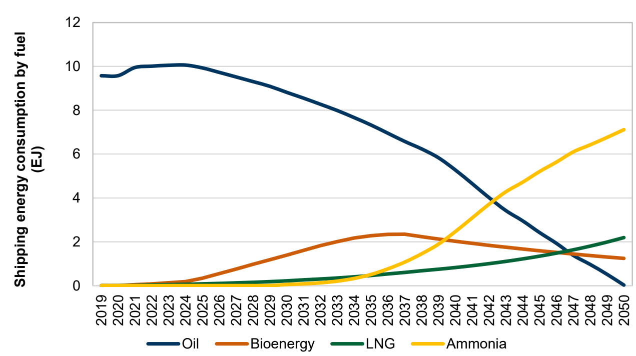
Maritime shipping is responsible for c.0.9 GtCO2eq (2019), accounting for a similar share of the global CO_2 emissions as aviation. Shipping is another sector with hard-to-abate emissions, given a lack of widespread adoption of the available low-carbon de-carbonization technologies at scale, and the relatively long operating life of vessels. Similar to aviation, we do not expect gross emissions in shipping to reach absolute zero in 2050, yet we do model a notable reduction in emissions, as alternative fuels become more widely adopted. Amongst these is liquefied natural gas (LNG), which whilst not a zero-emitting fuel, can play a key role as a transition fuel for the shipping sector. Longer term, we expected advanced biofuels, and clean ammonia and hydrogen, to play a larger role as the ultimate de-carbonization technologies for the sector. Internal combustion engines for ammonia-fueled vessels are currently being developed, and we expect they can be made readily available to the market by 2030. In our GS 1.5° path, clean ammonia accounts for c.67% of the total energy in shipping in 2050, sustainable biofuels provide c.20% of total shipping energy needs, with the remaining energy provided by fossil fuels (oil and LNG).

Exhibit 85: Based on our GS 1.5 path, fuel switching will be key in the de-carbonization of shipping...
Shipping distance travelled in trillion tonne km



Source: Goldman Sachs Global Investment Research

Exhibit 86: ...with clean ammonia, advanced biofuels and LNG all playing in a role in the energy transition
Shipping energy consumption by fuel (EJ)



Source: Goldman Sachs Global Investment Research

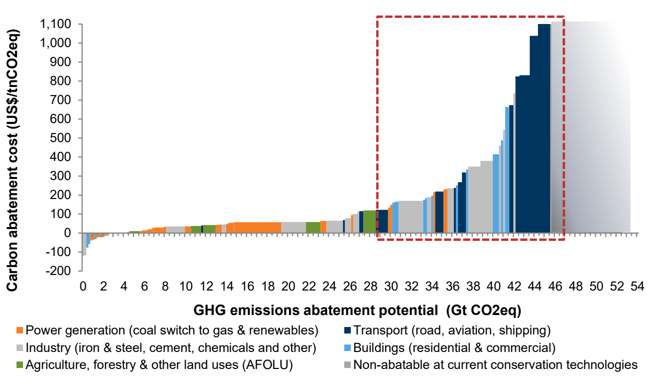
Rail: Currently the least carbon-intensive transport mode with further de-carboniation as the electrification process continues and hydrogen for long-haul heavy trips gets added to the mix

Rail is currently the least carbon-intensive and one of the most energy efficient transport modes. At present, more than 40% of rail energy is in the form of electricity, with the remaining energy consumption primarily in the form of diesel for heavy long-haul trips. In our GS GL0s path we assume rail activity continues to increase, and that the electrification process continues to unfold until hydrogen fuel cell electric trains (FCEs) unlock the final portion of carbon abatement for those harder-to-abate long-haul rail trips.

Battery technology at the core of the technological and cost evolution of road transport

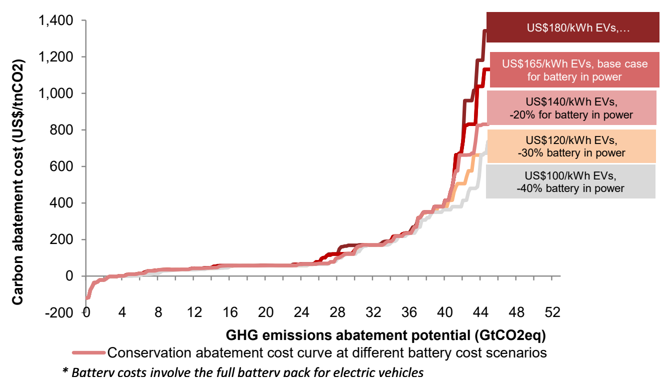
Battery technologies are critical to the de-carboazation of road transport, which accounts for >75% of the total transport emissions. As such, we address the technology in more detail in this section of the report. As we previously mentioned, transportation mostly occupies the high-cost end of our Carbonomics de-carbonization cost curve (Exhibit 87). Nonetheless, carbon abatement costs are highly sensitive to the evolution of battery costs and cost deflation. In Exhibit 88 shown below, we analyze the case for different battery cost scenarios (full battery pack cost) for electric vehicles, including short-haul trucks, and for energy storage in power generation. The resulting exhibit shows a relatively high sensitivity of the shape of the cost curve to battery costs, suggesting the battery technology has the potential to transform the higher end of the de-carbonization cost spectrum, which is dominated by transport. Lower battery costs for passenger EVs, both rural and urban, as well as trucks, could have a notable impact in reducing the overall cost of de-carbonization. However, battery technology in its current form remains unlikely to offer a solution to the de-carbonization of aviation and shipping, and seasonal variations in power demand, providing hydrogen with a key role to play in these areas, as we outlined in the previous section.

Exhibit 87: While transportation currently dominates the high end of the de-carbonization cost curve...
Conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



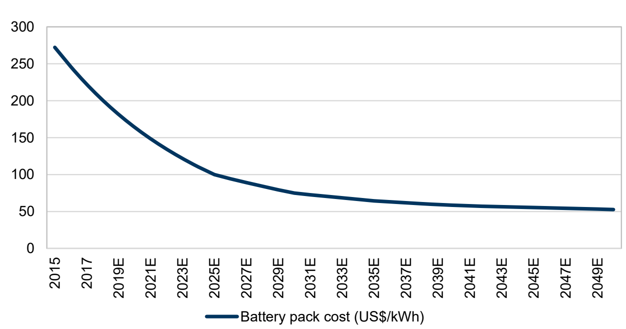
Source: Goldman Sachs Global Investment Research

Exhibit 88: ...the cost curve can evolve with innovation and ongoing cost deflation in technologies such as batteries
Conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



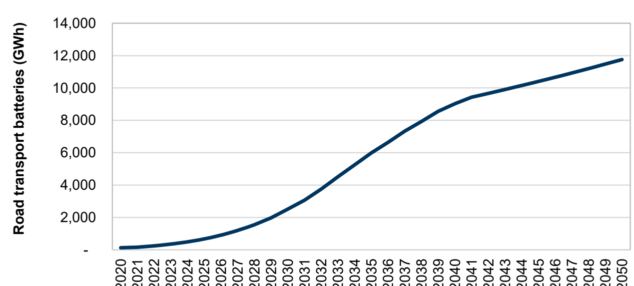
Source: Goldman Sachs Global Investment Research

Exhibit 89: Our GS GLOS path incorporates ongoing cost deflation in battery packs for road transport...
Battery pack cost (US$/kWh)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 90: ...with road transport batteries for NEVs facing stellar growth and exceeding 10,000 GWh by 2050E
Road transport batteries trajectory under GS GLOS (GWh)



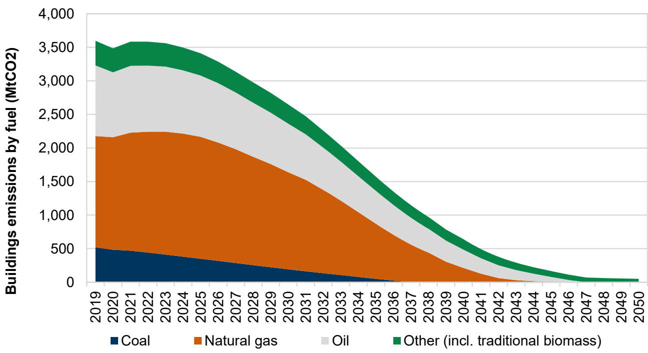
Source: Goldman Sachs Global Investment Research

Buildings: Fuel switch and efficiency to govern emissions reduction path

Direct carbon emissions from buildings, both residential and commercial, in 2019 accounted for c.9% of total global CO_2 emissions, primarily attributed to the use of fossil fuels for space and water heating (natural gas and oil predominantly, as shown in Exhibit 91). Whilst based on our GS 1.5° scenario we continue to see global activity in the sector increasing, with the global floor area increasing from 240 bn meters squared to c.410 bn meters squared by 2050, the transformational energy shift away from fossil fuels to cleaner alternatives, coupled with an acceleration in energy efficiency improvements, bring the overall carbon intensity of buildings close to zero in the 2040s. Whilst the key technologies that govern the de-carbonization of buildings in the near and medium term are readily available, including electric heat pumps (air and ground source) and residential solar, geothermal, and bioenergy, the long lifespan of buildings makes the need for comparatively costly retrofits essential to achieve net zero emissions by 2050, particularly for residential buildings where the switch is largely reliant on consumer preference. As such, any aspiration for gross zero emissions in buildings has to come with the need for an accelerated pace of retrofits.

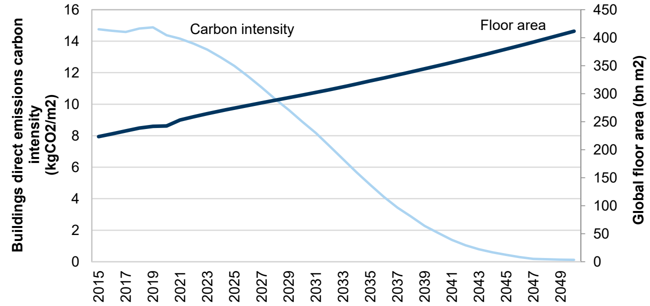
Our net zero pathway by 2050, GS 1.5°, requires a step change in the pace of acceleration of energy efficiency, as well as the flexibility of the stock and a shift away from fossil fuels. The former can be achieved by a combination of measures, including the switch to best-available technology (BAT) across appliances, automation and smart meters, and will largely be governed by underlying building codes and standards. The latter is largely dependent on the cost of the clean fuel alternative technologies. As shown in Exhibit 94, electricity accounts for around one third of the total final energy consumption of buildings, and we expect its share to almost double, reaching c.65% by 2050 whilst direct renewable energy, such as the share of residential solar, geothermal and bioenergy is also increasing over time, reaching c.22% by 2050. Finally, clean hydrogen could be a key complementary heating technology, given the gas-like properties of the fuel, which could help preserve some of the newer gas pipeline infrastructure and avoid stranded assets. Clean hydrogen could be a key technology in seasonal storage, essential for heating applications that extend beyond buildings into other sectors such as industry.

Exhibit 91: The direct emissions from buildings are currently dominated by the use of natural gas and oil, used primarily for heating applications...
Buildings emissions by fuel (MtCO2)



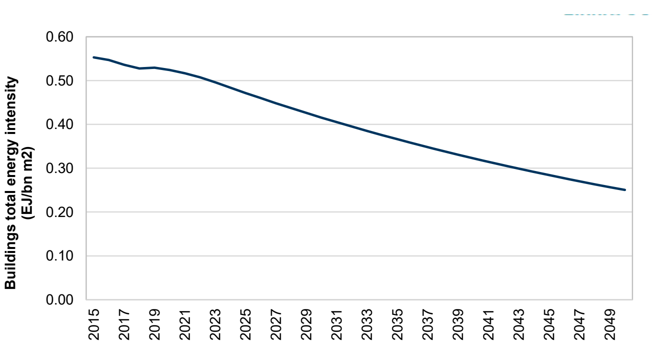
Source: Goldman Sachs Global Investment Research

Exhibit 92: ...and our GS 1.5 path requires the carbon intensity per square meter of global floor area to reduce over time, reaching net zero in the 2040s despite the increase in global floor area
Buildings direct emissions carbon intensity (kgCO2/m2)



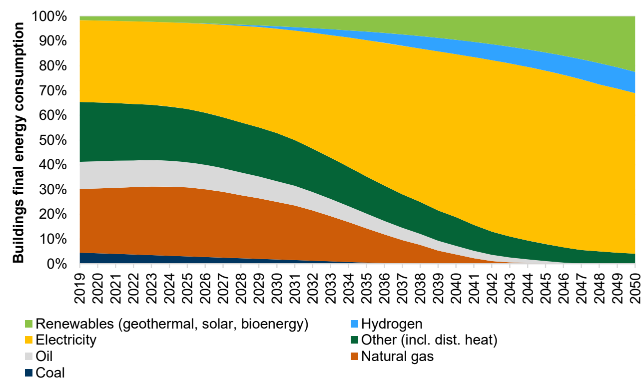
Source: Goldman Sachs Global Investment Research

Exhibit 93: De-carbonization in buildings is primarily driven by an ongoing improvment in energy efficiency, with the energy intensity (both direct and indirect) for buildings halving by 2050...
Buildings total energy intensity (EJ/bn m2)



Source: Goldman Sachs Global Investment Research

Exhibit 94: ...as well as fuel switching away from fossil fuels and towards electrification, distributed renewable energy and clean hydrogen
Buildings total final energy consumption fuel mix evolution (%)

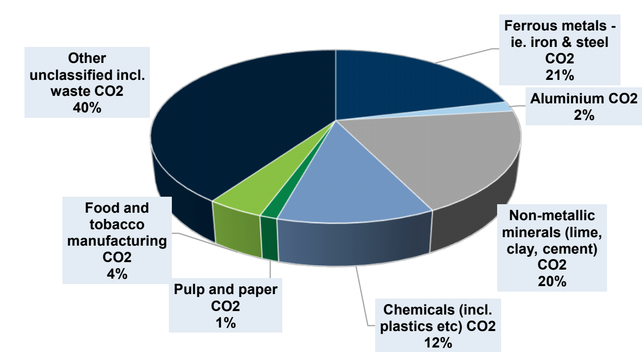


Source: Goldman Sachs Global Investment Research

Industry, waste & other fugitive: Clean hydrogen, CCUS, efficiency, circular economy and electrification setting the scene for a new industrial technology revolution

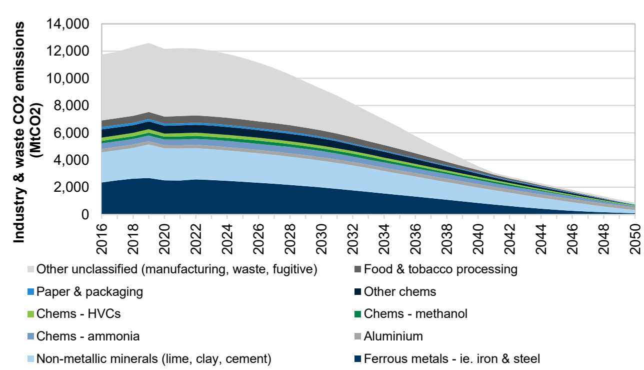
Industry is the sector with the second-largest contribution to global CO_2 emissions, accounting for c.30% of global anthropocentric CO_2 emissions in 2019. Industrial emissions for the purpose of this analysis incorporate all industrial combustion, industrial processes, waste and other fugitive emissions (including those associated with the extraction of fossil fuels). While the exact split of all the different industrial sub-sector emissions is subject to uncertainty, with differences between sources, we estimate that c.55% of global industry & other industrial waste emissions stem from the heavy industries as shown in Exhibit 99 (ferrous and non-ferrous metals manufacturing, non-metallic minerals such as cement and petrochemicals) and are predominantly produced in emerging economies.

Exhibit 95: c.55% of industrial & other waste emissions stemming from the heavy industries (ferrous and non-ferrous metalsm non-metallic minerals such as cement and chemicals)...
Approximate split of global industrial & other waste emissions (%, 2019)



Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research, IEA, Goldman Sachs Global Investment Research

Exhibit 96: ..with these industries being some of the hardest to de-carbonize given the current lack of large-scale, developed, and economic, cleaner alternatives
Industry & waste GS GL0S CO2 emissions (MtCO2eq)



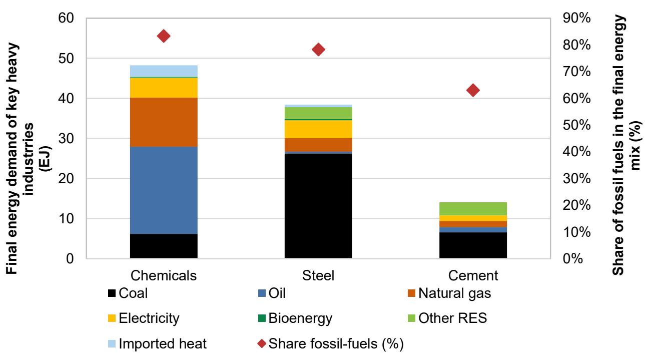
Source: Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Heavy industries the key contributors to global industrial & waste emissions, with clean available alternatives in need of further technological innovation and large-scale deployment

Iron & Steel: The iron & steel industry accounts for c.2.6 $GtCO_2$ of total emissions (2019), the single highest emitter among industrial sub-sectors. However, a combination of fuel switches and innovative process routes can aid the low-carbon transition path for these ferrous alloys. Our GS 1.5° scenario sees a radical technological transformation of the iron & steel sub-sector, largely based on the ongoing shift from coal blast furnace routes, which currently account for c.70% of total steel energy consumption (conventional BF-BOF), to electric arc furnace routes (either through natural gas, clean hydrogen or scrap). Iron & steel is a highly energy-intensive industry, consuming c.26.3 EJ of energy in 2019 and accounting for c.15% of global primary coal demand. By 2050, in our GS 1.5° path, electricity and non-fossil fuels account for c.70% of the tonnes of steel produced, whilst the remaining fossil-fuel reliant plants are retrofitted with CCUS. CCUS and the switch from coal BF-BOF to natural gas DRI-EAF and scrap are the key near-term de-carbonization tools for steel, before the rapid uptake of the clean hydrogen process (H2 DRI-EAF) post 2030. Over the past few years, we have seen a number of innovative alternative clean steel production processes being developed, primarily focusing on the increasing use of electricity and clean hydrogen.

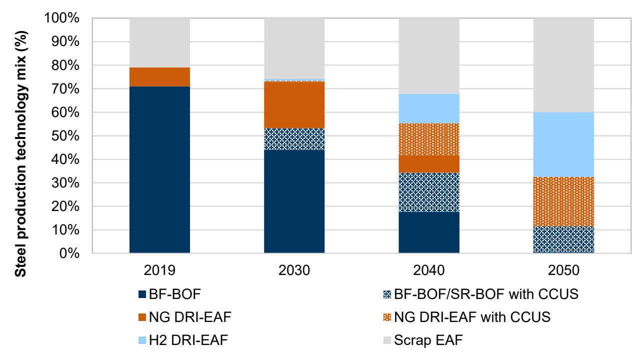
Our GS 1.5° model's architecture for heavy industries consists of three main components: **activity projections** (largely depending on the underlying macro GDP assumptions and material substitution, circular economy), **technology mix modeling** (the selection of technologies and mix required to meet these activity levels) and finally **emissions modeling**, largely relying on the technology mix and incorporating energy and material efficiency where appropriate.

Exhibit 97: Final energy consumption of the steel industry is dominated by coal, which accounts for c.70% of the sub-sector's energy mix...
Final energy demand of key heavy industry sub-sectors and share of fossil fuels (2019)



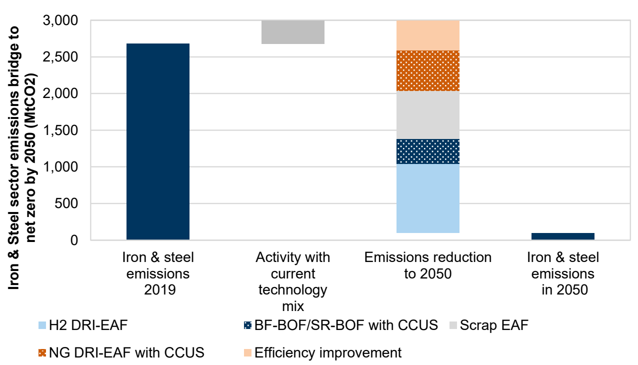
Source: IEA, Goldman Sachs Global Investment Research

Exhibit 98: ...and our GS 1.5 path assumes a radical transformation of the sector with c.70% of global steel produced in 2050 sourced from non-fossil fuel processes with the remaining largely retrofitted with CCUS
Steel production technology mix (%)



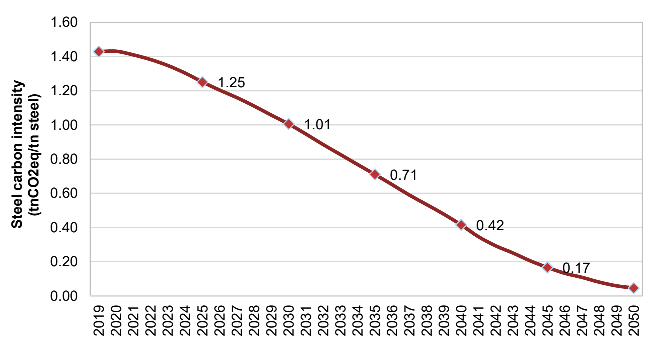
Source: Goldman Sachs Global Investment Research

Exhibit 99: Our GS 1.5 path assummes a combination of technologies in the steel sector will contribute to the sector almost being entirely carbon-free by 2050
Iron & Steel sector emissions bridge to net zero by 2050 (MtCO2)



Source: Goldman Sachs Global Investment Research

Exhibit 100: ...leading to a notable reduction in the overall steel carbon intensity (direct) over time
Steel direct emissions carbon intensity (tnCO2/tn steel)

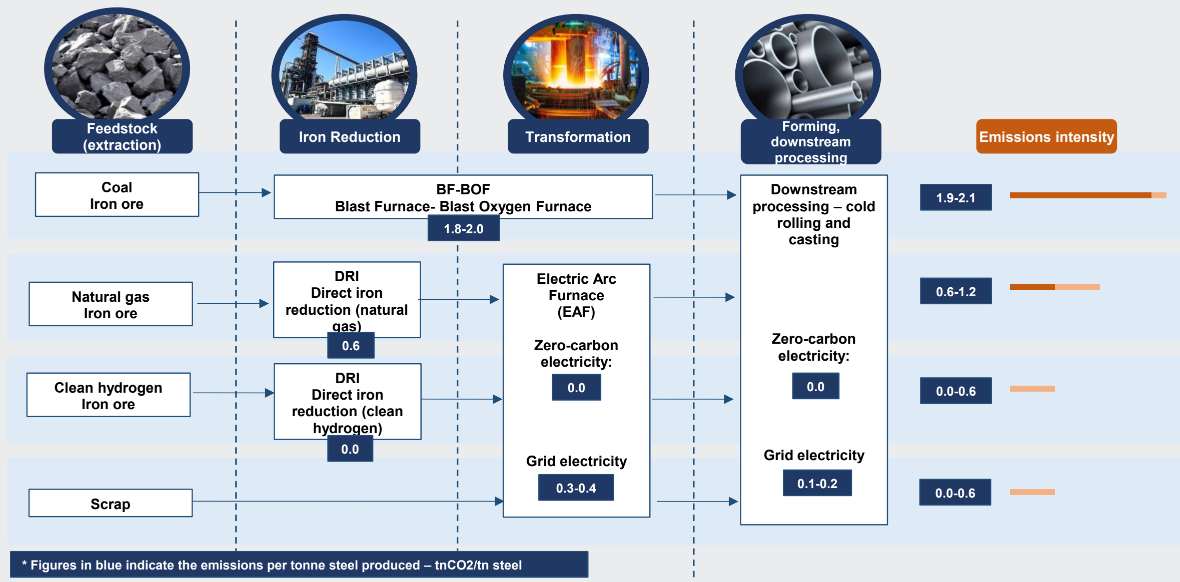


Source: Goldman Sachs Global Investment Research

Clean hydrogen and its role in the de-carbonization of steel

As we highlight in the section above, a key industrial application of clean hydrogen, and one that has recently attracted industry interest, is the production of net zero carbon steel, to help meet growing global steel demand with lower emissions.

Exhibit 101: Schematic summary of possible steel manufacturing routes and associated emissions intensity (tnCO2eq/tn steel)



Source: Energy Transitions Commission, Company data, Goldman Sachs Global Investment Research.

A number of projects are currently underway to develop these processes and move towards commercialization, as outlined below.

- **HYBRIT:** In 2016, SSAB, LKAB and Vattenfall formed a partnership for the de-carbonization of steel through a modified DRI-EAF process, aiming at producing the first fossil-free steel making technology with a net zero carbon footprint. During 2018, a pilot plant for fossil-free steel production in Luleå, Sweden, started construction. The total cost for the pilot phase is estimated at Skr1.4 bn. The Swedish Energy Agency will contribute more than Skr500 mn towards the pilot phase and the three owners, SSAB, LKAB and Vattenfall, will each contribute one third of the remaining costs. The Swedish Energy Agency earlier contributed Skr60 mn to the pre-feasibility study and a four-year research project.

- **SALCOS:** An initiative undertaken by Salzgitter AG and the Fraunhofer Institute to develop a process for hydrogen-based reduction of iron ore using the DRI-EAF route. The process initially involves the reduction of iron ore to iron with the aid of natural gas and a higher volume of hydrogen in a direct reduction reactor. Based on this method, a reduction of iron of up to 85% can be achieved according to the operators, with CO_2 savings of initially up to 50% theoretically possible.

- **ΣIDERWIN:** A research project by ArcelorMittal which is in the pilot phase. It utilizes an electrochemical process supplied by renewable sources to transform iron oxides into steel plate with a significant reduction of energy use.

- **COURSE 50:** An initiative from the Japanese Iron and Steel Federation which aims to reduce the carbon footprint of steel production through the use of a higher proportion of hydrogen for iron ore reduction, as well as capture the CO_2 content of the process streams.

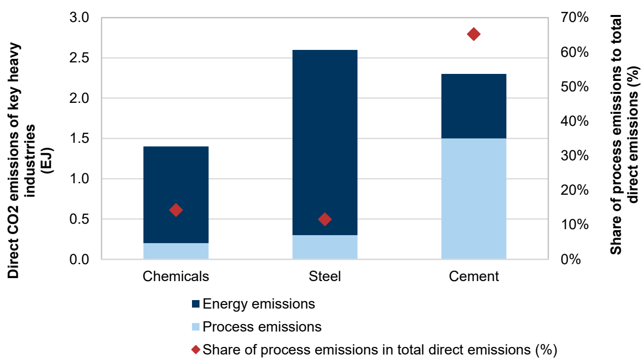
- **HIsarna:** In 2004, a group of European steel companies (including Tata Steel) and research institutes formed ULCOS, which stands for Ultra-Low Carbon Dioxide Steel making. Its mission is to identify technologies that might help reduce carbon emissions of steel making by 50% per tonne by 2050. HIsarna is one of these technologies and is a process involving an upgraded smelt reduction that processes iron in a single step. The process does not require the manufacturing of iron ore agglomerates such as pellets and sinter, nor the production of coke, which are necessary for the blast furnace process.

Cement and construction materials: Cement is the second most highly emitting industrial sub-sector with a tonne of cement today having an average carbon intensity of 0.5-0.6 $tnCO_2$/tonne, largely attributed to the process emissions associated with the carbon emitted from the raw materials and processes involved. Energy emissions account for <40% of the total direct emissions of the cement industry, as shown in Exhibit 102, in contrast to other key emitting heavy industries such as steel and chemicals (where energy emissions account for c.90% of total direct emissions). Cement is the binding agent for concrete, one of the key inputs to the construction industry which is itself one of the highest emitting global industries on a Scope 1 and 2 basis.

Central to the process of cement production is the production of the clinker in the kiln, the key active ingredient in cement, which requires large amounts of energy primarily in the form of high-temperature heat. The calcination process is responsible for the vast majority of process emissions. In practice these emissions can be reduced through **a reduction of the clinker to cement ratio** through blending of clinker with other cementious materials (such as fly ash, limestone, calcinated clay). Currently the clinker to cement ratio stands around 0.7, according to the IEA, and can technically be reduced to 0.5. However, most technologies and innovative materials are still in research and the early stage of development. As such, a reduction in the clinker to cement ratio alone is not sufficient to achieve net zero in the cement industry. Instead, CCUS is, in our view, the most promising technology for effective de-carbonization of cement. Our GS 1.5° scenario for net zero by 2050 sees c.66% of total cement production in 2050 retrofitted with CCUS. Furthermore, cement plants have a typically long operating life, and therefore the pace of replacement using lower emission technologies in the absence of early retirements is constrained, with many of these facilities added to the existing stock in the past decade. Retrofits of existing capacity with CCUS technologies are therefore likely necessary.

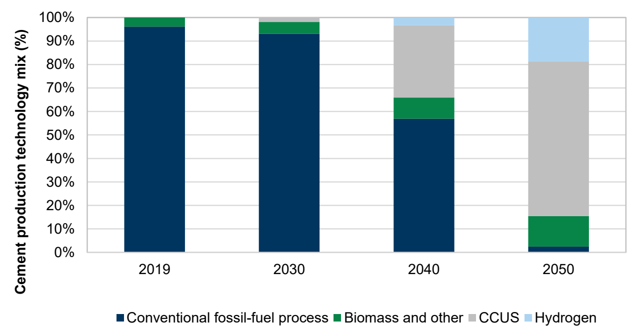
Regarding energy emissions, most are attributed to the use of coal fuel as shown in Exhibit 97, and currently c.3 GJ of energy are required to produce just one tonne of cement on average. While alternative fuels like bioenergy and waste are key alternative options, sustainable biomass availability is limited, while the CO_2 footprint of non-renewable waste is very variable. In our GS 1.5° scenario, we assume c.13% of cement production relies on sustainable biomass as the primary fuel. Given the high temperature heat and the large quantities of energy needed for kilns, switching to direct electrification would be technically challenging and very costly. Clean hydrogen could be a key solution for high-temperature heat, and could aid the de-carbonization of energy emissions in the cement industry: in our GS 1.5° model it accounts for a little less than 20% of final cement production in 2050.

Exhibit 102: Cement is one of the hardest-to-abate industrial sub-sectors, primarily owing to the high proportion of direct emissions stemming from processes as opposed to energy...
Direct CO2 emissions and share of process emissions to the total direct emissions (2019)



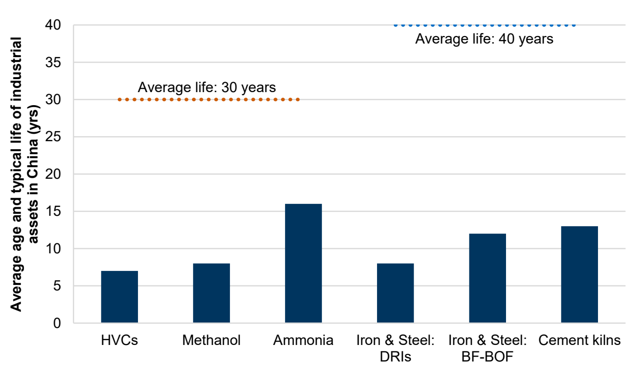
Source: IEA, Goldman Sachs Global Investment Research

Exhibit 103: ...and we expect a major technological mix change for the industry, primarily in the form of retrofits for CCUS and fuel switch to biomass and clean hydrogen for the high-temperature heat
Cement production technology mix (%)



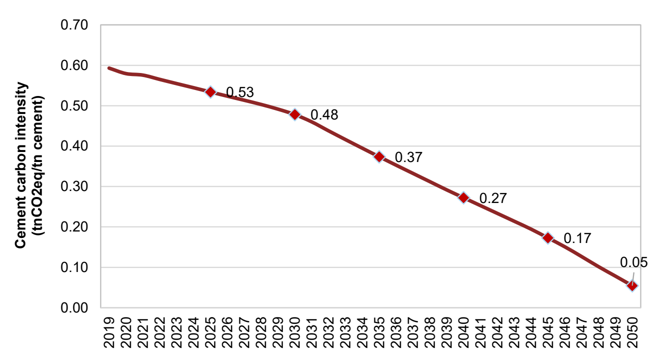
Source: Goldman Sachs Global Investment Research

Exhibit 104: Carbon capture can be a key de-carbonization solution for many hard-to-abate industrial emissions, particularly given the relatively young industrial plant base in emerging economies
Average age and typical life of industrial assets (years)



Source: IEA, Goldman Sachs Global Investment Research

Exhibit 105: Based on our GS 1.5 path, the carbon intensity of cement reduces steadily over time, with energy and material efficiency improvements contributing most in the near term, before the acceleration of CCUS retrofits and cleaner fuel adoption begins in the 2030s
Cement direct emissions carbon intensity (tnCO2/tn cement)



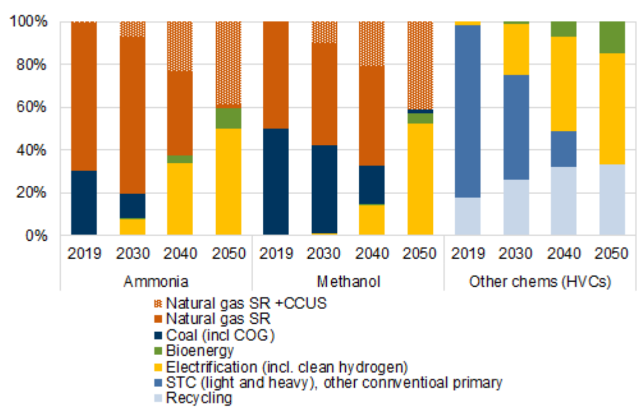
Source: Goldman Sachs Global Investment Research

Chemicals: Chemicals is a broad sub-sector including a very large variety of commodity petrochemicals, specialty chemicals and products including plastics, fertilisers, pharmaceuticals, explosives, paints, solvents and more. The resulting carbon intensity varies greatly depending on the final product. In this analysis, we primarily focus on the bulk commodity chemicals, namely ammonia, methanol and high-value-chemicals (HVCs, include ethylene, propylene, benzene and other olefins and aromatics), which together make up the majority of emissions from the chemicals and petrochemicals industry. The chemicals sector is the largest industrial consumer of energy globally, with energy consumption amounting to c.48 EJ in 2019, and with the energy mix primarily constituting of fossil fuels (c.85%) including oil (c.45% of final energy demand), coal (13%), and natural gas (c.25%). Nonetheless, because around half of the energy inputs are used for chemical feedstocks, a large proportion of the carbon content associated with the energy demand ends up in the final product, rather than being released into the atmosphere, and as such the sector produces fewer CO_2 emissions than other key heavy industries such as steel and cement.

The available clean alternative technologies for chemicals are primarily concerned with a fuel switch, given the dominance of energy, as opposed to process direct emissions. Fuel switch examples include from coal and oil to natural gas, bioenergy or electrification (including the production of green hydrogen). Furthermore, energy efficiency, as well as circular economy (plastics recycling and re use, more efficient use of nitrogen fertilisers), will also play a critical role in the transition, reducing over time primary chemicals demand. Beyond 2030, further emission reduction could be achieved through CCUS, as well as the accelerated uptick of green electrolytic hydrogen.

Exhibit 106: The evolution of the energy mix and circular economy are likely to be key for the emissions abatement of the sector...

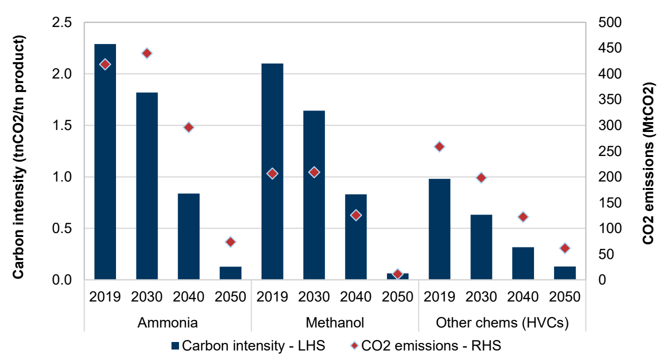
Chemicals technology mix across three key categories (%)



Source: Goldman Sachs Global Investment Research

Exhibit 107: ...with varying carbon intensity paths for each chemical product

GS 1.5 key chemicals carbon intensity and CO2 emissions evolution

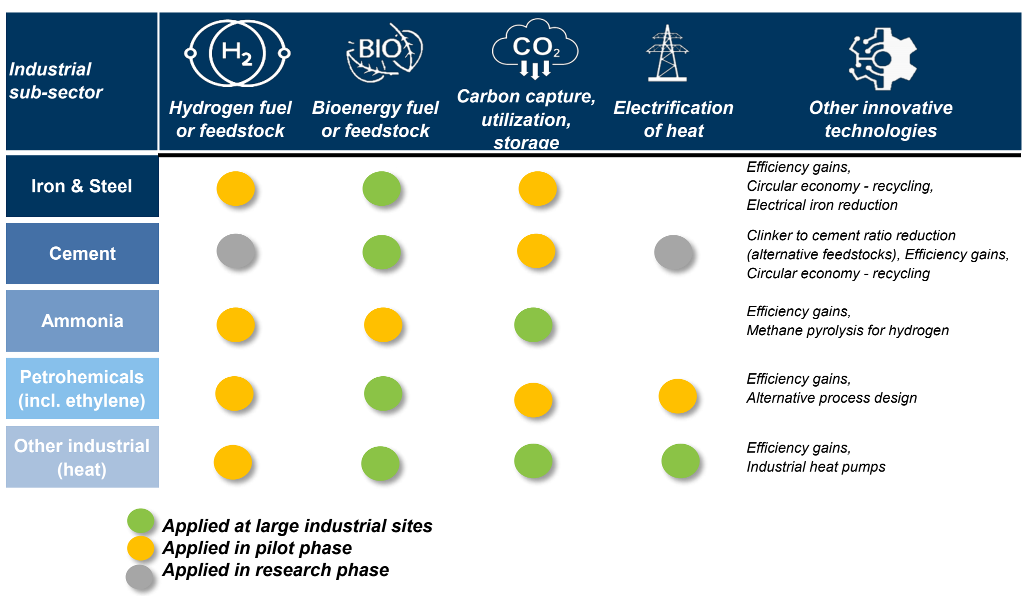


Source: Goldman Sachs Global Investment Research

Other industrial emissions: In our GS 1.5° model we also consider the emissions trajectories of other industrial sub-sectors, including paper & packaging, aluminum and non-ferrous metals, as well as other unclassified broader industrial manufacturing, waste and fugitive emissions. Whilst these segment contribute less direct emissions than the three heavy industries described above, in aggregate, across all sub-categories, they account for the remaining industrial emissions. The lack of thorough disclosure of the emission split and source makes their detailed modeling harder. More broadly, we assume the path of de-carbonization for the broader manufacturing, waste and other unclassified fugitive emissions will be similar, and identify the key technologies that can facilitate that de-carbonization path: electrification and other clean fuel switch, energy and material efficiency and finally carbon capture. Based on our GS 1.5° path, emissions from light industries decline by 40%/95%/97% (vs. 2019) by 2030/40/50 respectively, as in contrast to the heavy industries, the clean alternative technologies for these sectors are readily available.

The ability of processes to be electrified largely depends on the temperature requirements for the supply of heat across them. Low and medium-temperature heat is assumed to be readily electrified, primarily in the form of industrial heat pumps, whilst high-temperature heat for heavy industries such as steel and cement, in the absence of further technological innovation, largely relies on alternative fuel switch, with bioenergy, clean hydrogen and natural gas retrofitted with CCUS all key in facilitating the carbon neutrality path.

Exhibit 108: Summary of key de-carbonization technologies for the major industrial emitting sub-sectors



Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 109: Electrification is a promising solution for energy emissions associated with fuel consumption for low and medium-temperature heat, whilst CCUS and clean hydrogen are mostly included in our GS GLOS path to address high-temperature heat

	Heat temperature	Examples of processes	Available clean technologies
c.30%	**Very high-temperature heat >1,000 degrees**	Calcination of limestone for cement production Melting in glass furnace Reheating for slab in hot strip mill	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c.16%	**High-temperature heat 400-1,000 degrees**	Steam reforming and cracking in petrochemicals (ammonia, methanol)	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c.20%	**Medium-temperature heat 100-400 degrees**	Drying, evaporation, distillation activation Broader manufacturing	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c. 15%	**Low-temperature heat < 100 degrees**	Washing, rinsing, food preparation Broader manufacturing	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c.20%	**Other unclassified**		

Source: JRC Scientific and Policy report, McKinsey, Goldman Sachs Global Investment Research

An ecosystem of key transformational technologies

Our GS models for global net zero incorporate our view for the role of key de-carbonization technologies and how these are likely to pave the way for carbon neutrality, leveraging our Carbonomics cost curve. Our path consistent with net zero by 2050 calls for an evolution of the de-carbonization process from one dimensional (renewable power) to a multi-dimensional ecosystem. Four technologies are emerging as transformational in our view:

(a) Renewable power: The technology that dominates the 'low-cost de-carbonization' spectrum today and has the potential to support a number of sectors that require electrification, as well as being critical for the production of clean hydrogen longer term ('green' hydrogen).

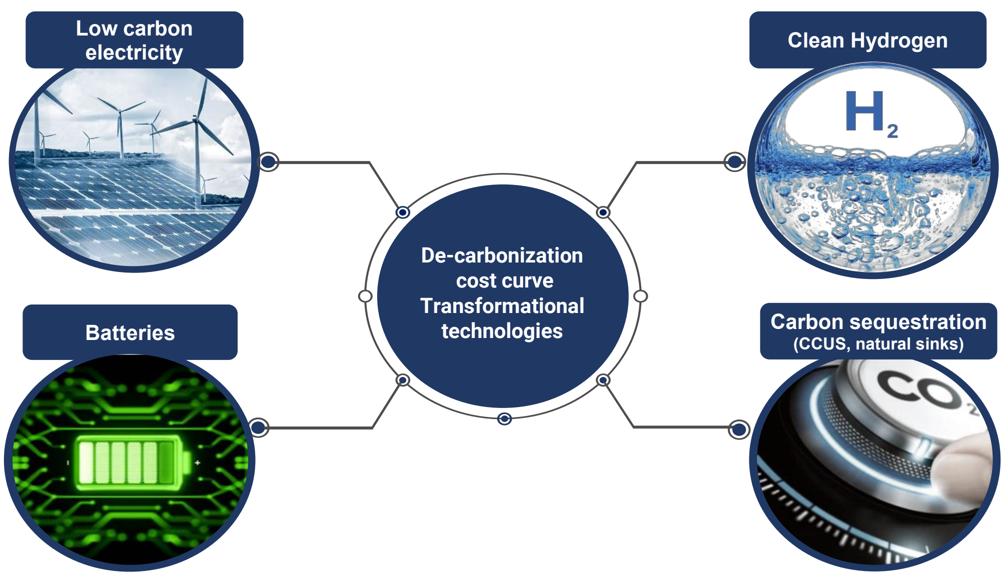
(b) Clean hydrogen: A transformational technology for long-term energy storage enabling increasing uptake of renewables in power generation, as well as aiding the de-carbonization of some of the harder-to-abate sectors (iron & steel, long-haul transport, heating, petrochemicals).

(c) Battery energy storage: Extends energy storage capabilities, and is critical to the de-carbonization of short-haul transport through electrification.

(d) Carbon capture technologies: Vital for the production of clean ('blue') hydrogen in the near term, while also aiding the de-carbonization of industrial sub segments with emissions that are currently non-abatable under alternative technologies.

We have already addressed in detail the critical need of renewable power and batteries (see Transportation and Power generation sections) and we address the latter two in the sections that follow.

We identify four transformational technologies that we expect to lead the evolution of de-carbonization

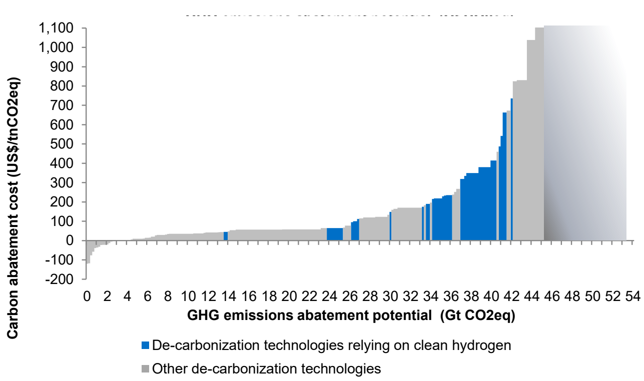


Source: Goldman Sachs Global Investment Research

Clean hydrogen: A rising technology with multiple applications

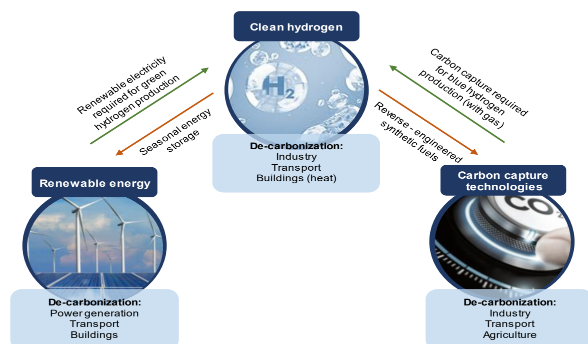
Hydrogen has a critical role to play in any aspiring path targeting carbon neutrality by 2050 in our view, with a wide range of applications across sectors including but not limited to its potential use as an energy storage (seasonal) solution that can extend electricity's reach, industrial energy source and industrial process feedstock including its potential use in replacing coal in steel mills, serving as a building block for some primary chemicals and providing an additional clean fuel option for high temperature heat, and long-haul heavy transport. Clean hydrogen is a fuel, but as an energy vector can also be produced by increasingly abundant technologies such as renewables and carbon capture. While the basic scientific principles behind clean hydrogen are well understood, most of these technologies applied in their respective industrial sectors are still at the demonstration or pilot stage. We estimate that clean hydrogen can contribute to c.20% of global de-carbonization with its **addressable market growing 7x from c.75 Mt in 2019 to c.520 Mtpa on the path to global net zero by 2050.**

Exhibit 110: We estimate that c.20% of global GHG emissions could be abated through technologies that rely on clean hydrogen...



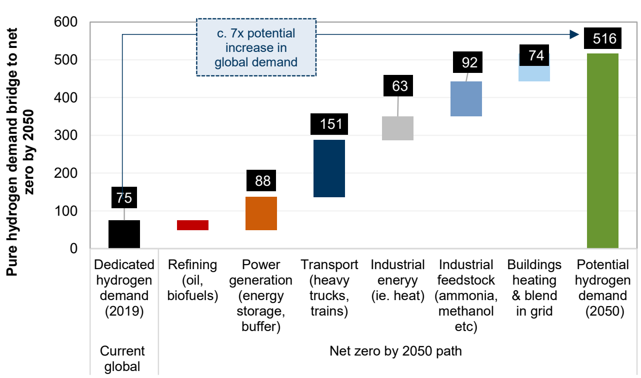
Source: Goldman Sachs Global Investment Research

Exhibit 111: ...with hydrogen forming a key connecting pillar between renewable power and carbon capture



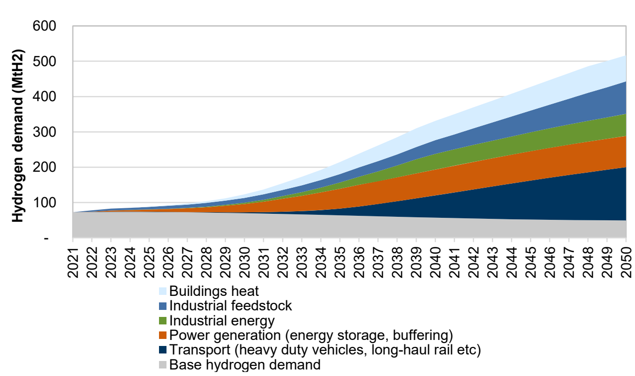
Source: Goldman Sachs Global Investment Research

Exhibit 112: Our GS 1.5 global net zero by 2050 path sees total hydrogen demand increasing seven-fold (7x) to 2050...
Global clean hydrogen addressable market for net zero by 2050 (Mtpa)



Source: Goldman Sachs Global Investment Research

Exhibit 113: ...with contribution across most key emitting sectors (transport, power generation, industry, buildings)
Total global hydrogen demand (MtH2)



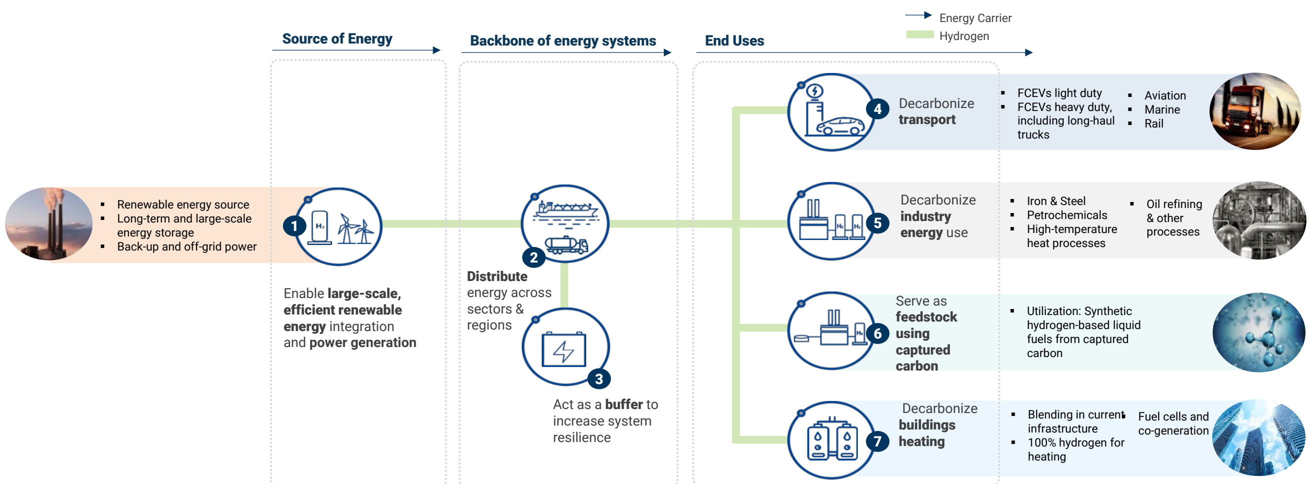
Source: Goldman Sachs Global Investment Research

The revival of hydrogen: A new wave of support and policy action

As highlighted in our primer report *Carbonomics: The rise of clean hydrogen*, hydrogen as a fuel screens attractively among other conventionally used fuels for its low weight (hydrogen is the lightest element) and high energy content per unit mass, >2.5x the energy content per unit mass of both natural gas and gasoline.

While hydrogen has gone through several waves of interest in the past 50 years, none has translated into sustainably rising investment and broader adoption in energy systems. Nonetheless, the recent focus on de-carbonization and the scaling up and accelerated growth of low-carbon technologies such as renewables have sparked a new wave of interest in the properties and the supply chain scale-up of hydrogen. Over the past few years, the intensified focus on de-carbonization and climate change solutions has led to renewed policy action aimed at the wider adoption of clean hydrogen. Policy support and economic considerations, and the acceleration of low-cost renewables and electrification infrastructure, seem to be converging to **create unprecedented momentum in the use of hydrogen and paving the way for potentially more rapid deployment and investment** in hydrogen technologies and the required infrastructure.

Exhibit 114: Hydrogen could have a critical role in aiding de-carbonization longer term across a wide variety of sectors, including long-haul transport, industry, energy storage in power generation and heating in buildings



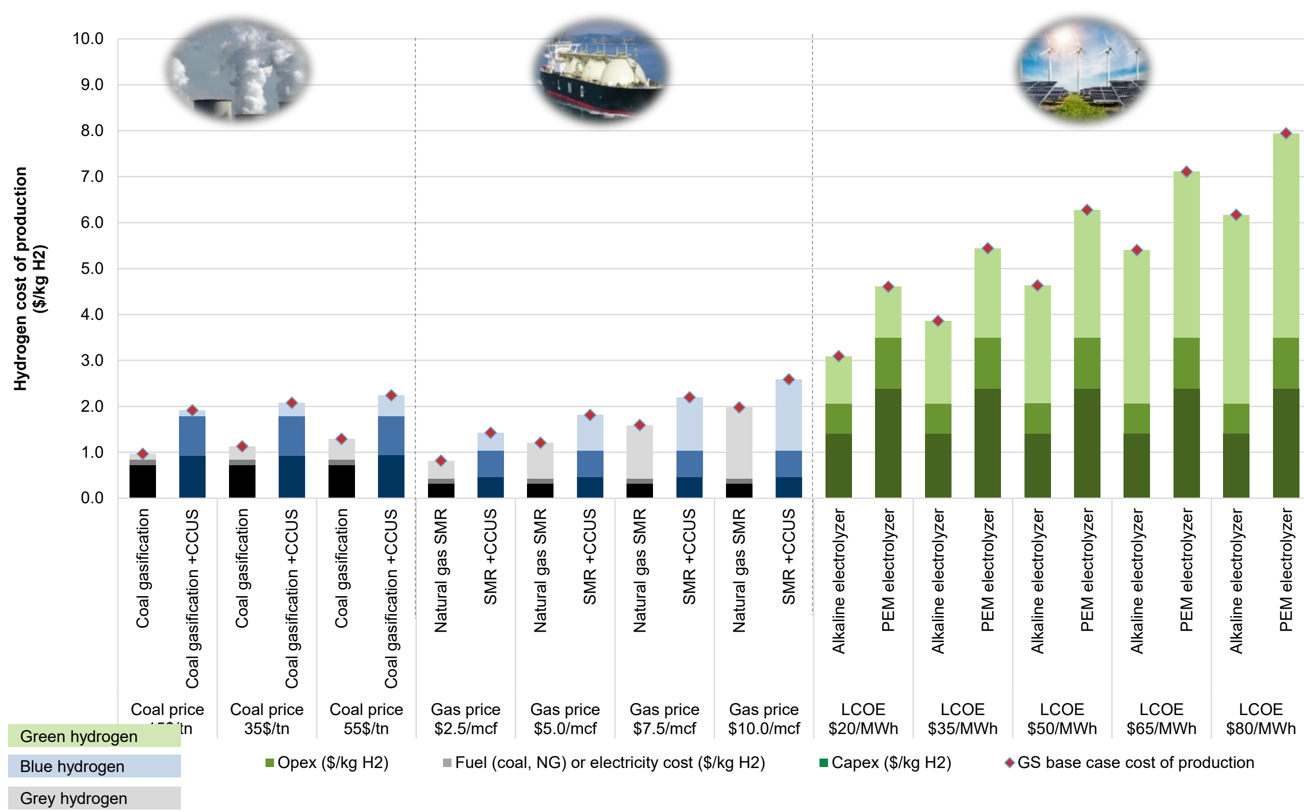
Source: Hydrogen Council, Goldman Sachs Global Investment Research

Clean hydrogen could be the key missing piece of the puzzle to reach net zero, connecting two critical components of the de-carbonization technological ecosystem: carbon sequestration and clean power generation

The low-carbon intensity pathways for hydrogen production and what makes the fuel **uniquely positioned to benefit from two key technologies in the clean tech ecosystem – carbon capture and renewable power generation –** are '**blue**' and '**green**' hydrogen. 'Blue' hydrogen refers to the conventional natural gas-based hydrogen production process (SMR or ATR) coupled with carbon capture, while 'green' hydrogen refers to the production of hydrogen from water electrolysis whereby electricity is sourced from zero carbon (renewable) energies.

While 'blue' and 'green' hydrogen are the lowest-carbon-intensity hydrogen production pathways, our hydrogen cost of production analysis, shown in Exhibit 115, suggests that both of these technologies are more costly when compared with the traditional hydrocarbon-based 'grey' hydrogen production. For 'blue' hydrogen, the cost of production is dependent on a number of technological and economics factors, the price of natural gas being the most critical followed by the additional cost for carbon capture technology integration with the SMR plant.

Exhibit 115: 'Blue' and 'green' hydrogen set the stage for de-carbonization, with 'blue' currently having a lower cost of production compared with 'green' hydrogen, but both being more costly than traditional 'grey' hydrogen

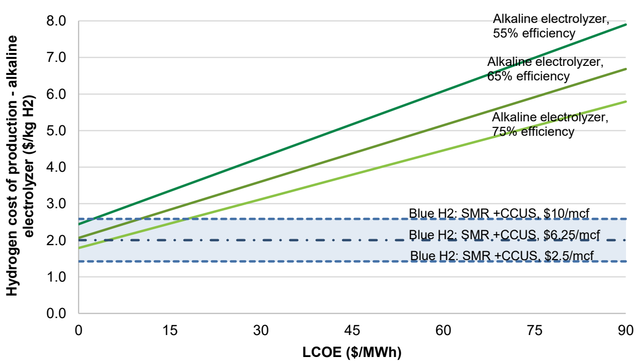


Source: Company data, Goldman Sachs Global Investment Research

Overall, we estimate that under current electricity and electrolyzer costs the cost of production of green hydrogen is currently c.1.3-5x that of blue hydrogen, depending on the price of natural gas and the LCOE. This leads us to conclude that **both 'blue' and 'green' hydrogen will form key pillars of the low-carbon transition**, but with **'blue' facilitating the near- and medium-term transition** until **'green' reaches cost parity around the end of this decade**. We incorporate the critical role of both blue and green hydrogen in our GS 1.5° path to carbon neutrality by 2050, assuming a 1/2 vs. 2/3 split for 'blue' and 'green' hydrogen respectively. The rise of green hydrogen which we expect to start to accelerate from 2030 should lead to a very strong increase in electrolyzer capacity, which in our GS 1.5° path reaches c.3,500 GW by 2050, as well as an increase in power demand of >20,000 TWh, representing c.27% of total power generation in 2050.

Exhibit 116: A LCOE of $5-25/MWh is required for 'green' hydrogen to be at cost parity with the high-cost 'blue' hydrogen scenario for an alkaline electrolyzer efficiency of 55-75% (assuming electrolyzer capex and cost of carbon capture remain at current levels)...

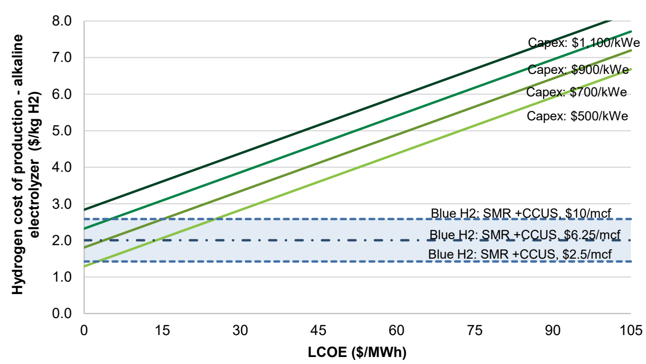
Hydrogen cost of production ($/kg H2) vs LCOE ($/MWh)



Source: Goldman Sachs Global Investment Research

Exhibit 117: ...but the cost of the electrolyzer also impacts the overall cost of producing 'green' hydrogen, with a LCOE of <$35/MWh required for electrolyzers with capex exceeding $500/kWe to reach cost parity with high-cost 'blue' hydrogen

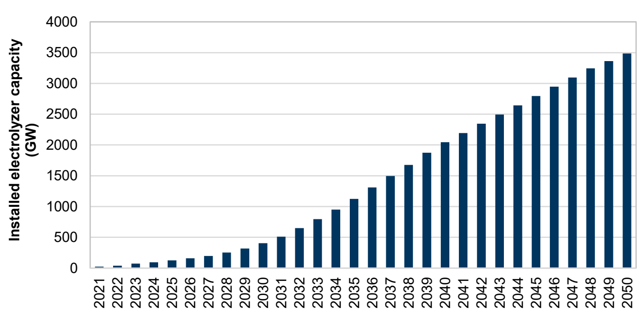
Hydrogen cost of production ($/kg H2) vs LCOE ($/MWh)



Source: Goldman Sachs Global Investment Research

Exhibit 118: Given the rising importance of green hydrogen, we see very strong growth in electrolyzer capacity as part of our GS GLOS path, reaching c.3,500 GW by 2050...

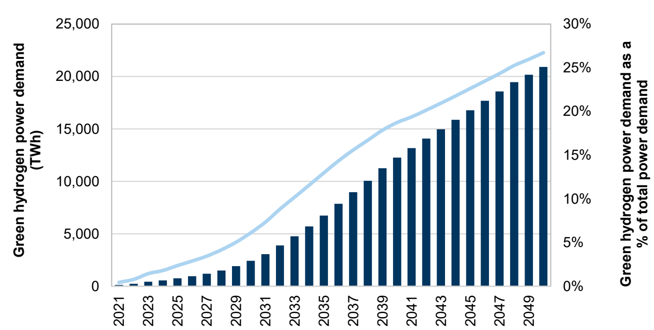
Green hydrogen installed electrolyzer capacity (GW)



Source: Goldman Sachs Global Investment Research

Exhibit 119: ...and >20,000 TWh of power demand stemming from the production of green hydrogen by 2050, representing c.27% of total power demand

Green hydrogen power demand (TWh)



Source: Goldman Sachs Global Investment Research

Carbon sequestration: CCUS, DACCS and natural sinks all key to unlocking net zero emissions

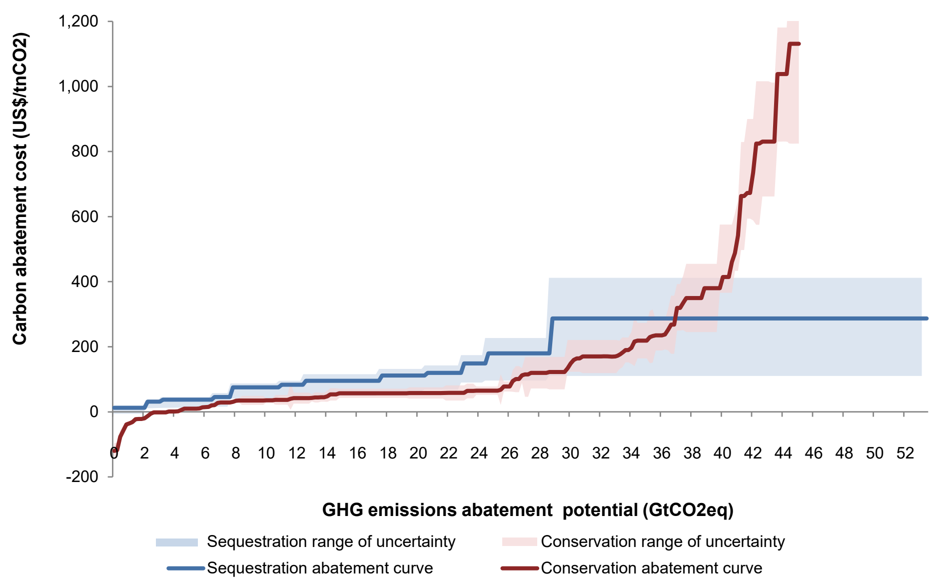
Conservation efforts alone are highly unlikely to achieve net zero carbon by 2050 in the absence of carbon sequestration

We envisage two complementary paths to enable the world to reach net zero emissions: conservation and sequestration. The former refers to all technologies enabling the reduction of gross greenhouse gases emitted and the latter refers to natural sinks and carbon capture, usage and storage technologies (CCUS) that reduce net emissions by subtracting carbon from the atmosphere. The need for technological breakthroughs to unlock the potential abatement of the **emissions that cannot at present be abated** through existing conservation technologies **makes the role of sequestration a critical piece of the puzzle in solving the climate change challenge and leading the world to net zero carbon** emissions at the lowest possible cost. We believe that carbon sequestration can be an attractive competing technology for sectors in which emissions are harder or more expensive to abate, with industry being a prominent example.

The cost curves for sequestration and conservation are both presented in Exhibit 120 below. While the conservation cost curve has larger scope for low-cost de-carbonization opportunities and a smaller range of uncertainty, it steepens exponentially at higher levels of de-carbonization. The sequestration cost curve, on the other hand, offers fewer low-cost solutions and has greater cost uncertainty, but provides tremendous long-term potential if a commercially feasible solution for Direct Air Carbon Capture and Storage (DACCS) is developed.

Exhibit 120: The path to de-carbonization will be driven by technological innovation and economies of scale for both conservation and sequestration initiatives

Carbon abatement cost curves (US$/tnCO2) for conservation and sequestration technologies vs. the GHG emissions abatement potential (GtCO2eq)



Source: Goldman Sachs Global Investment Research

The carbon sequestration cost curve

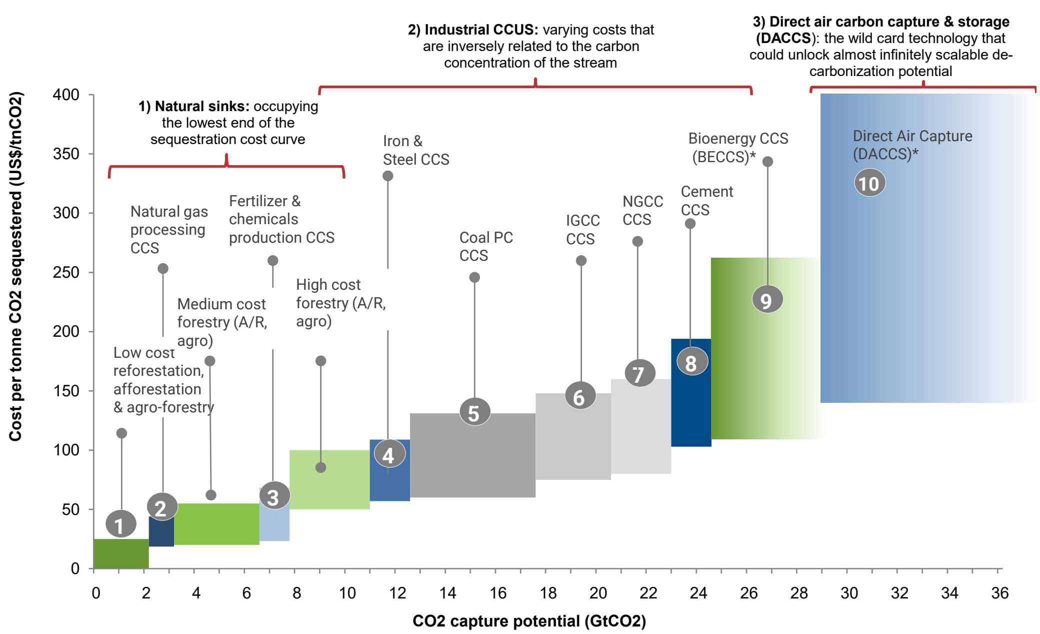
As part of our analysis, we have constructed a carbon abatement cost curve for sequestration (Exhibit 121), although we see a greater range of uncertainty in these technologies, given their under-invested state and the largely pilot nature of the CCUS plants. **Carbon sequestration** efforts can be broadly classified into three main categories:

1) Natural sinks, encompassing natural carbon reservoirs that can remove carbon dioxide. Efforts include reforestation, afforestation and agro-forestry practices.

2) Carbon capture, utilization and storage technologies (CCUS) covering the whole spectrum of carbon capture technologies applicable to the concentrated CO_2 stream coming out of industrial plants, carbon utilization and storage.

3) Direct air carbon capture and storage (DACCS), the pilot carbon capture technology that could recoup CO_2 from the air, unlocking almost infinite de-carbonization potential, irrespective of the CO_2 source.

Exhibit 121: The carbon sequestration curve is less steep vs. the conservation curve but has a higher range of uncertainty given the limited investment to date and the largely pilot nature of these technologies
Carbon sequestration cost curve (US$/tnCO2eq) and the GHG emissions abatement potential (GtCO2eq)



* Indicates technologies primarily in early development/ pilot phase with wide variability in the estimates of costs

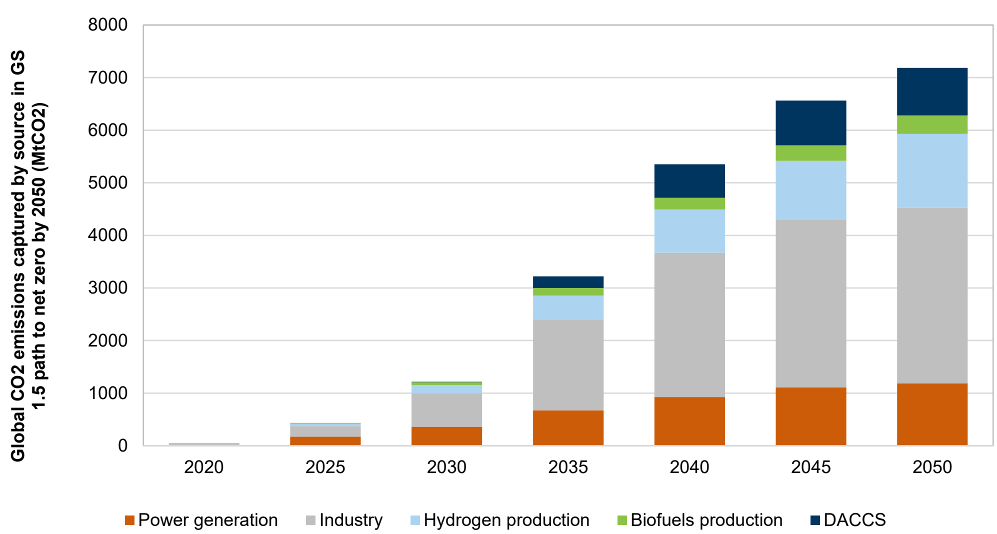
Source: IPCC, Global CCS Institute, Goldman Sachs Global Investment Research

Carbon Capture: A largely under-invested technology coming back after a 'lost decade'

CCUS technologies can be an **effective route to global de-carbonization for some of the 'harder-to-abate' emission sources**: they can be used to significantly reduce emissions from coal and gas power generation, as well as across industrial processes with emissions characterized as 'harder to abate' such as iron & steel, cement and chemicals. CCUS can also facilitate the production of clean alternative fuels such as blue hydrogen, as mentioned in the previous section, as well as advanced biofuels (BECCS).

CCUS encompasses a range of technologies and processes that are designed to capture the majority of CO_2 emissions from large industrial point sources and subsequently provide long-term storage solutions or utilization. We have incorporated carbon capture technologies in our GS 1.5° path for carbon neutrality by 2050, **with CCUS across sectors contributing to annual CO2 abatement of c.7.2 GtCO2 by 2050**, as shown in Exhibit 122 below. The single largest contributor to the CCUS abatement is industry, with sectors such as cement, steel, non-ferrous metals, fugitive and waste emissions all in need of carbon sequestration technologies in the absence of technological breakthroughs. This is followed by the CCUS retrofits required for the production of clean hydrogen from industrial hydrogen plants (blue hydrogen). Finally, CCUS can be retrofitted to the newest gas and coal power plants in power generation, as well as contribute to the full abatement of emissions through the use of biofuels (we assume the use of advanced biofuels in our analysis, yet we appreciate the potential availability constraint of waste and other advanced biofuels' sources and as such we further incorporate some CCUS to complement the use of bioenergy). DACCS, the potentially infinitely scalable de-carbonization technology complements process-specific CCUS and contributes to c.1 GtCO1 annual abatement by 2050.

Exhibit 122: Our GS 1.5 path highlights the importance of CCUS, with the annual CCUS abatement reaching c.7.2 GtCO2 by 2050 with industrial sources the key contributor
Global CO2 emissions captured by source in our GS GLOS (MtCO2)



Source: Goldman Sachs Global Investment Research

Exhibit 123: Based our GS GLOS path to net zero by 2050, c.100 GtCO2 will be captured in total by 2050 (cumulative) across sectors...
Cumulative CO2 abated through CCUS (MtCO2)

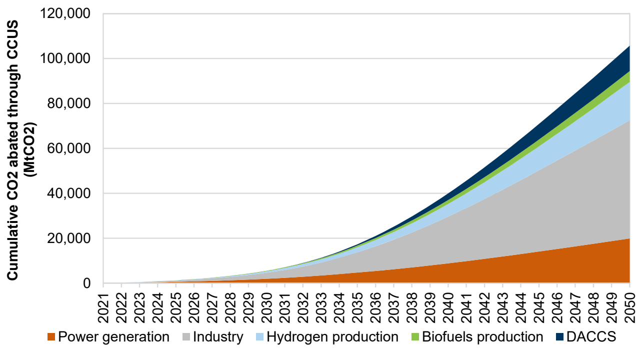
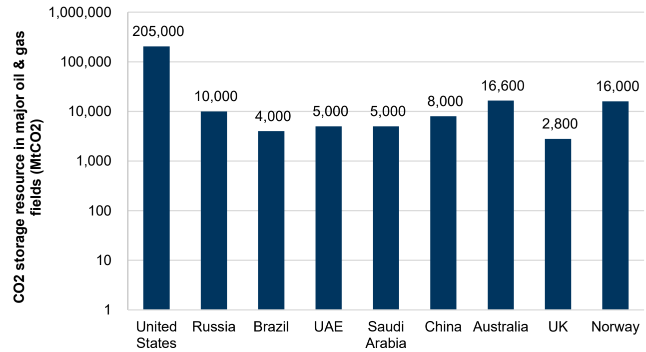


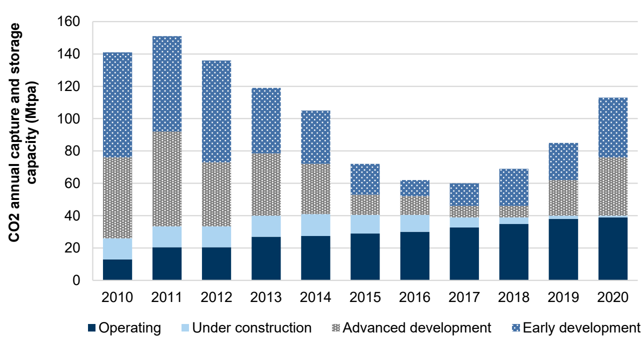
Exhibit 124: ...with the global CO2 storage resource potential in major oil & gas fields alone more than sufficient to compensate for this, according to the Global CCS Institute
CO2 storage resource in majors oil & gas fields (MtCO2)



Source: Goldman Sachs Global Investment Research

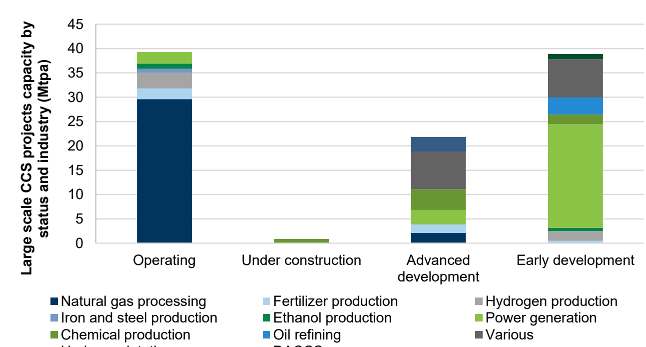
Despite its critical role to any aspirational path aiming to reach net zero by 2050, carbon capture technologies have been to date largely under-invested. We nonetheless believe in the return of interest in the technology following a lost decade with more projects under development. Currently, we identify more than 20 large-scale CCS facilities operating globally (mostly in the US, Canada and Norway), with a total capacity around 40 Mtpa. 2019 was marked by the advancement of two large-scale CCS facilities: the start of CO_2 injection at the Gorgon natural gas processing plant in Australia, the largest dedicated geological CO_2 storage facility when ramped up to full capacity (4.0 Mtpa of CO_2), and the Alberta Carbon Trunk Line (ACTL) development. In 2020, the Northern Lights project made its entry. According to the involved companies, Phase 1 includes capacity to transport, inject and store up to 1.5 $MtCO_2$ per year. Once the CO_2 is captured onshore, it will be transported by ships, injected and permanently stored in the North Sea.

Exhibit 125: The pipeline of large-scale CCS facilities is regaining momentum after a 'lost decade'...
Annual CO2 capture & storage capacity from large-scale CCS facilities



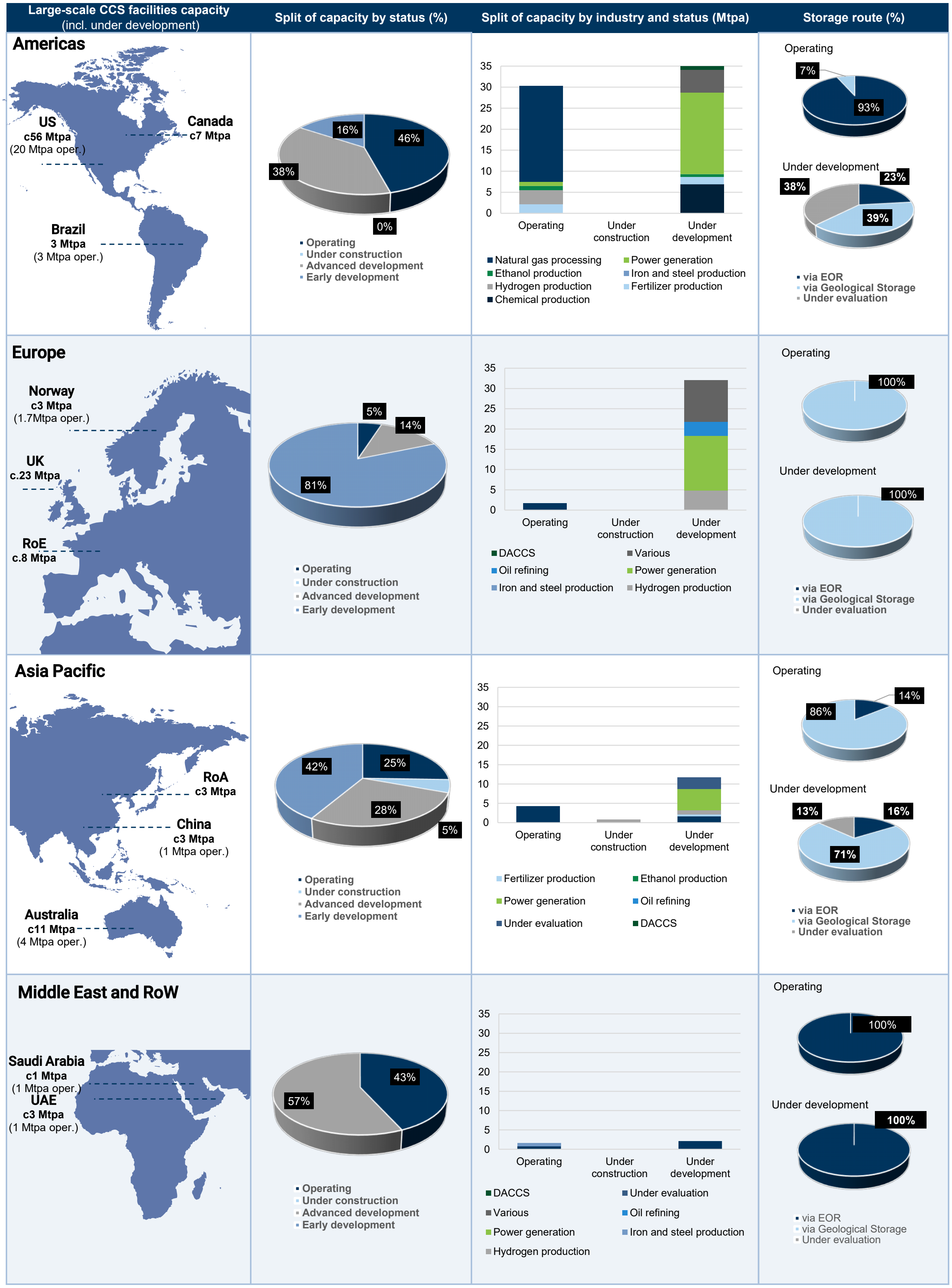
Source: Global CCS Institute Status Report 2020

Exhibit 126: ...as more projects in the development stage start to focus on industries with lower CO2 stream concentrations (industrial & power generation as opposed to natural gas processing)
Large-scale CCS projects by status and industry of capture (Mtpa, 2019)



Source: Global CCS Institute, Goldman Sachs Global Investment Research

Exhibit 127: Summary of global large-scale CCS projects (capacity >0.4Mtpa) including operating, under construction and under early development projects



Source: Global CCS Institute CO2RE, Data compiled by Goldman Sachs Global Investment Research

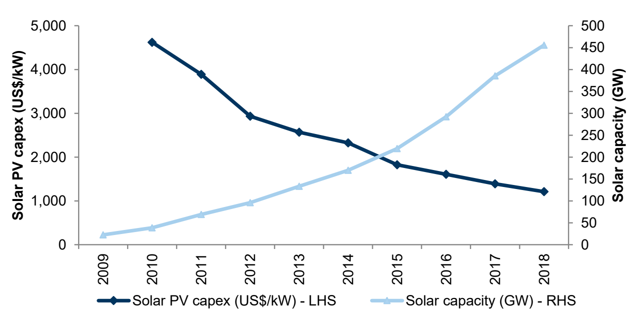
Historical under-investment in CCUS has held back large-scale adoption and economies of scale. However, the tide may be turning, with several projects moving forward in Europe and North America

Cost remains the primary barrier to the deployment of CCS technologies. The incremental costs of capture and the development of transport and storage infrastructure are not sufficiently offset by government and market incentives, albeit efforts have intensified in regions such as Norway (where carbon prices are at the higher end of the global carbon price spectrum) and the US (with the introduction of the 45Q scheme). The cost of individual CCS projects can vary substantially depending on the source of the carbon dioxide to be captured, the distance to the storage site and the characteristics of the storage site, although the cost of capture is typically the largest driver of the total expense and it shows an inverse relation to the concentration of CO_2 in the stream of capture.

Although carbon sequestration has seen a revival in recent years, it **has not yet reached large-scale adoption and economies of scale that traditionally lead to a breakthrough in cost competitiveness**, especially when compared with other CO_2-reducing technologies such as renewables. Despite the key role of sequestration in any scenario of net carbon neutrality, investments in CCS plants over the past decade have been <1% of the investments in renewable power. Although we are seeing a clear pick-up in CCS pilot plants after a 'lost decade', we do not yet know where costs could settle if CCS attracted similar economies of scale as solar and wind. The vast majority of the cost of carbon capture and storage comes from the process of sequestration and is inversely related to the CO_2 concentration in the air stream from which CO_2 is sequestered. The cost curve of CCS therefore follows the availability of CO_2 streams from industrial processes and reaches its highest cost with direct air carbon capture and storage (DACCS), where economics are highly uncertain, with most estimates at US$40-400/ton and only small pilot plants currently active. The importance of DACCS lies in its potential to be almost infinitely scalable and standardized, therefore setting the price of carbon in a net zero emission scenario.

Exhibit 128: Solar PV cost per unit of electricity has fallen 70%+ over the last decade as cumulative solar capacity has increased exponentially...

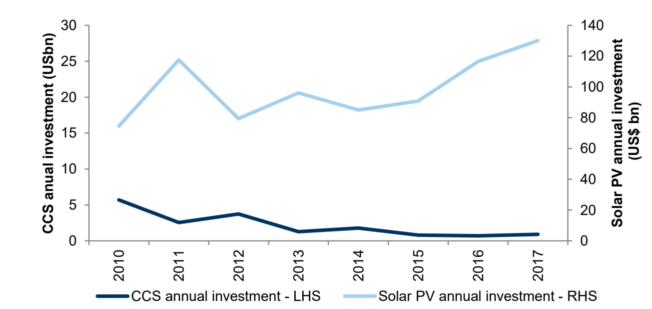
Solar PV capex (US$/kW) vs. global cumulative solar PV capacity (GW)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 129: ...while the languishing investment in CCS sequestration technologies has possibly prevented a similar cost improvement

Annual investment in solar PV (LHS) and large-scale CCS (RHS)

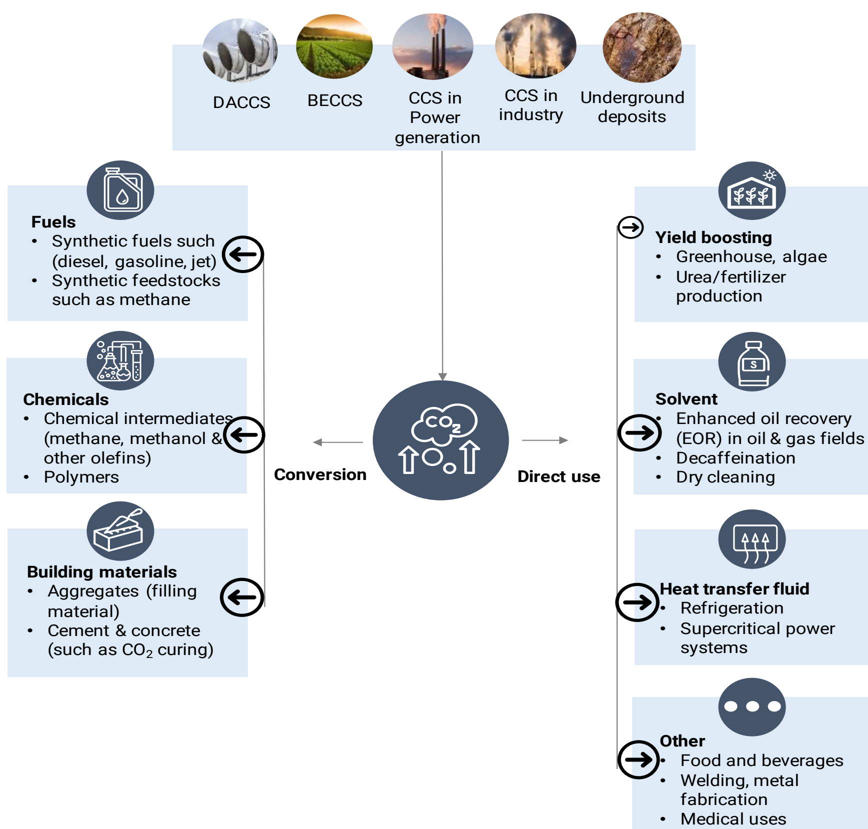


Source: Company data, IEA, IRENA, Goldman Sachs Global Investment Research

Captured CO_2 Utilization: A potentially valuable commodity in search of new markets

Globally, >200 Mtpa of CO_2 is used every year, with the majority of demand coming from the fertilizer industry, the oil & gas industry for enhanced oil recovery (EOR), and food & beverages. The rising focus on CO_2 emissions reduction and carbon capture technologies has sparked further interest in CO_2 utilization across a number of applications, involving both direct use (CO_2 not chemically altered) and CO_2 transformation or conversion. CO_2 has, as a molecule, some attractive qualities for utilization purposes, including its stability, very low energy content and reactivity. The most notable examples of those include the use of captured CO_2 with hydrogen to produce synthetic fuels and chemicals, the production of building materials such as concrete (replacing water during concrete production, known as CO_2 curing, as well as a feedstock to produce aggregates during the grinding phase) and crop yield boosting for biological processes. CO_2 utilization can form an important complement to carbon capture technologies, provided the final product or service that consumed the CO_2 has a lower life-cycle emission intensity when compared with the product/process it displaces. For CO_2 utilization to act as an efficient pathway for emissions reduction, there are therefore a few key parameters that need to be assessed, including: the source of CO_2, the energy intensity and the source used in the process (net zero energy is vital in most cases where electricity and heat requirements are large) and the carbon's retention time in the product (can vary from one year for synthetic fuels to hundreds of years in building materials).

Exhibit 130: There exists a very wide range of potential uses and applications for captured CO2 globally, involving both direct use and conversion



Source: IEA, Goldman Sachs Global Investment Research

The most scalable technology: Direct Air Carbon Capture and Storage (DACCS)

Direct air capture (DAC) is a different form of sequestration, as it does not apply to a specific process (like traditional CCUS), but takes CO_2 from the air in any location and scale. Nascent DAC technologies are capable of **achieving physical and/or chemical separation and concentration of CO_2 from atmospheric air**, unlike CCS, which captures carbon emitted from 'point source' industrial processing streams (flue gas). Carbon captured through DAC can then be repurposed for other uses, for example to make carbon-neutral hydrocarbon fuels. It is early days for DACCS, however, as the technology is still being developed and existing implementation projects are small-scale and very high cost. Nonetheless, we identify this technology as a potential wild card in the challenge of climate change as **it could in theory unlock almost infinitely scalable de-carbonization potential**. A summary of the most prominent DACCS designs to date and the associated details is described in the summary box that follows.

Exhibit 131: DACCS: A roadmap of challenges with yet unique opportunities ahead

Direct Air Carbon Capture (DACCS)		
Strengths	**Challenges**	**Opportunities**
1) Very large cumulative potential in relation to other carbon removal pathways that could be infinitely scalable	**1)** New concept in need of further technological innovation required to bring energy requirements and costs down to a level that is commercially competitive.	**1)** Primary energy consumption in DACCS is attributed to the heat required for sorbent/solvent regeneration. Identifying sorbents that optimize the binding to CO2 such that it is strong enough to enable efficient capture but weak enough to reduce heat requirement during regeneration is key.
2) DACCS can be sited in a very wide range of locations including areas near high energy sources and geological storage potential since there is no need to be close to sources of emissions	**2)** The very small concentration of CO2 in air (c0.04%) compared to industrial streams makes the economics of the capture process unattractive and calls for further innovation.	**2)** Reaction kinetics are important as they impact the rate at which CO2 can be removed from air. If the rate is low a much larger area for air-sorbent/solvent material contact will be required which translates into a large air contactor area and thus higher capital costs. Optimization of air contactor design through geomtery and pumping strategy is another key technological aspect.
3) There are limited land and water requirements for DAC relative to other pathways such as natural sinks or BECCS.	**3)** Given the high energy intensity of carbon capture technologies, there is an evident need for zero carbon electricity for the most efficient, from a climate change standpoint, operation.	**3)** CO2 offtake, transport and utilization is a key component for an efficient system operation. Finding new opportunities for CO2 utilization is therefore vital. Examples include synthetic fuels and petrochemicals.
4) Technological advantages over conventional CCS include the absence of high levels of contaminants present in plants' flue gas streams, and no need for a design targeting the complete CO2 capture with a single stream pass which is usually the case for CCS applied to industrial flue gas streams.		

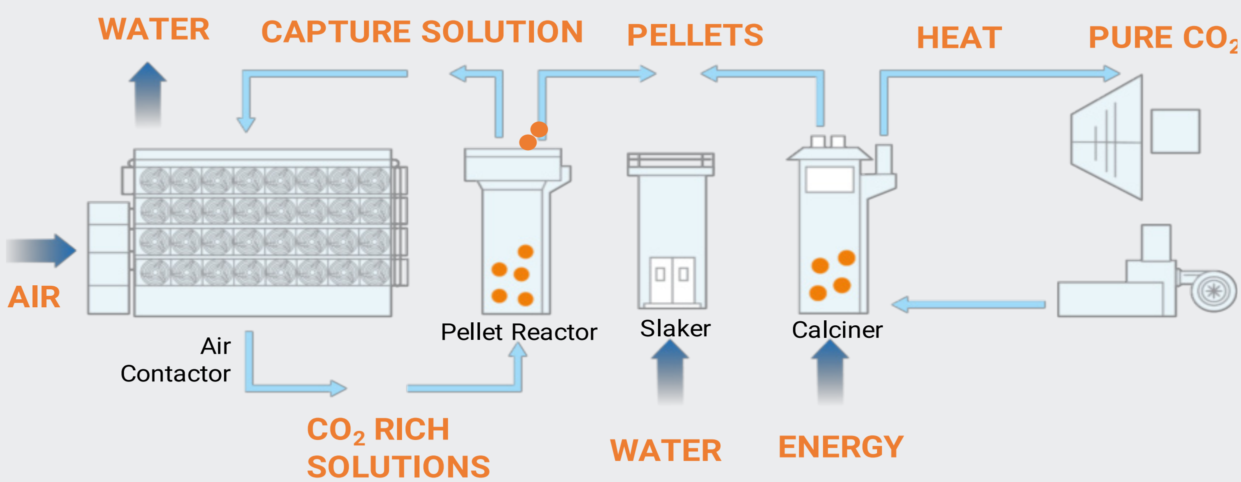
Source: ICEF Roadmap, Goldman Sachs Global Investment Research

Direct Air Carbon Capture: Companies leading the race

Carbon Engineering Ltd

Carbon Engineering (Canada-based) was founded in 2009 and is currently adopting a solvent-based cycle process for direct air carbon capture. The process involves an air contactor which includes a fan that brings air into the structure. The air is then passed over thin plastic surfaces that contain the solvent — an aqueous solution of potassium hydroxide solution that binds to the CO_2 molecules, capturing them in a liquid solution (forming carbonate salt). A series of chemical processes subsequently increase the CO_2 concentration. Those processes involve salt separation from the solution into small pellets (pellet slurry reactor), the heating of the pellets in a calciner releasing the captured CO_2 in gaseous form and recycling the pellets (through hydration in a slaker) back in the system for further capture. The captured CO_2 is then used for geological storage or the production of synthetic fuels. Carbon Engineering is currently the only known company to use a liquid-solvent based approach to DACCS, enabling the potential for a continuous process which could operate at steady state. Its process relies mostly on equipment that are widely used in industry and that therefore have an established supply chain and performance.

Exhibit 132: Schematic of the DACCS process adopted by Carbon Engineering

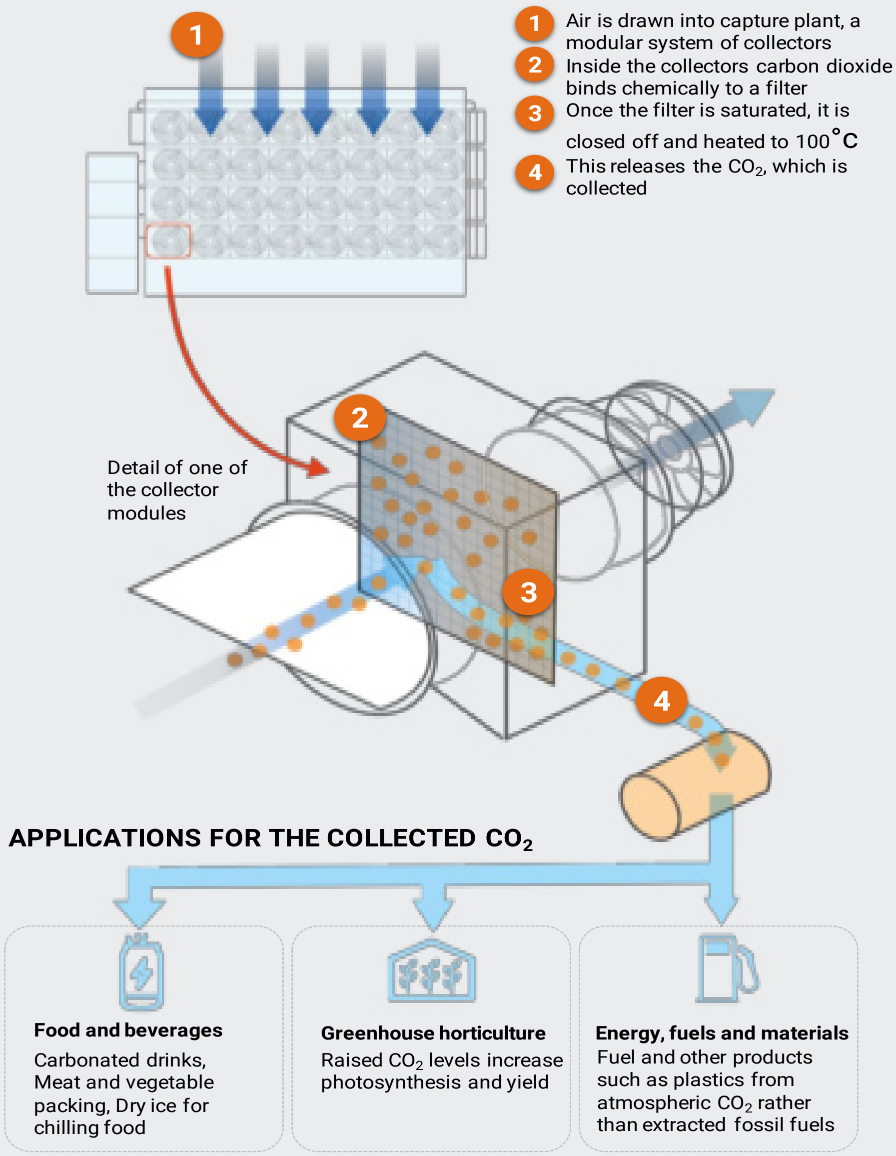


Source: Carbon Engineering

Climeworks

Climeworks is another company that is focused on delivering direct air carbon capture solutions. It currently has several pilot plans in operation, notably the ones in Switzerland, Iceland and Italy, which capture c.900/50/150 tCO_2pa, respectively. The sorbent used to capture CO_2 is an amine supported on solid porous granules arranged on a filter. The air contactor system consists of fans that move air horizontally across the sorbent filters. Once those filters become saturated with CO_2, they are heated at temperatures around 100°C (combined temperature and pressure swing regeneration process) with the gaseous CO_2 being released from the filter and collected as concentrated CO_2 supply. Climeworks was the first company to deliver commercial CO_2 from DACCS and sell it as a commercial product, with its facility in Switzerland being the first DACCS facility operating with a capacity near $ktCO_2$pa. The captured CO2 is used to supply greenhouses (Gebruder Meier in Switzerland), food & beverages and for the production of synthetic fuels (partnership with Audi and Sunfire).

Exhibit 133: Schematic of ClimeWorks DACCS project



Source: Climeworks

Global Thermostat

Founded in 2010, Global Thermostat's DACCS approach involves amine-based chemical sorbents that are bounded to porous ceramic 'monolith' structure. The captured CO_2 is then stripped and collected over steam at temperatures of 80-100°C with the sorbent regenerated (temperature-vacuum swing regeneration). The plants are modular in design and can be stand-alone. Global Thermostat's monolith design for air contraction provides a high surface area per unit of pressure drop, reducing the energy requirement of air flow through the contactor. The company is partnering with some major companies including Exxon Mobil.

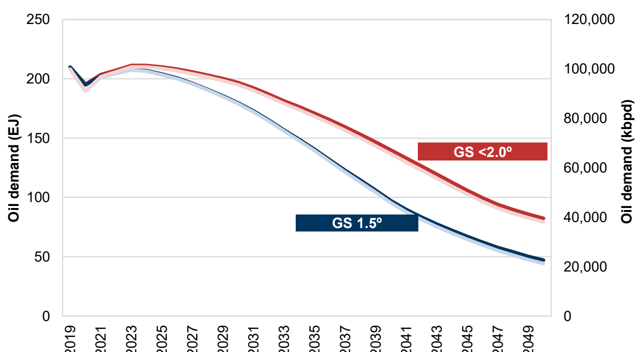
Fossil fuel investments: Investments in oil and natural gas continue to be needed for at least another decade

Whilst the global total oil & gas demand eventually declines substantially under both our GS 1.5 and GS <2.0 global net zero scenarios, as shown in Exhibit 134 and Exhibit 40, we note that near-term growth and underlying decline rates in the industry still support ongoing investments in oil for the next one to two decades (depending on the scenarios) and in gas for the next one to three decades.

Yet we estimate that tightening financing conditions for new hydrocarbon developments are already bringing an end to non-OPEC growth, a steepening of the cost curve and shrinking reserves: oil reserve life shrinks to c.25 years, a 50% reduction from 2014, as the industry stops exploring for new resources. We outline these supply dynamics in detail in our annual oil & gas industry deepdive report *Top Projects*. This comes at a time when the focus on the fossil fuel consumers does not match the intensified focus on the producers.

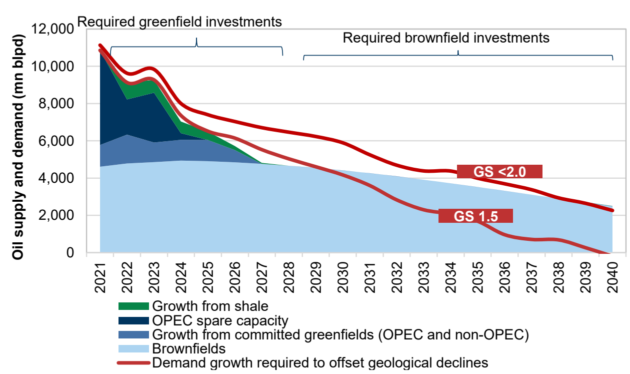
In this section of the report we look at the implications of the two global net zero scenarios on the need for incremental investments in oil & gas. Our results for oil are presented in Exhibit 135. As shown, under both global net zero scenarios we expect investments in oil to still be required for another 2 decades (to 2040) with **greenfield oil investments needed to 2025-2030 and brownfield oil investments needed to 2040** even under the stricter (from a carbon budget perspective) GS 1.5° scenario. Similarly, we estimate that investments in natural gas will be needed for at least another decade, and perhaps much longer if the GS <2.0° scenario is considered, as we show in Exhibit 137.

Exhibit 134: While oil demand gradually declines under both our global net zero scenarios...
Oil demand (EJ and kbpd) under our two global net zero models



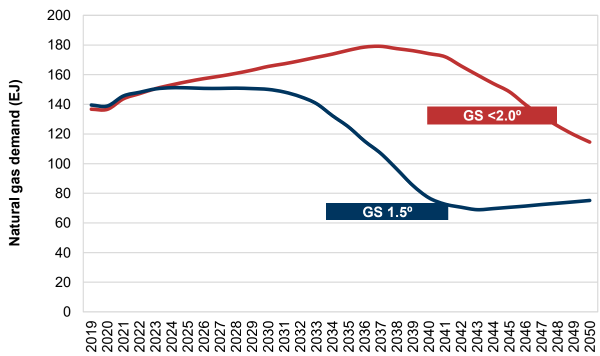
Source: Goldman Sachs Global Investment Research

Exhibit 135: ...we estimate that investments in oil will continue to be needed to 2040, with greenfield to 2030 and brownfield investments thereafter
New production from greenfield and brownfield projects required to balance the oil market



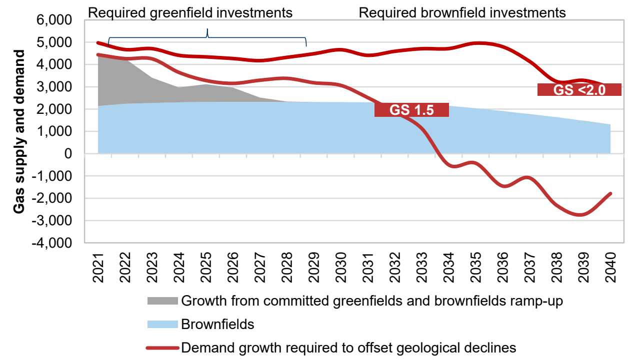
Source: Goldman Sachs Global Investment Research

Exhibit 136: The role of natural gas deviates more between our two global net zero scenarios compared to oil...
Natural gas demand (EJ)



Source: Goldman Sachs Global Investment Research

Exhibit 137: ...leading to very different needs for natural gas investments in the coming decades
New production from greenfield and brownfield projects required to balance the gas market



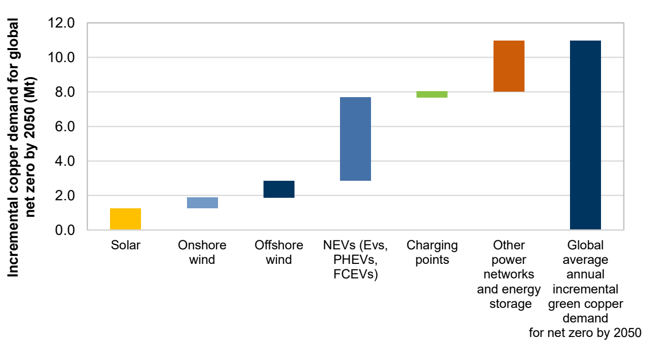
Source: Goldman Sachs Global Investment Research

Natural resources: At the heart of the global net zero evolution

At the heart of the any aspirational global path for net zero lies the need for access to clean energy and an accelerated pace of electrification that is likely to drive the next natural resources super-cycle in the coming decades. **Electrification and clean energy is likely to have an impact on total demand for natural resources, and in particular metals** such as aluminium, copper, lithium and nickel, demand for which relies heavily on an acceleration in technologies such as renewables (solar panel, wind turbines manufacturing), power network infrastructure, charging infrastructure, electric vehicles and battery manufacturing. We attempt to quantify the potential impact that the path to net zero by 2050 (GS 1.5°), as laid out in previous sections, will have on the demand for each of these metals, as shown in the exhibits that follow.

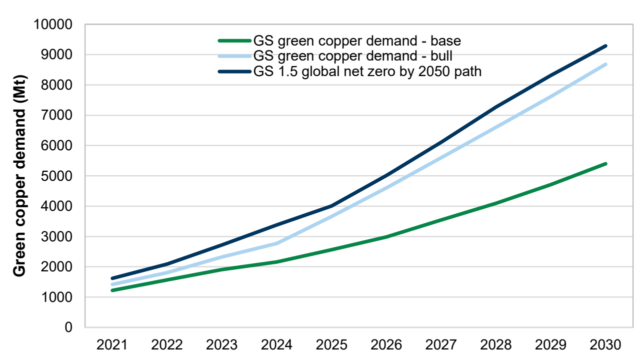
The results of this analysis are calculated on the basis of incremental demand for each clean technology relative to the conventional technology (such as incremental copper demand per electric vehicle compared with conventional ICE vehicles). We find that annual green copper demand in a global net zero path by 2050 will rise by c.10 Mtpa, a c.40% increase from the global copper demand in 2019. Similarly, the global average incremental annual green aluminum demand is estimated to be around 25Mtpa to 2050, c.40% of the total global aluminium demand in 2019, both suggesting material upside in the demand of those metals if such an aspirational global net zero carbon by 2050 scenario materializes. For further details on the GS Commodities green metals analysis please see the team's report on Green Copper and Green Aluminium.

Exhibit 138: We estimate c. 10 Mt of average annual incremenal copper demand by 2050 for our aspirational global net zero by 2050 path (GS 1.5), representing a c40% increase from current annual copper demand..
Incremental green copper demand for global net zero by 2050



Source: Company data, Goldman Sachs Global Investment Research

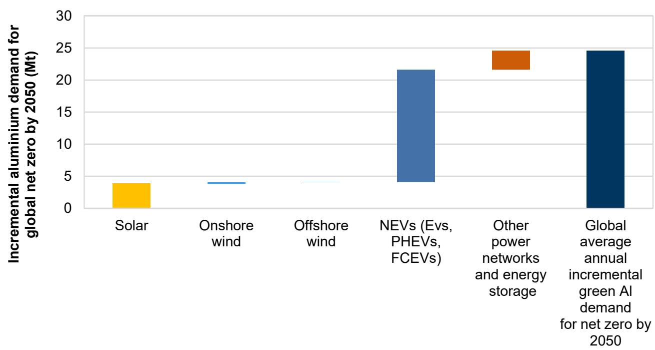
Exhibit 139: ...with a large acceleration occuring this decade, and our global net zero by 2050 model exceeding even the GS green copper demand bull case to 2030
Green copper demand to 2030 (Mt)



Source: Goldman Sachs Global Investment Research

Exhibit 140: We estimate c.25 Mt of average annual incremental aluminium demand by 2050 for our aspirational global net zero by 2050 path (GS 1.5), representing a c. 40% increase from current annual aluminium demand...

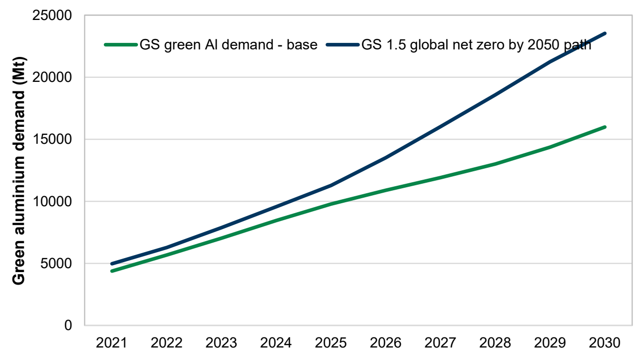
Incremental green aluminium demand for global net zero by 2050



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 141: ...leading to further upside to our GS green aluminium base case by 2030 if such a path was to materialize

Green aluminium demand (Mt)

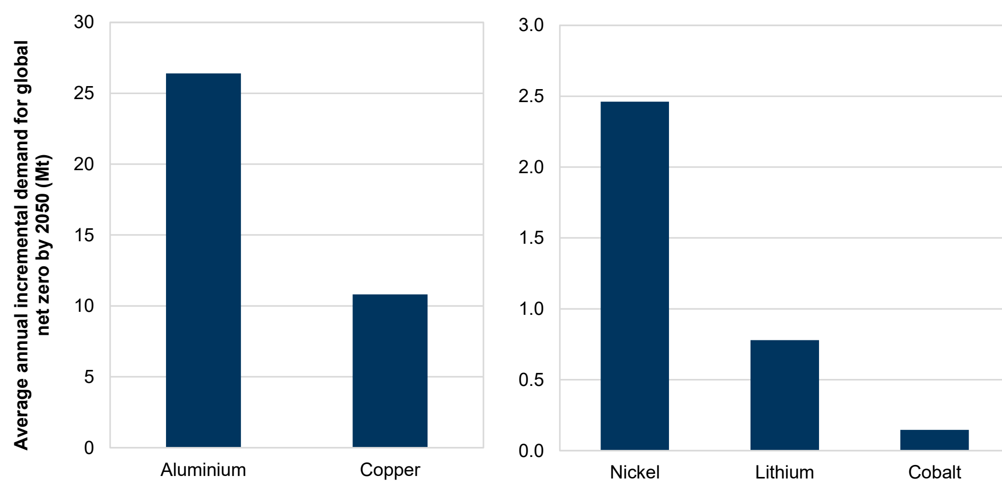


Source: Goldman Sachs Global Investment Research

Finally, we expect the demand for minerals such as lithium, nickel and cobalt to increase given the stellar growth we anticipate in energy storage (both in new energy vehicles and in utility grid storage). Overall we estimate c.0.8 Mt average incremental lithium demand to 2050 under our GS 1.5 path, c.2.5 Mt of nickel demand and c.0.2 Mt of cobalt demand in a similar timeframe, multi-fold increases for all three metals compared to current demand levels. This is largely relying on the new energy vehicles (primarily BEVs) battery mix.

Exhibit 142: We expect multi-fold increases in the demand for minerals such as lithium, nickel and cobalt in the coming decades..

Incremental Li, Ni, Co average annual demand to net zero by 2050



Source: Company data, Goldman Sachs Global Investment Research

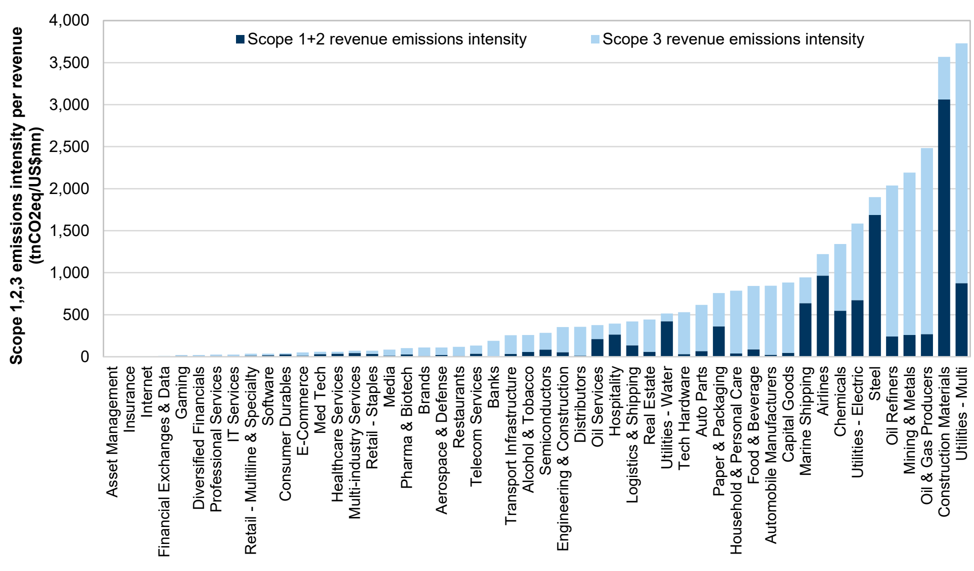
A step further: Adopting our sectoral approach for global net zero to construct corporate carbon intensity paths

We have applied our GS 1.5° net zero by 2050 and GS <2.0° net zero by 2060 scenarios to **construct corporate emission reduction paths by industry for the highest emitting industries globally on Scope 1 and 2 but also on Scope 3 for sectors where Scope 3 emissions are material.** That provides a tool to screen corporates against the aspirational net zero by 2050/2060 paths and assess their current emissions intensity reduction targets. We primarily formulate these corporate paths for a **carbon intensity measure** rather than absolute emissions (to adjust for market share movements).

In Exhibit 143 we present the average revenue carbon intensity (tnCO2eq/$mn revenue) by industry for corporates listed in Western Europe, based on the current corporate emissions disclosure. The highest emitting sectors are shown to be primarily fossil fuel producing and directly consuming industries, such as multi-utilities, construction materials, oil & gas producers, metals & mining, oil refiners, steel producers, airlines, shipping and chemicals.

Exhibit 143: As part of this report we lay out the de-carbonization path by industry, primarily focusing on the industries with high over emissions intensity per unit of revenue

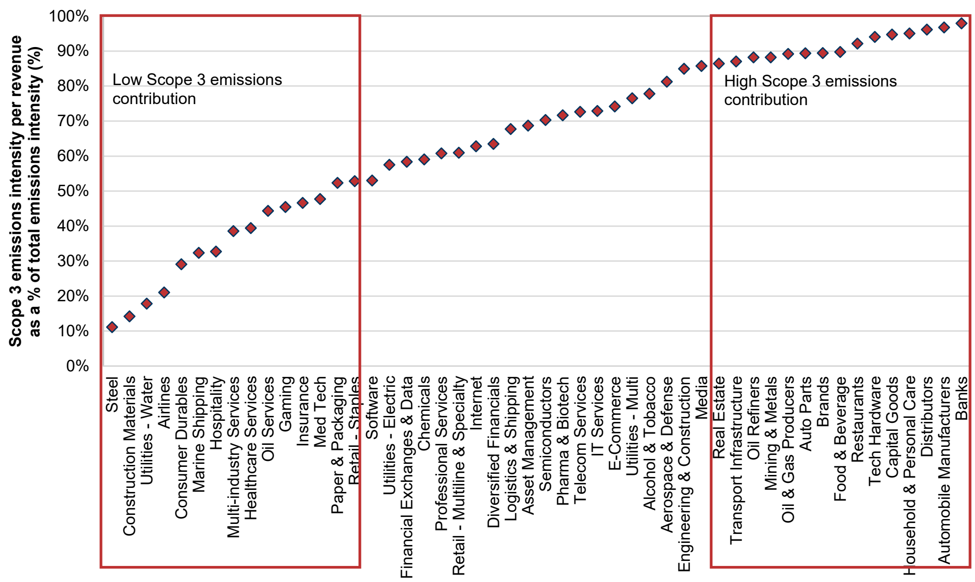
Scope 1,2,3 emissions intensity per unit of revenue (tnCO2eq/US$ mn revenue) for corporates listed in Europe



Source: Thomson Reuters, Bloomberg, MSCI, Company data, Goldman Sachs Global Investment Research

We also address the relative contribution to the average emissions intensity of revenue by industry for Scope 1 & 2 compared to Scope 3. In Exhibit 144 we plot the relative contribution of Scope 3 emissions to the average emissions intensity of each industry, aiming to identify the industries where Scope 3 emissions are of critical importance and dominate the total emissions reported and as such need to be addressed in our corporate emission pathways. Amongst these sectors are banks, automotive manufacturers, distributors, household & personal care, capital goods, oil & gas producers, metals & mining.

Exhibit 144: The importance of Scope 3 emissions varies widely depending on the industry considered. We address Scope 3 emissions primarily for companies which have a high Scope 3 emissions contribution
Scope 3 emissions intensity per unit of revenue as a % of total emissions intensity per unit of revenue (%, 2019, corporates listed in Europe)

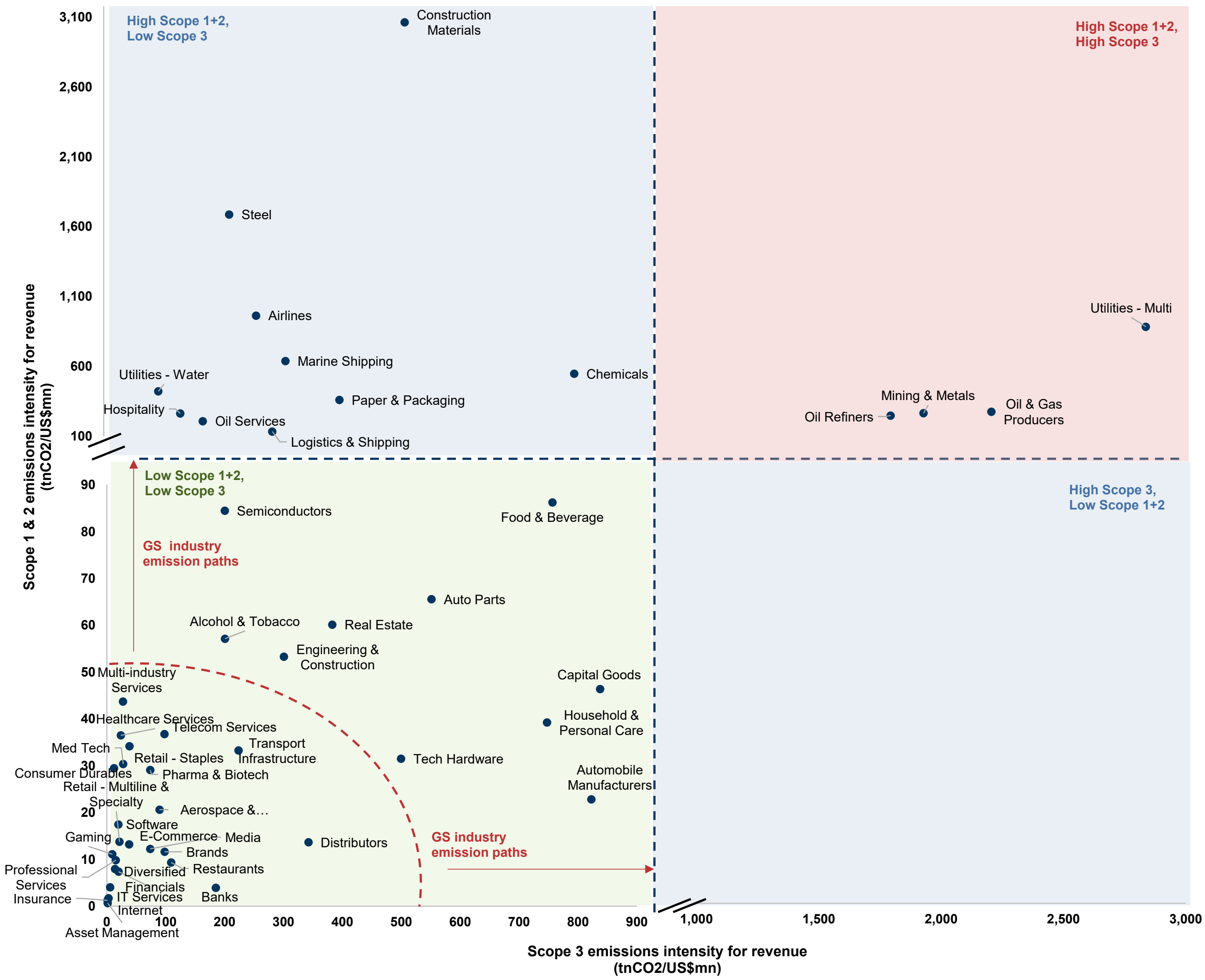


Source: Bloomberg, MSCI, Company data, Thomson Reuters Eikon, Goldman Sachs Global Investment Research

For the purpose of constructing our GS 1.5° industry emission reduction pathways, we primarily focus on industries with **high relative Scope 1 & 2 revenue emissions intensity and/or high Scope 3 revenue emissions intensity.** This is shown in the diagram below, Exhibit 145, with the dashed red line separating the areas of emission intensity materiality and immateriality. The corporate industries addressed in our emission reduction paths are the ones found on the right of the dashed red line (inside the 'materiality' space). Corporate industries found on the left of the red dashed materiality line are considered to be industries with immaterial emissions intensity both on Scope 1 & 2 and Scope 3 on a comparative basis and as such are excluded from the industry emission pathways analysis that follows. On the contrary, industries placed in the top right box (high scope 1,2,3 intensity) are considered the most critical industries from a de-carbonization perspective and as such are analysed in detail in our industry paths both on scope 1&2 and on scope 3. We note that the accuracy of the data presented in the exhibit below with regards to the relative emission intensity by scope for each industry is largely reliant on the current emission disclosure quality of each industry.

Exhibit 145: We contruct emission reduction pathways for corporate industries with high Scope 1 &2 and/or high Scope 3 emissions intensity per revenue, as shown by the dashed red line in the diagram below, with all industries on the right of this forming part of our analysis.

Scope 1 & 2 emissions intensity for revenue (y-axis) vs Scope 3 emissions intensity for revenue (x-axis) for corporates listed in Europe



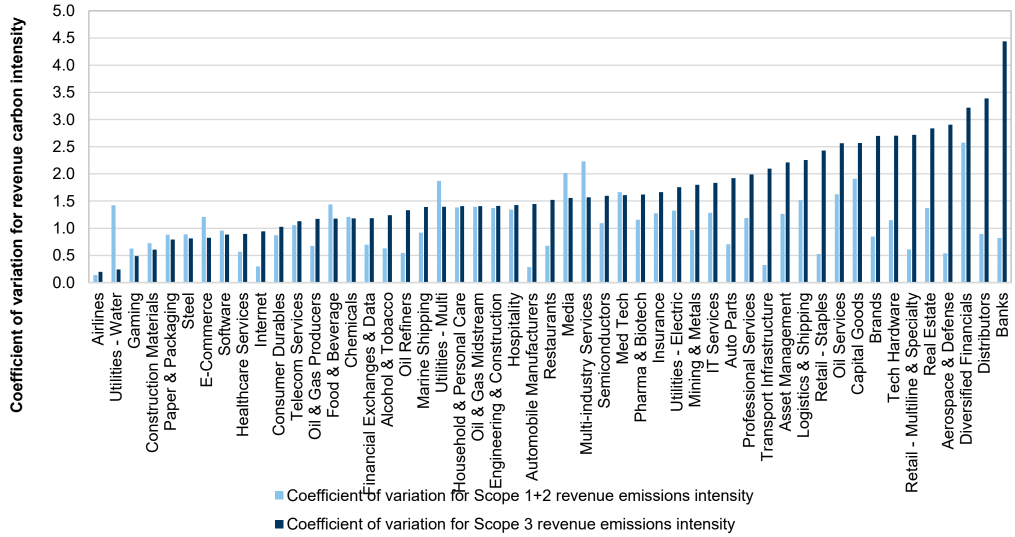
Source: Bloomberg, MSCI, Thomson Reuters Eikon, Company data, Goldman Sachs Global Investment Research

The level of disclosure, consistency and level of homogeneity of emissions disclosed by corporates within each industry varies greatly, especially with regards to Scope 3 emissions

We note that the level of disclosure, consistency and homogeneity of emissions disclosed by corporates within each industry varies greatly. In order to assess the level of consistency and homogeneity of an industry with regards to its constituents and their associated emission disclosure we calculate the coefficient of variation of the revenue carbon intensity for each industry. The results are presented in Exhibit 146 with the coefficient of variation of the revenue emissions intensity being very different, both for Scope 1 & 2 intensity but also on scope 3 across sectors. Overall, for the vast majority of industries, the coefficient of variation for Scope 3 emissions intensity is higher compared to Scope 1 & 2 given the wide variety, detail and categories of Scope 3 disclosure.

Exhibit 146: The emissions intensity of corporates within each industry show great variability for scope 1 & 2 but also, and to a greater extend, for scope 3 as shown by the coefficient of variation for revenue carbon intensity below

Coefficient of variation for revenue carbon intensity (for corporates listed in Europe)

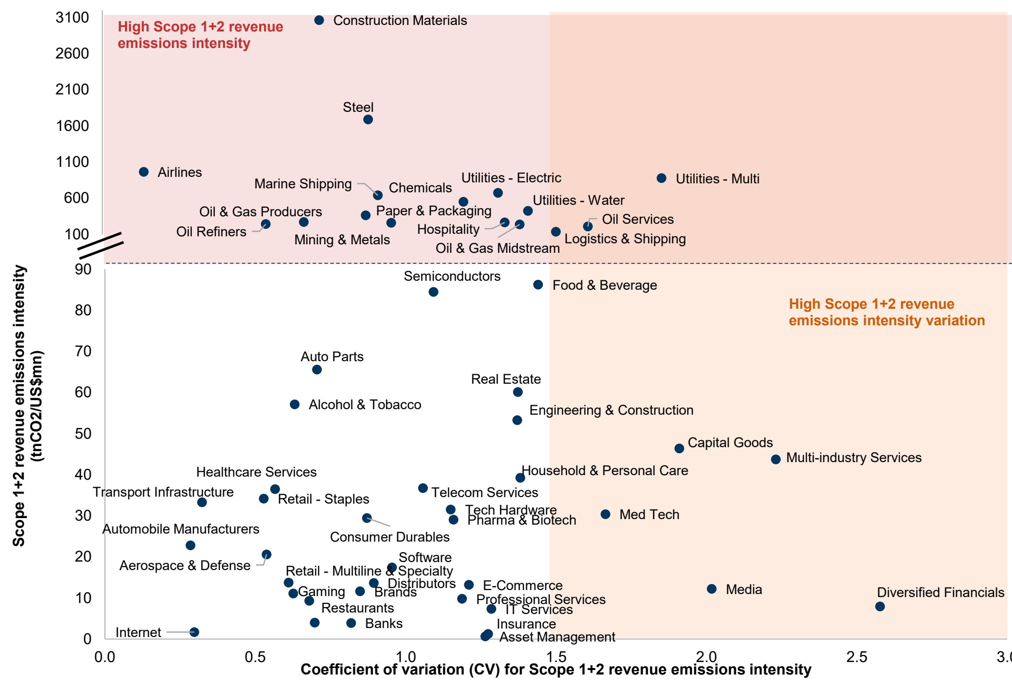


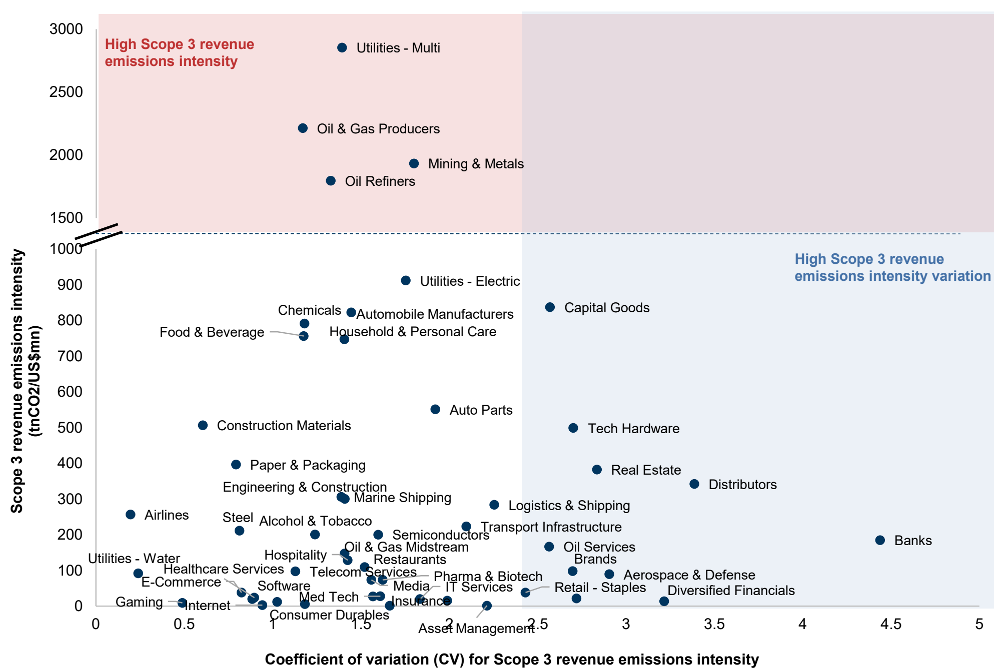
Source: Bloomberg, MSCI, Thomson Reuters Eikon, Company data, Goldman Sachs Global Investment Research

The exhibits that follow show the industries with the highest coefficient of variation for scope 1 &2 and scope 3 emissions respectively. For scope 1 & 2 emission intensity diversified financials, multi-industry, media, capital goods, multi-utilities show higher variability as shown by their larger coefficient of variation given the diverse natural of the corporates involved in each of these sectors. For Scope 3, the industries showing the higher variability in emissions intensity include banks, distributors, real estate, capital goods, diversified financials, aerospace and defense, brands, tech hardware. This reflects both the wide variety of companies (from an operational business mix perspective) which make up each of these industries but also the varying degree of disclosure and methodology with regards to Scope 3 emissions and its sub-categories.

Exhibit 147: The level of disclosure, consistency of emissions disclosed by corporates within each industry varies greatly, especially with regards to Scope 3 emissions

Scope 1&2 and Scope 3 revenue emissions intensity (tnCO2/US$mn) vs coefficient of variation of revenue emissions intensity





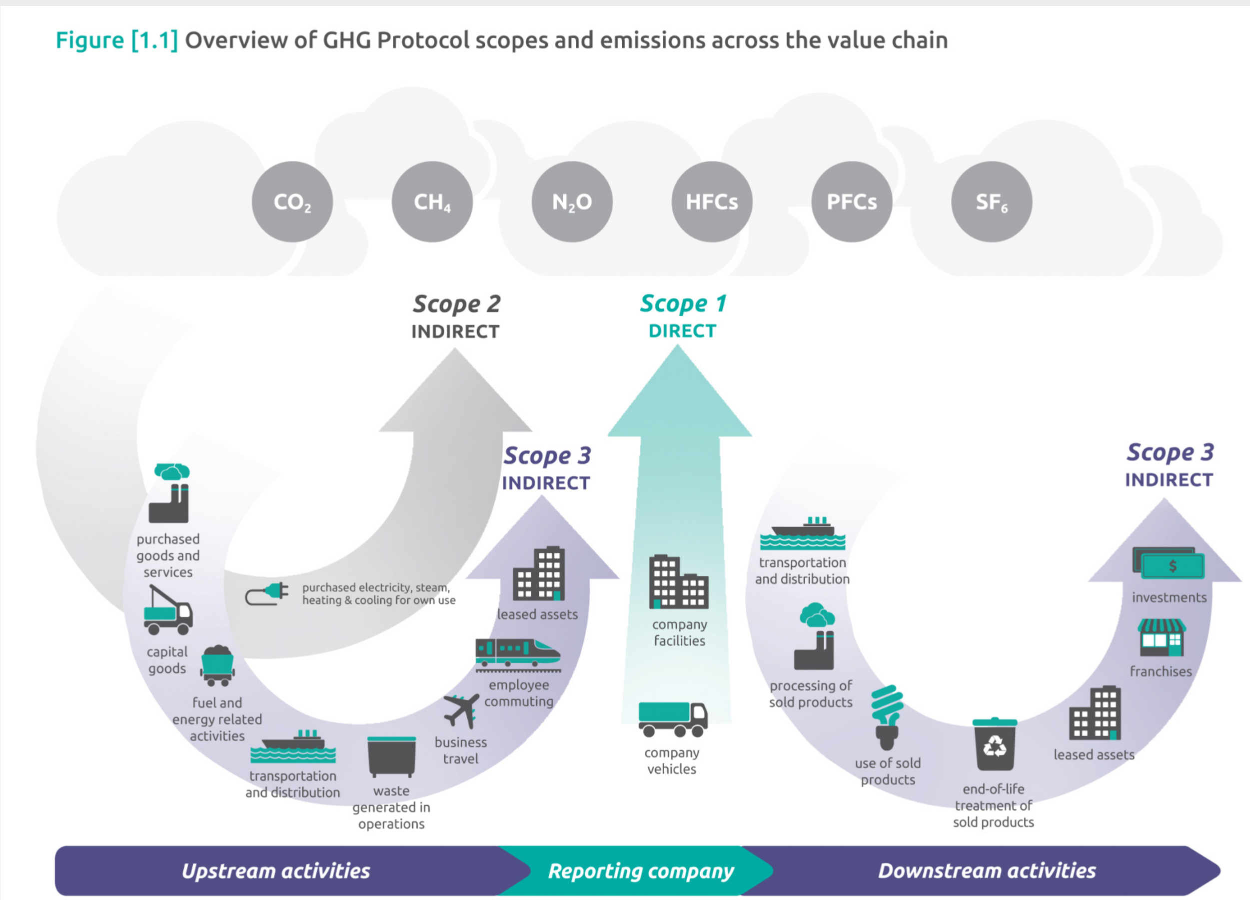
Source: Goldman Sachs Global Investment Research

Defining different GHG emission Scopes

The Greenhouse Gas (GHG) Protocol, developed by World Resources Institute (WRI) and World BusinessCouncil on Sustainable Development (WBCSD), sets the global standard for how to measure, manage, and report greenhouse gas emissions. GHG emissions are categorised by companies under three main buckets:

- **Scope 1** (direct emissions) occurs from the companies' owned or controlled by the operating entity, including for example flaring, venting and fugitive emissions from oil & gas production facilities.
- **Scope 2** (indirect emissions) refers to indirect GHG emissions that are a consequence of the activities of the reporting entity, but occur at sources owned or controlled by another entity emissions. For scope 2 in particular this includes primarily emissions from the consumption of purchased electricity, heat, or steam.
- **Scope 3** (indirect emissions), refers to all other indirect emissions, such as the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities not covered in Scope 2, outsourced activities, waste disposal and more.

Exhibit 148: Defining the three scopes in the GHG Protocol: Scope 1, direct emissions; Scope 2, indirect emissions; and Scope 3, other indirect emissions in the value chain



Source: World Resources Institute

Corporate carbon intensity de-carbonization pathways by industry consistent with 1.5°C and <2.0°C global warming

As mentioned previously, we have applied our GS 1.5° net zero by 2050 and GS <2.0° net zero by 2060 scenarios to **construct corporate emission reduction paths by industry** for the highest emitting industries globally on Scope 1 and 2 but also on Scope 3 for sectors where Scope 3 emissions are material. That provides a tool to screen corporates against the aspirational net zero by 2050/2060 paths and assessing the suitability of their current emissions intensity reduction targets. We primarily formulate these corporate paths for a carbon intensity measure rather than absolute emissions.

Adopting a sectoral approach for corporate carbon intensity paths:

We more broadly classify the major corporate industries into two buckets:

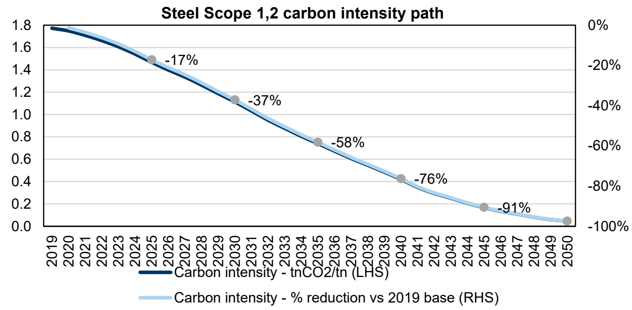
- **Homogeneous industries with a defined unit of production:** Defined as corporate industries whose emissions are homogeneous, and are largely relying on a single activity metric. Examples include the electric utilities sector, where a carbon intensity measure can be derived by dividing the total emissions with the activity metric such as kgCO2/GWh with the power generation (GWh) being the key activity metric, autos sector (gCO2/km), airlines (gCO2/pkm), pure single metal producers and construction materials (tnCO2/tn metal or cement), real estate (gCO2/meter square of floor area) and more.

- **Heterogeneous sectors:** There are sectors where a carbon intensity measure cannot be derived from a single activity metric. Examples include hospitality, household products, food retail, capital goods and more. **For these sectors, instead of an absolute carbon intensity measure, we have constructed an index for emissions reduction based on the current emissions split and emissions sourcing of key corporates in each sector** (ie. Siemens/ABB in capital goods, Tesco in food retail, Infineon in semiconductors, Deutsche Post in logistics & shipping, Nestle and Danone for food & beverage, Imperial Brands for tobacco, Unilever for household & personal care, BASF for diversified chemicals, BHP/Rio Tinto for diversified miners).

Case Study 1: Examining an example of a homogeneous industry: Steel

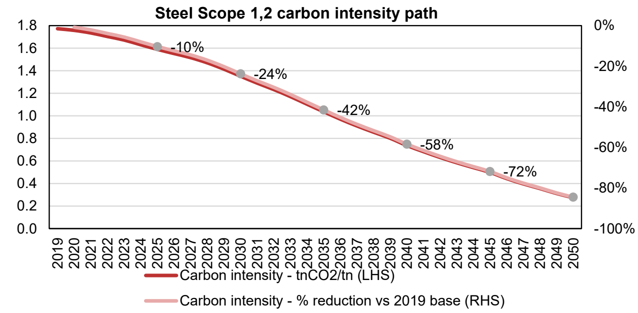
Assuming that corporate carbon intensity levels will converge to the global industry average over time, trending towards zero, the carbon intensity targets for a company in the steel industry are expected to be equal to the sectoral carbon intensity constructed by our global net zero GS 1.5 and GS <2.0 paths by 2050. As part of our bottoms up sectoral global carbon neutrality models we have modeled the global emissions from the steel industry and the global steel production volumes by technology enabling us to devise a global average carbon intensity measure in tnC02/tn steel. This refers to a direct Scope 1 and indirect Scope 2 (assuming the current global average carbon intensity of power generation for the electrified routes) corporate carbon intensity measure.

Exhibit 149: We have created corporate industry carbon intensity paths consistent with net zero by 2050 (GS 1.5 scenario)...
Carbon intensity for steel (tnCO2/tn steel) and % reduction vs 2019 base



Source: Goldman Sachs Global Investment Research

Exhibit 150: ..and for a path consistent with limiting global warming to below 2 degrees and achieving net zero by 2060 (GS <2.0)
Carbon intensity for steel (tnCO2/tn steel) and % reduction vs 2019 base

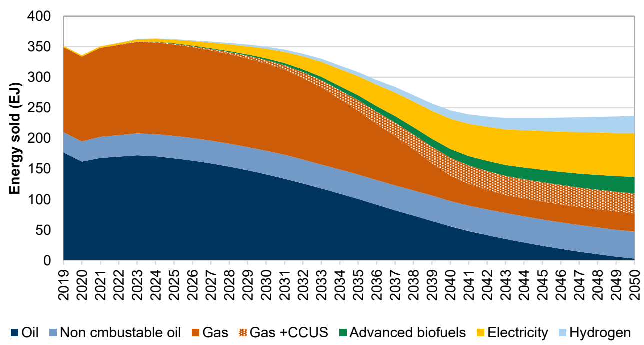


Source: Goldman Sachs Global Investment Research

Case Study 2: Examining an example of a complex homogeneous industry: Oil & gas

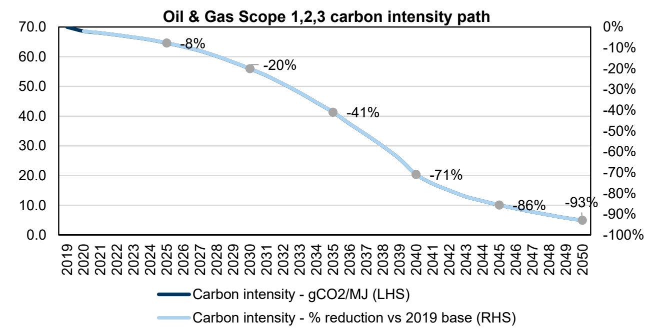
Whilst the oil & gas industry is in theory considered a homogeneous one, with the key activity metric being the amount of energy that is sold in Joules (the universal unit for energy), the wide range of activities and energy products that the integrated oil & gas companies sell makes the carbon intensity evolution analysis more complex than the pure industry example of steel described in Case Study 1. We have constructed a carbon intensity pathway for the oil & gas industry, encompassing all of Scope 1,2 and 3, given the significance of scope 3 emissions for the sector (as shown in Exhibit 144). We have assumed for the purpose of this analysis that the companies maintain their current market share in their respective oil & gas end markets yet the mix of their energy product offering evolves with the de-carbonization of these markets (such as transport, industry, buildings for oil, power generation, industry and buildings for natural gas). In other words, whilst these companies maintain their current market share when it comes to energy sales, the form of energy sold evolves with the de-carbonization of each respective end market, away from fossil fuels in most cases and towards power, bioenergy, clean hydrogen and more. We note that this analysis does not include carbon offsets (natural sinks) and is solely based on the carbon intensity reduction from a technological evolution perspective.

Exhibit 151: We model the oil & gas industry's sales over time, assuming producers maintain their current share of energy sales...



Source: Goldman Sachs Global Investment Research

Exhibit 152: ..resulting in our overall carbon intensity path for integrated producers consistent with global net zero by 2050
Oil & gas scope 1,2,3 carbon intensity path

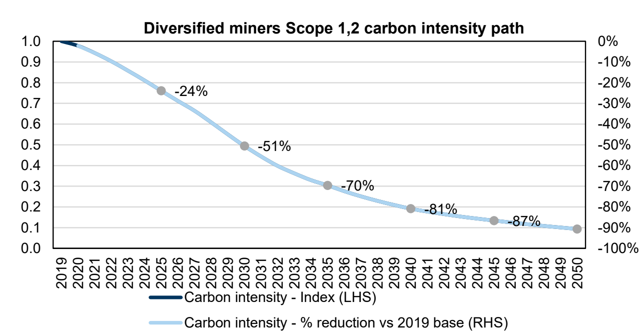


Source: Goldman Sachs Global Investment Research

Case Study 3: Examining an example of a heterogeneous industry: Diversified miners

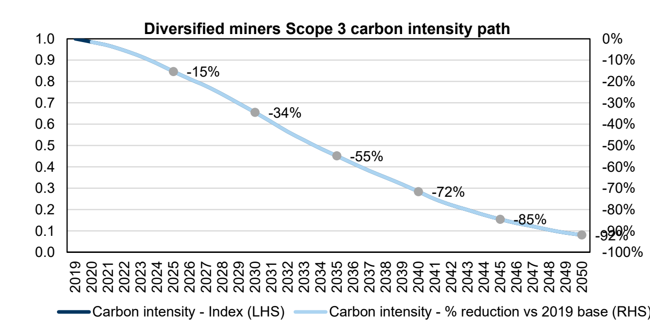
In this case study we focus on a sector which is classified as heterogeneous. As mentioned above, these are sectors where a carbon intensity measure cannot be derived from a single activity metric. **For these sectors, instead of an absolute carbon intensity measure, we have constructed an index for emissions reduction based on the current emissions split and emissions sourcing of key corporates in each sector.** Here we look into the example of diversified miners, where the different product mix of different corporates in the industry makes a single activity metric hard to derive. We have used BHP Billiton and Rio Tinto as the two key examples when formulating our suggested carbon intensity path for that sector. Assuming the companies maintain their current (2019) relative product mix (in terms of metals such as coppers, aluminium, iron ore and more and energy such as thermal and met coal) we can form a volume-weighted index for scope 1,2 and 3 emissions (mostly dominated by steel emissions - the scope 3 emissions associated with iron ore). We show the resulting carbon intensity path for diversified miners (average of Rio Tinto and BHP Billiton) in the charts that follow.

Exhibit 153: We have constructured carbon intensity reduction pathways for heterogeneous sectors such as diversified miners...
Diversified miners Scope 1,2 carbon intensity for net zero by 2050 (GS 1.5)



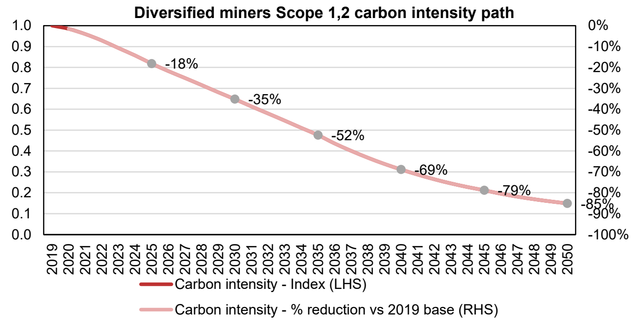
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 154: ...across all 3 scopes for industries where the Scope 3 emissions constribution is material
Diversified miners Scope 3 carbon intensity for net zero by 2050 (GS 1.5)



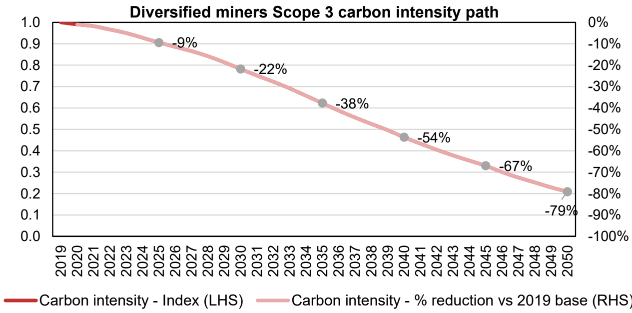
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 155: We have also constructed carbon intensity reduction pathways consistent with Paris Agreement ambitions to maintain global warming below 2 degrees...
Diversified miners Scope 1,2 carbon intensity for net zero by 2050 (GS <2.0)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 156: ...giving perhaps a more gradual and realistic path of emissions reduction compared to the global net zero by 2050
Diversified miners Scope 3 carbon intensity for net zero by 2050 (GS <2.0)

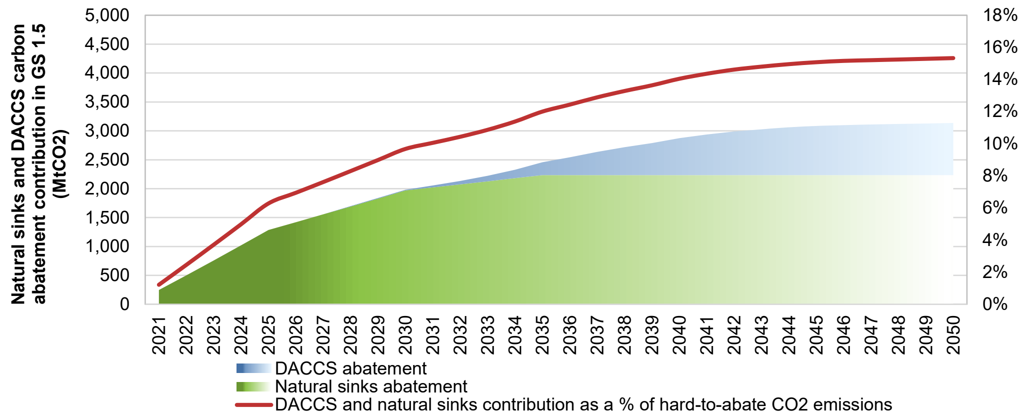


Source: Company data, Goldman Sachs Global Investment Research

Limitations to our corporate industry carbon intensity paths:

- **Regional differences:** The carbon intensity paths for corporate industries were constructed on the basis of our global net zero models which do not differentiate between regions. Whilst that provides a fair representation of the speed of de-carbonization across sectors on a global basis on average, we note that different regions' de-carbonization process will likely move at different speeds based on the current economic and policy framework in place. Similarly, corporates listed in different regions and with operations across different regions globally may end up de-carbonizing at a pace that differs from the one suggested by our corporate carbon intensity charts. For instance, most corporates in Europe will likely have a carbon intensity that is already well below the global average and therefore may need to move their de-carbonization process at a different pace to converge with the global average carbon intensity path.
- **Absence of carbon offsets:** The carbon intensity paths constructed above do not incorporate the role of carbon offsets such as natural sinks. This implies that for instance the carbon intensity reduction of 20% by 2030 required for integrated oil & gas companies is the one required purely from a technological and energy mix evolution perspective. Once the impact of carbon offsets is incorporated these targets will likely be higher. We do consider carbon offsets as a critical tool for net zero to be plausible and do incorporate natural sinks into our global net zero models (GS 1.5 and GS <2.0), yet to attribute them amongst sectors poses an additional challenge when it comes to constructing corporate industry carbon intensity pathways. Carbon offsets in the form of natural sinks and DACCS are critical for the path to global net zero, especially for harder-to-abate sectors in the absence of further technological innovation. We estimate that natural sinks and DACCS' contribution to the de-carbonization of harder-to-abate sector emissions (defined as the CO2 emissions with a carbon abatement cost above US$100/tnCO2 in our cost curve) is around 15% by 2050 as shown in the exhibit below.

Exhibit 157: Natural sinks and DACCS are an important component to our global net zero path, contributing to c. 15% abatement of hard-to-abate CO2 emissions (defined as those with a carbon abatement cost above US$100/tnCO2 in our Carbonomics cost curve)



Source: Goldman Sachs Global Investment Research

- **Heterogeneous sectors:** As we mentioned previously, these are sectors where a carbon intensity measure cannot be derived from a single activity metric. Examples include hospitality, household products, food retail, capital goods and more. For these sectors, instead of an absolute carbon intensity measure, we have constructed an index for emissions reduction based on the current emissions split and emissions sourcing of key corporates (benchmarks) in each sector. The key issue with this approach is of course that it cannot be readily applied to all corporates within each industry. For instance, following on from our Case study 3 above, Rio Tinto and BHP Billiton are not representative of the whole diversified miners corporate universe and may have different product splits (dictating the pace of de-carbonization of Scope 1 emissions as well as different relative emission contributions from Scope 1,2,3). Indeed more heterogeneous sectors also have a wider variety of corporates in each, a prominent example being capital goods with different companies exposed to different end markets and with different emissions composition.

Exhibit 158: Table summarizing our corporate carbon intensity pathways by industry for a global net zero by 2050 scenario (GS 1.5°)

Sector	Industry	Carbon intensity measure	Activity indicator	Scopes coverage	% Reduction in carbon intensity vs 2019 base						Carbon intensity value (stated units)						
					2025	2030	2035	2040	2045	2050	2019	2025	2030	2035	2040	2045	2050
Energy	Oil & Gas Integrated producers	gCO2/MJ	energy sold	Scope 1,2,3	-8%	-20%	-41%	-71%	-85%	-93%	70.2	64.8	56.1	41.3	20.3	10.2	5.1
	Oil refiners	gCO2/MJ	energy sold	Scope 1,2,3	-8%	-24%	-46%	-71%	-87%	-97%	74.8	68.5	57.0	40.2	22.0	9.9	2.4
	Gas producers	gCO2/MJ	energy sold	Scope 1,2,3	-6%	-13%	-32%	-73%	-83%	-83%	63.2	59.4	54.7	43.0	17.2	10.7	10.6
	Electric Utilities	kgCO2/MWh	energy produced	Scope 1,2	-38%	-71%	-92%	-99%	-100%	-100%	504.3	310.4	147.1	38.8	5.0	0.8	0.8
Transportation	Airlines	gCO2/pkm	fleet	Scope 1,2	-14%	-29%	-50%	-68%	-82%	-94%	110.4	95.3	78.2	55.1	35.1	20.0	6.8
	Aerospace & defence	gCO2/pkm	aircrafts sold	Scope 1,2,3	-13%	-29%	-50%	-68%	-82%	-94%	67.6	58.5	48.0	33.9	21.6	12.3	4.2
	Automotive manufacturers - LDV	gCO2/km	vehicles sold	Scope 1,2,3	-14%	-45%	-84%	-99%	-100%	-100%	175.6	151.5	96.1	28.4	1.7	0.3	0.3
	Automotive manufacturers - HDV	gCO2/km	vehicles sold	Scope 1,2,3	-9%	-30%	-76%	-98%	-99%	-99%	631.3	577.1	440.8	151.9	9.5	6.5	6.0
	Maritime Shipping	gCO2/tkm	fleet	Scope 1,2	-17%	-35%	-51%	-68%	-86%	-97%	6.9	5.7	4.5	3.4	2.2	1.0	0.2
	Logistics & Shipping	Index		Scope 1,2,3	-15%	-31%	-52%	-71%	-85%	-96%							
Basic materials	Copper	tnCO2/tn	tonnes refined	Scope 1,2	-30%	-58%	-78%	-88%	-93%	-96%	4.0	2.8	1.7	0.9	0.5	0.3	0.2
	Steel	tnCO2/tn	tonnes produced	Scope 1,2	-17%	-37%	-58%	-76%	-91%	-97%	1.77	1.47	1.11	0.74	0.42	0.17	0.05
	Cement (Construction materials)	tnCO2/tn	tonnes produced	Scope 1,2	-11%	-22%	-40%	-56%	-72%	-91%	0.62	0.55	0.49	0.38	0.27	0.17	0.05
	Aluminium (all)	tnCO2/tn	tonnes produced	Scope 1,2	-27%	-58%	-75%	-80%	-83%	-87%	8.6	6.3	3.7	2.1	1.7	1.5	1.1
	Aluminium primary	tnCO2/tn	tonnes produced	Scope 1,2	-28%	-57%	-74%	-78%	-80%	-81%	12.8	9.2	5.5	3.3	2.8	2.6	2.4
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2	-16%	-46%	-73%	-95%	-98%	-98%	0.0105	0.0089	0.0057	0.0028	0.0005	0.0002	0.0002
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2,3	-17%	-37%	-58%	-77%	-91%	-97%	1.21	1.00	0.76	0.50	0.28	0.11	0.03
	Coal mining	tnCO2/tn	tonnes produced	Scope 1,2	-18%	-40%	-56%	-72%	-84%	-90%	0.061	0.050	0.037	0.027	0.017	0.010	0.006
	Nickel	tnCO2/tn	tonnes produced	Scope 1,2	-23%	-44%	-59%	-68%	-76%	-81%	11.20	8.65	6.27	4.54	3.57	2.73	2.11
	Diversified metals & mining	Index		Scope 1,2	-24%	-51%	-70%	-81%	-87%	-91%							
	Diversified metals & mining	Index		Scope 3	-15%	-34%	-55%	-71%	-84%	-92%							
	Paper & packaging	tnCO2/tn	tonnes produced	Scope 1,2	-33%	-64%	-87%	-95%	-97%	-98%	0.8	0.5	0.3	0.1	0.0	0.0	0.0
Chemicals	Chemicals- ammonia	tnCO2/tn	tonnes produced	Scope 1	-7%	-21%	-44%	-63%	-79%	-94%	2.3	2.1	1.8	1.3	0.8	0.5	0.1
	Chemicals- methanol	tnCO2/tn	tonnes produced	Scope 1	-8%	-22%	-41%	-61%	-81%	-97%	2.1	1.9	1.6	1.2	0.8	0.4	0.1
	Chemicals- HVCs	tnCO2/tn	tonnes produced	Scope 1	-19%	-35%	-52%	-68%	-82%	-87%	0.98	0.80	0.63	0.48	0.32	0.18	0.13
	Diversified chemicals	Index		Scope 1,2	-27%	-50%	-68%	-80%	-89%	-92%							
	Diversified chemicals	Index		Scope 3	-13%	-32%	-49%	-67%	-81%	-89%							
Other	Real estate	tnCO2/m2	square meter	Scope 1,2	-33%	-59%	-82%	-95%	-99%	-100%	0.039	0.027	0.016	0.007	0.002	0.000	0.000
	Real estate	tnCO2/m2	square meter	Scope 1	-16%	-40%	-67%	-88%	-97%	-99%	0.015	0.012	0.009	0.005	0.002	0.000	0.000
	Semiconductors	Index		Scope 1,2	-30%	-62%	-86%	-98%	-99%	-99%							
	Hospitality	Index		Scope 1,2	-32%	-62%	-85%	-96%	-99%	-100%							
	Household & Personal Care	Index		Scope 1,2	-22%	-53%	-79%	-96%	-98%	-98%							
	Household & Personal Care	Index		Scope 3	-16%	-38%	-62%	-81%	-93%	-96%							
	Food & beverage	Index		Scope 1,2	-24%	-55%	-80%	-97%	-99%	-99%							
	Food & beverage	Index		Scope 3	-7%	-18%	-30%	-45%	-55%	-61%							
	Food retail	Index		Scope 1,2	-26%	-58%	-82%	-97%	-99%	-99%							
	Food retail	Index		Scope 3	-8%	-19%	-33%	-48%	-58%	-65%							
	Tobacco	Index		Scope 1,2	-25%	-56%	-81%	-97%	-99%	-99%							
	Tobacco	Index		Scope 3	-10%	-22%	-36%	-52%	-61%	-68%							
	Capital goods	Index		Scope 1,2	-25%	-56%	-81%	-96%	-98%	-99%							
	Capital goods	Index		Scope 3	-15%	-33%	-54%	-72%	-85%	-93%							

Source: Goldman Sachs Global Investment Research

Exhibit 159: Table summarizing our corporate carbon intensity pathways by industry for a global net zero by 2060 scenario (GS <2.0)

Sector	Industry	Carbon intensity measure	Activity indicator	Scopes coverage	% Reduction in carbon intensity vs 2019 base						Carbon intensity value (stated units)						
					2025	2030	2035	2040	2045	2050	2019	2025	2030	2035	2040	2045	2050
Energy	Oil & Gas Integrated producers	gCO2/MJ	energy sold	Scope 1,2,3	-7%	-14%	-25%	-40%	-58%	-75%	70.0	65.3	60.4	52.8	41.7	29.3	17.7
	Oil refiners	gCO2/MJ	energy sold	Scope 1,2,3	-6%	-15%	-29%	-48%	-68%	-83%	74.4	69.6	63.4	52.8	38.7	24.0	12.8
	Gas producers	gCO2/MJ	energy sold	Scope 1,2,3	-6%	-11%	-16%	-28%	-42%	-59%	63.2	59.3	56.3	52.8	45.4	36.4	25.7
	Electric Utilities	kgCO2/MWh	energy produced	Scope 1,2	-26%	-44%	-63%	-79%	-89%	-96%	504.3	370.7	280.2	186.7	103.6	53.6	21.4
Transportation	Airlines	gCO2/pkm	fleet	Scope 1,2	-11%	-23%	-37%	-53%	-64%	-74%	110.4	98.2	85.1	70.0	51.7	39.4	28.5
	Aerospace & defence	gCO2/pkm	aircrafts sold	Scope 1,2,3	-11%	-23%	-36%	-53%	-64%	-74%	67.6	60.2	52.3	43.0	31.8	24.2	17.5
	Automotive manufacturers - LDV	gCO2/km	vehicles sold	Scope 1,2,3	-11%	-29%	-55%	-76%	-88%	-96%	175.6	156.5	124.3	78.9	42.2	20.4	7.3
	Automotive manufacturers - HDV	gCO2/km	vehicles sold	Scope 1,2,3	-8%	-18%	-36%	-68%	-94%	-97%	631.3	580.8	516.1	406.1	202.0	36.1	17.5
	Maritime Shipping	gCO2/tkm	fleet	Scope 1,2	-17%	-34%	-49%	-63%	-80%	-89%	6.9	5.7	4.6	3.5	2.6	1.4	0.7
	Logistics & Shipping	Index		Scope 1,2,3	-13%	-27%	-42%	-59%	-71%	-81%							
Basic materials	Copper	tnCO2/tn	tonnes refined	Scope 1,2	-22%	-40%	-58%	-75%	-86%	-93%	4.0	3.1	2.4	1.7	1.0	0.5	0.3
	Steel	tnCO2/tn	tonnes produced	Scope 1,2	-10%	-24%	-42%	-58%	-72%	-85%	1.77	1.59	1.35	1.04	0.74	0.50	0.27
	Cement (Construction materials)	tnCO2/tn	tonnes produced	Scope 1,2	-10%	-19%	-27%	-42%	-57%	-73%	0.62	0.56	0.51	0.45	0.36	0.27	0.17
	Aluminium (all)	tnCO2/tn	tonnes produced	Scope 1,2	-21%	-39%	-56%	-70%	-78%	-83%	8.6	6.8	5.2	3.8	2.6	1.9	1.5
	Aluminium primary	tnCO2/tn	tonnes produced	Scope 1,2	-22%	-39%	-55%	-68%	-76%	-80%	12.8	10.0	7.9	5.8	4.1	3.1	2.6
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2	-7%	-17%	-40%	-61%	-78%	-88%	0.0105	0.0098	0.0087	0.0063	0.0041	0.0023	0.0012
	Iron ore	tnCO2/tn	tonnes produced	Scope 1,2,3	-10%	-24%	-42%	-58%	-72%	-85%	1.21	1.09	0.92	0.71	0.50	0.34	0.19
	Coal mining	tnCO2/tn	tonnes produced	Scope 1,2	-16%	-34%	-50%	-68%	-81%	-89%	0.061	0.051	0.040	0.030	0.020	0.011	0.006
	Nickel	tnCO2/tn	tonnes produced	Scope 1,2	-17%	-30%	-44%	-58%	-70%	-79%	11.20	9.34	7.81	6.25	4.71	3.34	2.35
	Diversified metals & mining	Index		Scope 1,2	-18%	-35%	-53%	-69%	-81%	-87%							
	Diversified metals & mining	Index		Scope 3	-9%	-21%	-37%	-53%	-67%	-79%							
	Paper & packaging	tnCO2/tn	tonnes produced	Scope 1,2	-22%	-39%	-58%	-75%	-86%	-93%	0.8	0.6	0.5	0.3	0.2	0.1	0.1
Chemicals	Chemicals- ammonia	tnCO2/tn	tonnes produced	Scope 1	-3%	-9%	-22%	-40%	-53%	-64%	2.3	2.2	2.1	1.8	1.4	1.1	0.8
	Chemicals- methanol	tnCO2/tn	tonnes produced	Scope 1	-7%	-16%	-28%	-42%	-58%	-74%	2.1	1.9	1.8	1.5	1.2	0.9	0.5
	Chemicals- HVCs	tnCO2/tn	tonnes produced	Scope 1	-11%	-23%	-35%	-47%	-60%	-71%	0.98	0.87	0.75	0.63	0.51	0.39	0.29
	Diversified chemicals	Index		Scope 1,2	-17%	-32%	-46%	-60%	-72%	-81%							
	Diversified chemicals	Index		Scope 3	-13%	-31%	-47%	-65%	-80%	-89%							
Other	Real estate	tnCO2/m2	square meter	Scope 1,2	-26%	-44%	-60%	-77%	-89%	-96%	0.039	0.029	0.022	0.016	0.009	0.004	0.001
	Real estate	tnCO2/m2	square meter	Scope 1	-15%	-33%	-54%	-75%	-92%	-98%	0.015	0.013	0.010	0.007	0.004	0.001	0.000
	Semiconductors	Index		Scope 1,2	-19%	-35%	-55%	-73%	-86%	-93%							
	Hospitality	Index		Scope 1,2	-24%	-42%	-61%	-79%	-90%	-96%							
	Household & Personal Care	Index		Scope 1,2	-12%	-25%	-47%	-66%	-82%	-90%							
	Household & Personal Care	Index		Scope 3	-14%	-30%	-48%	-67%	-83%	-91%							
	Food & beverage	Index		Scope 1,2	-14%	-27%	-48%	-67%	-82%	-91%							
	Food & beverage	Index		Scope 3	-6%	-13%	-24%	-37%	-49%	-57%							
	Food retail	Index		Scope 1,2	-16%	-30%	-51%	-70%	-84%	-92%							
	Food retail	Index		Scope 3	-5%	-12%	-23%	-36%	-49%	-59%							
	Tobacco	Index		Scope 1,2	-15%	-28%	-50%	-69%	-83%	-91%							
	Tobacco	Index		Scope 3	-9%	-17%	-29%	-41%	-53%	-62%							
	Capital goods	Index		Scope 1,2	-15%	-29%	-51%	-69%	-83%	-92%							
	Capital goods	Index		Scope 3	-9%	-21%	-37%	-53%	-68%	-80%							

Source: Goldman Sachs Global Investment Research

Disclosure Appendix

Reg AC

We, Michele Della Vigna, CFA and Zoe Stavrinou, hereby certify that all of the views expressed in this report accurately reflect our personal views about the subject company or companies and its or their securities. We also certify that no part of our compensation was, is or will be, directly or indirectly, related to the specific recommendations or views expressed in this report.

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