Note: The following is a redacted version of the original report published November 27, 2023 [34 pgs].

Goldman Sachs

EQUITY RESEARCH | November 27, 2023 | 5:22AM CET

Carbonomics

Updated cost curve shows diverging trends between power and transport

We update our Carbonomics cost curve to reflect innovation, supply chain changes, commodity prices and higher interest rates through >100 different applications of de-carbonization technologies across all key emitting sectors globally and arrive at five key conclusions:

1) Low cost de-carbonization becomes more expensive, driven by the increase in LCOE of renewable power generation by c. 11% yoy and 42% vs. the trough observed in 2020, on the back of higher interest rates and cost inflation in wind power;

2) High cost de-carbonization, dominated by transport, gets 30% cheaper as batteries resume their deflationary trend. Lower raw material costs and simpler cell-to-vehicle integration bring the target 3-year payback in sight by mid-decade;

3) The impact of higher interest rates on the overall cost curve is actually limited, although it is material for the carbon abatement cost in the renewable power sector (driving 25% of total increase);

4) Policy remains supportive and we identify $500 bn of project announcements driven by the IRA. Yet political uncertainty and delays in some key specifications may lead to project delays;

5) Bio-energy continues to grow its role with RNG and SAF, gaining momentum in heavy transport, industry and buildings.

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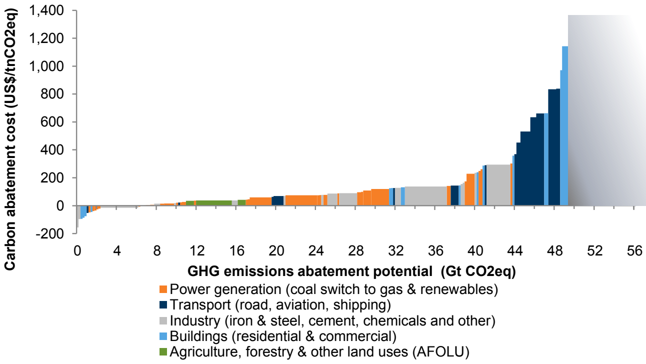
Carbonomics in 12 charts

Exhibit 1: Our Carbonomics cost curve models the cost of net zero carbon across >100 de-carbonization technologies...

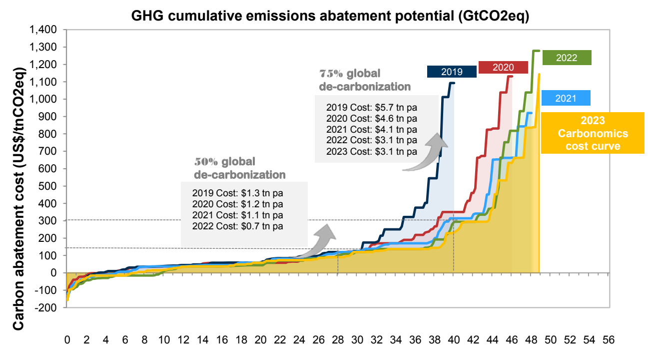
Carbonomics cost curve of decarbonisation for anthropogenic GHG emissions (GtCO2eq)



Source: Goldman Sachs Global Investment Research

Exhibit 2: ...showing a consistent flattening of the cost curve since its 2019 inception.

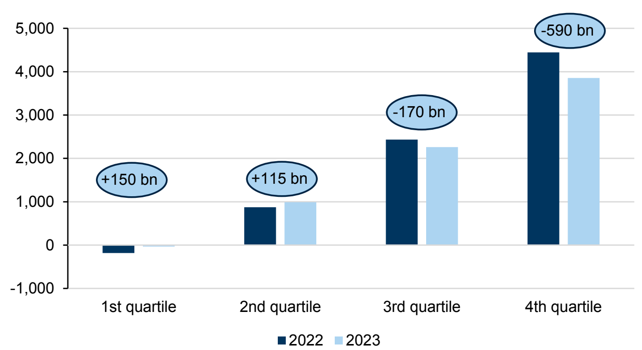
2023 vs. 2022/2021/2020/2019 Carbonomics cost curve for anthropogenic GHG emissions - comparison of the cumulative area under each curve, based on current technologies, assuming economies of scale for technologies in pilot



Source: Goldman Sachs Global Investment Research

Exhibit 3: This year we see an increase in costs in the lower half of the cost curve, driven mostly by cost inflation and higher interest rates...

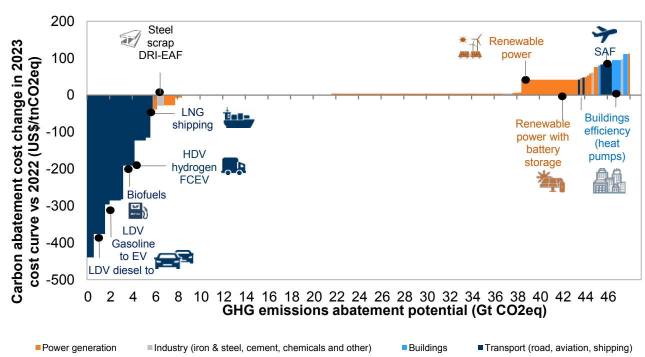
2023 Carbonomics cost curve for anthropogenic GHG emissions - comparison of the annual abatement cost for each quartile



Source: Goldman Sachs Global Investment Research

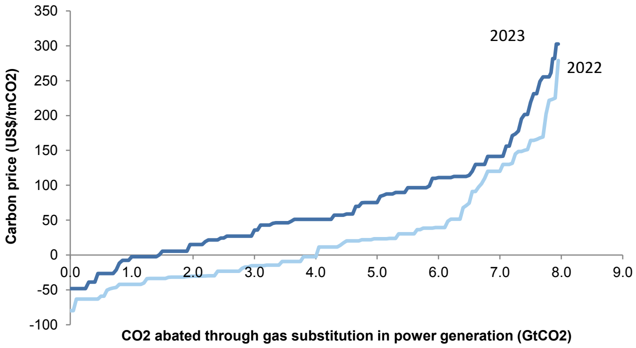
Exhibit 4: ...while the high end of the cost curve benefits from a material improvement in battery costs for transport.

Carbon abatement cost change in the 2023 Carbonomics cost curve vs 2022 by technology (US$/tnCO2)



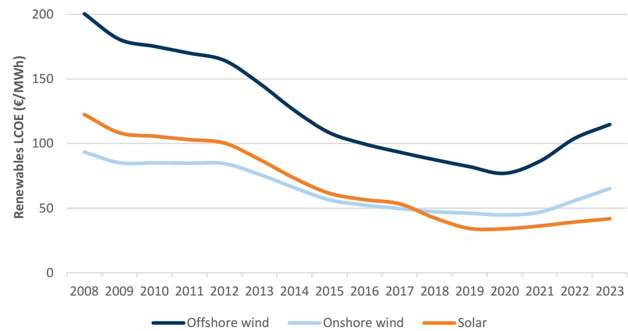
Source: Goldman Sachs Global Investment Research

Exhibit 5: In power generation, this year's cost curve shows a material increase...
2023 vs 2022 Power generation switch from natural gas to renewables (and storage) de-carbonization cost curve



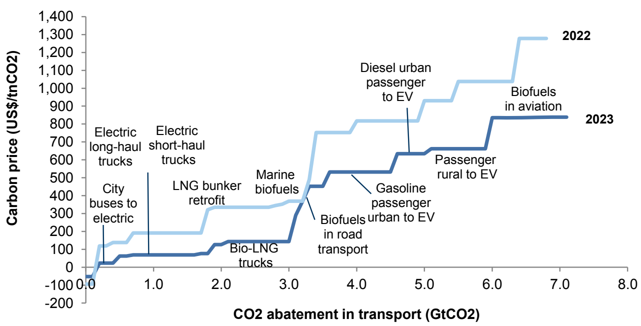
Source: Goldman Sachs Global Investment Research

Exhibit 6: ...as renewable power technologies fully reflect the impact of cost inflation and higher interest rates.
LCOE for solar PV, wind onshore and wind offshore for select regions in Europe (EUR/MWh)



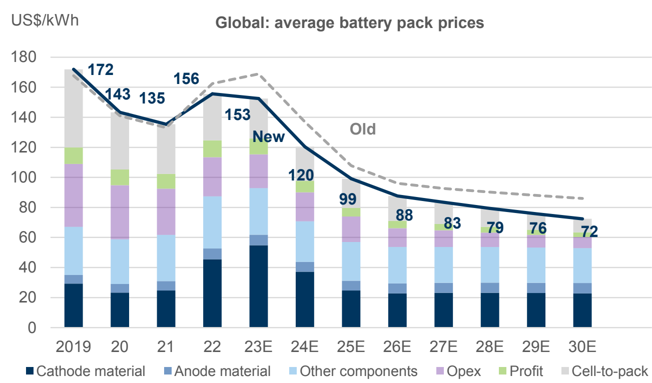
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 7: Transport instead enjoys a major improvement in the cost curve...
2023 vs 2022 Carbon abatement cost curve for anthropogenic GHG emissions in transport sector, based on current technologies and associated costs



Source: Goldman Sachs Global Investment Research

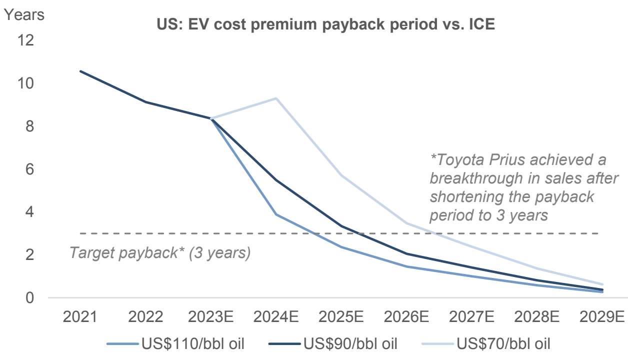
Exhibit 8: ...as battery costs return to a de-flationary trend after the cost increases during the Covid period...
Global average battery pack prices



Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Global Investment Research

Exhibit 9: ...implying that the three year payback period is within reach by mid-decade.

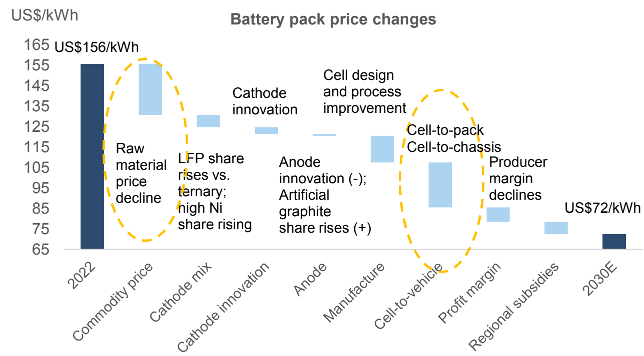
EV cost premium payback period vs ICE in the US



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 10: The main drivers for declines in battery prices include lower raw material costs and simpler cell-to-vehicle integration

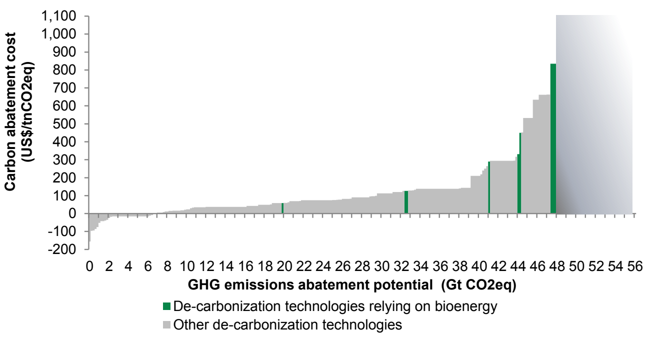
Battery pack price changes ($/KWh)



Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Global Investment Research

Exhibit 11: Bio-energy addresses some of the harder-to-abate sectors in transport and buildings...

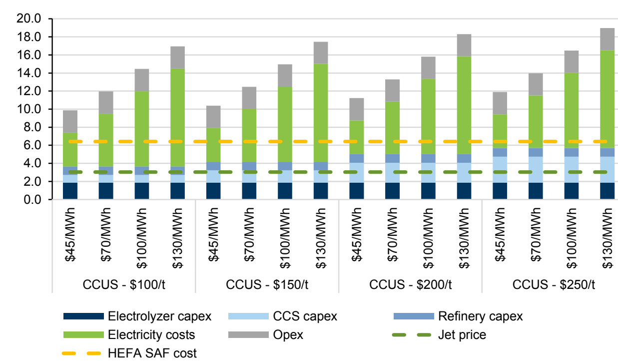
2023 carbon abatement cost curve for anthropogenic GHG emissions, with green indicating bioenergy-reliant technologies



Source: Goldman Sachs Global Investment Research

Exhibit 12: ...and remains more competitive than e-fuels, especially in aviation

Levelized production cost of e-SAF 2023E, $/gallon



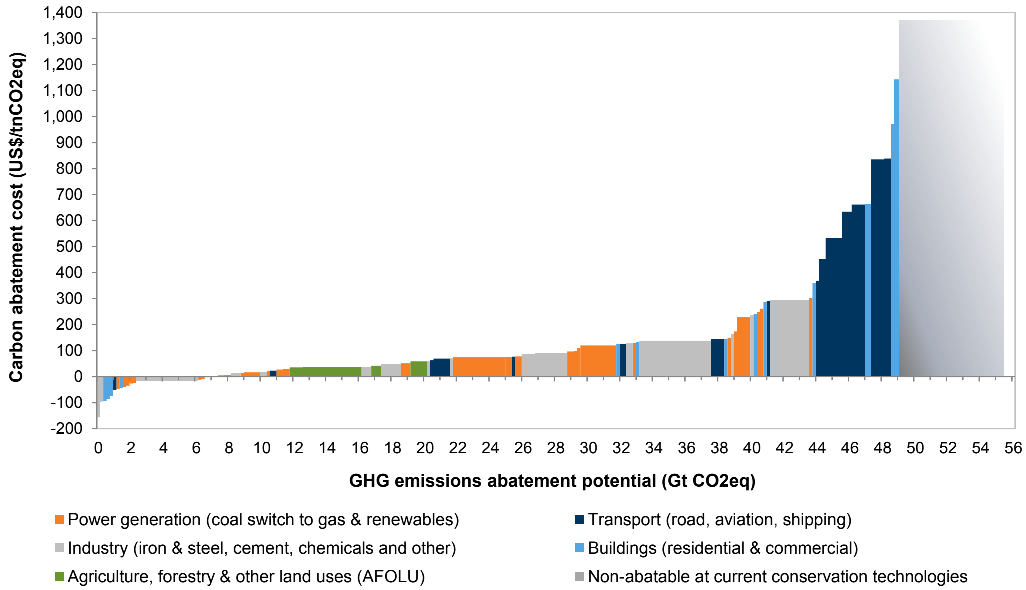
Source: Goldman Sachs Global Investment Research

Lower energy prices, clean tech inflation and higher interest rates impact the Carbonomics cost curve, with gas-substituting technologies moving higher on the cost curve, whilst battery cost deflation moves the cost curve lower

In our first deep-dive de-carbonization report, *Carbonomics: The future of energy in the Age of Climate Change* in 2019, we introduced our inaugural estimate of the carbon abatement cost curve. The **Carbonomics cost curve shows the reduction potential for anthropogenic GHG emissions relative to the latest reported global anthropogenic GHG emissions**. It comprises de-carbonization technologies that are currently available at commercial scale (commercial operation & development), presenting the findings at the current costs associated with each technology's adoption. We include conservation technologies and process specific sequestration technologies (process specific carbon capture) across all key emission-contributing industries globally: power generation, industry and industrial waste, transport, buildings and agriculture. **In this report, we update our Carbonomics cost curve of de-carbonization for the fifth consecutive year**, **encompassing >100 different applications of GHG conservation technologies across all key emitting sectors globally**. The newly updated de-carbonization cost curve is shown in Exhibit 13 and the transformation of the 2023 Carbonomics cost curve and the comparison to the 2022/2021/2020/2019 comparable Carbonomics cost curves is shown in Exhibit 15.

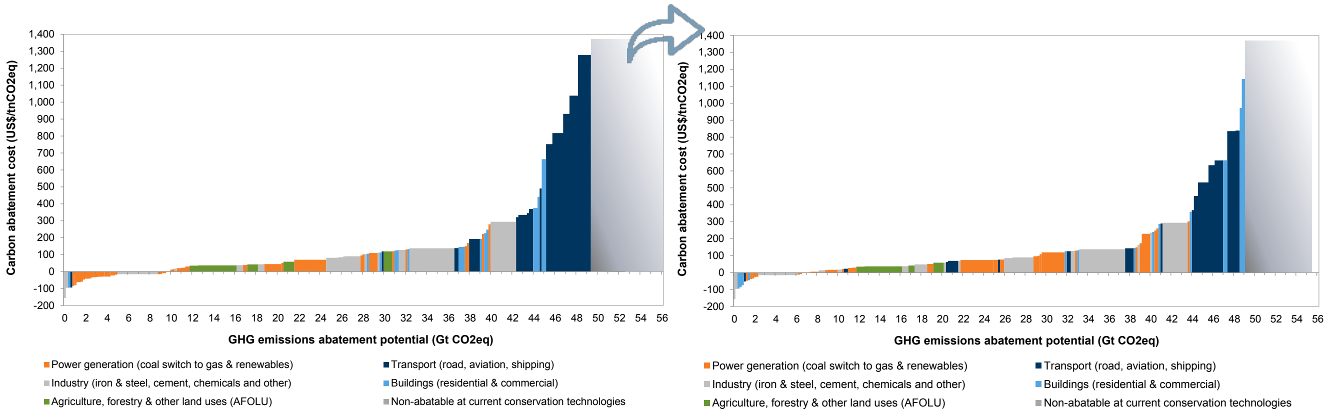
Exhibit 13: In this report, we update our Carbonomics cost curve of de-carbonization for the fifth consecutive year, encompassing >100 different applications of GHG conservation technologies across all key emitting sectors globally. A combination of lower energy prices, clean tech inflation, higher interest rates and lower battery prices impact the carbon abatement cost of technologies constituting our cost curve

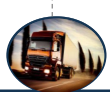
2023 carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase



Source: Goldman Sachs Global Investment Research

Exhibit 14: Summary of key technologies considered in the construction of the carbonomics cost curve





TRANSPORTATION

De-carbonization technologies

- **Aviation:** The switch to a more efficient aircraft model is considered a viable option for partial de-carbonization in the near-term. Sustainable aviation fuels (SAFs) remain the sole commercially available de-carbonization route longer term.
- **Shipping:** LNG ships a technological option for ships meeting a threshold size, marine biofuels another viable technology, with clean ammonia ships the key potential de-carbonization technology longer-term.
- **Road short-haul transport:** EVs the key technology for road passenger transport, with a small proportion of de-carbonization achieved through road biofuels for places with constrained electrification infrastructure.
- **Road long-haul transport:** Electrification of short and medium haul trucks and buses a viable option. Hydrogen FCEVs the most promising de-carbonization option for long-haul heavy truck routes and forklifts. Switch from diesel trucks to Bio-LNG trucks
- **Rail:** Electrification and hydrogen the key technologies considered with FC trains likely to be key for long-haul heavy rail.

POWER GENERATION

De-carbonization technologies

- **Switch from coal to gas:** Natural gas a key transition fuel for the near term, particularly in heavily coal-reliant power generation systems globally. Biogas and clean hydrogen co-firing in power plants is another possible technology considered longer-term.
- **Switch to renewables:** The ultimate de-carbonization route for power generation, which could unlock the full de-carbonizaation potential in the presence of energy storage.
- **Energy storage**: Batteries a key technology for intraday storage with clean hydrogen the ultimate solution for seasonal storage enabling the full uptake of renewables in the power generation system. both have been considered and added in our cost curve.
- **Carbon capture:** Carbon capture for natural gas and coal plants a de-carbonization technology that can be particularly useful in regions with young asset life of plants avoiding stranded assets.
- **Nuclear:** Another viable technology present in our Carbonomics cost curve.
- **Renewable natural gas:** Using biogas and adding biomethane to th grid

AFOLU

De-carbonization technologies

- **Improved land (cropland, grazing land) and livestock management practices**: Improved cropland, grazing land and livestock management practices can help to optimize resource use for the agriculture sector.
- **Precision agriculture**: The use of technology to optimize crop yields, minimize excess use of nutrients and pesticides could all potentially contribute to reduced raw material and energy needs for the sector.
- Reduction of deforestation, forest degradation, conversion of savvanas and natural grasslands, conversion, draining and burning of peatlands.

BUILDINGS

De-carbonization technologies

- **Heating fuel switch**: Hydrogen, biogas and clean power-run heat pumps are the two key technologies currently commercially available for de-carbonization of buildings. We consider both in our cost curve, both for new developments and retrofits, for commercial and residential buildings.
- **Efficiency**: Efficiency improvements can reduce the energy needs for heating and electricity and are thus viable options for de-carbonization. Switch to LED lighting, addition of cavity wall insulation, use of thermostats and highest efficiency HVAC systems can all contribute to efficiency improvements.

INDUSTRY & WASTE

De-carbonization technologies

- **Industrial combustion/ heating:** Across major emitting industrial sectors, a considerable amount of emissions are associated with the use of energy, primarily through industrial combustion (heat) processes. Switch from coal, natural gas to biomass, biogas, clean hydrogen or electrification (in cases of low temperature heat) are the key technologies in de-carbonizing energy-related emissions.
- **Cement**: Process emissions (c60%) associated with the materials involved such as clinker. Reducing the ratio of clinker to cement a key technology, along with CCUS.
- **Iron & Steel**: The switch from BF-BOF process to natural gas or hydrogen based DIR-EAF a possible near term de-carbonization option. Scrap DRI-EAF and circular economy also have a role to play. CCS for younger plants has also been considered.
- **Petrochemicals:** Clean hydrogen could aid the de-carbonization of process/raw material-related emissions. This can be in the form of blue (CCS), green electrolytic hydrogen or biogas. Circular economy and other efficiency gains also important.

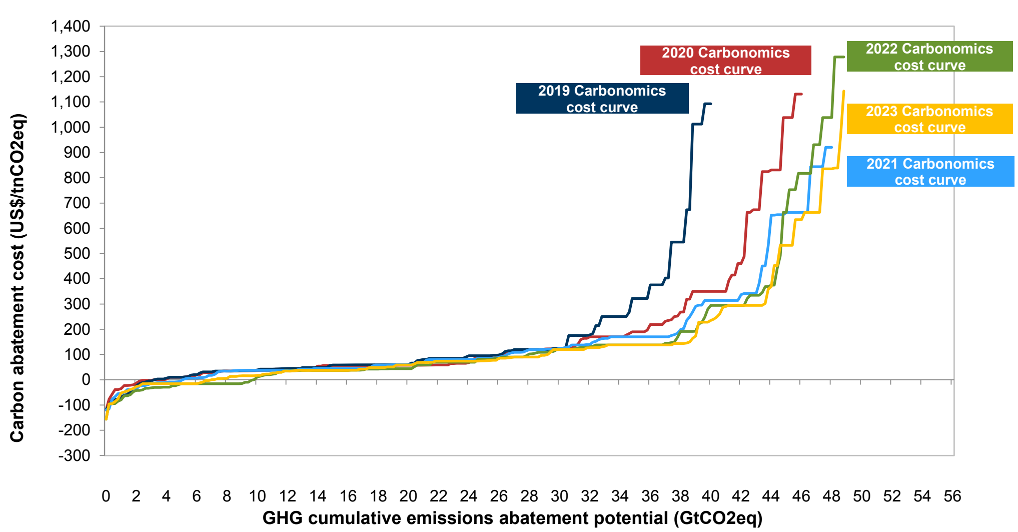
Source: Goldman Sachs Global Investment Research

The Carbonomics cost curve is updated for the fifth consecutive year, with lower energy prices, clean tech inflation and higher interest rates moving the Carbonomics cost curve higher, whilst deflation in battery prices moves the cost curve lower

Exhibit 15 shows the comparison between the 2023 Carbonomics cost curve and the 2022/2021/20/19 comparable cost curves. As shown in the exhibit, the 2023 Carbonomics cost curve this year shows a mix of technologies moving lower and higher on the cost curve relative to last year. Overall, the lower end of the cost curve moved higher whilst the higher end of the cost curve has moved notably lower. This is driven by contributions from **(a) lower long-term energy prices** (natural gas, coal, power, oil products) post 2022 peaks **increasing the implied cost of the switch to cleaner alternative technologies** and **(b) clean tech cost inflation** for existing technologies (such as equipment costs in renewable power generation, especially in offshore wind), (c) **higher interest rates** increasing cost of capital for existing technologies (primarily, in power generation), (d) **battery cost deflation** and **EV economies of scale** driving down EV costs and decreasing the implied cost of the switch to EVs from ICEs. **Overall, clean technologies at the low cost end of de-carbonization, dominated by renewable power, become more expensive yoy, driven by lower energy prices, higher interest rates and cost inflation. At the same time, technologies at the high cost end of de-carbonization, dominated by transportation move lower on the cost curve as batteries resume their deflationary trend. Lower raw material costs and simpler cell-to-vehicle integration bring the target 3-yr payback in sight by mid-decade.** The impact described above is summarized in Exhibit 16 below, which shows the change in carbon abatement cost for technologies in the 2023 Carbonomics cost curve vs last year's cost curve.

Exhibit 15: We update our Carbonomics cost curve for the fifth consecutive year, indicating a move higher for the bottom end of the curve and a move lower for the upper end of the cost curve relative to last year

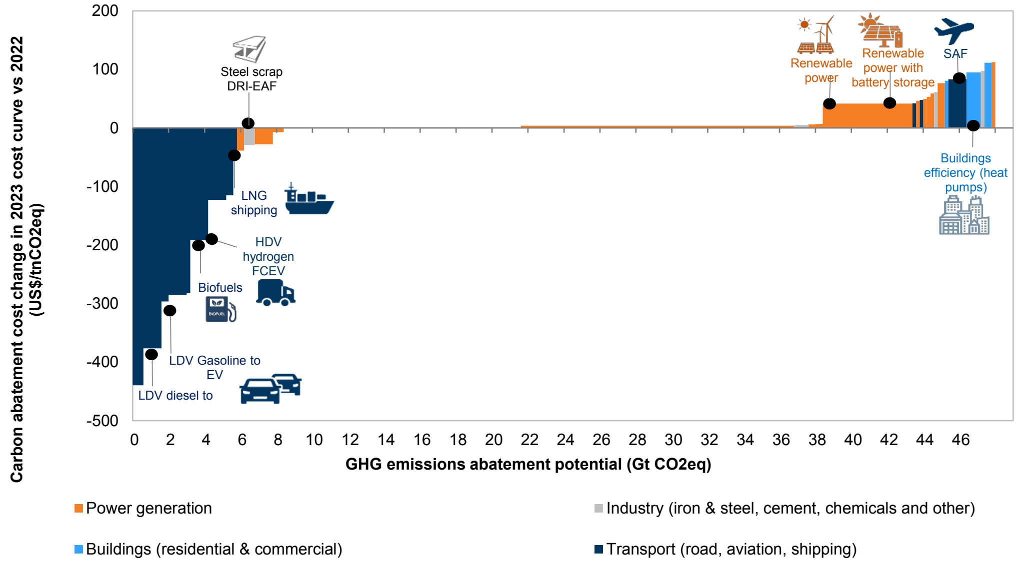
2023 vs 2022/2021/20/19 comparable carbon abatement cost curves for anthropogenic GHG emissions, based on current technologies and costs, assuming economies of scale for technologies in pilot phase



Source: Goldman Sachs Global Investment Research

Exhibit 16: Overall, clean technologies at the low cost end of de-carbonization, dominated by renewable power, become more expensive yoy, driven by lower energy prices, higher interest rates and cost inflation. At the same time, technologies at the high cost end of de-carbonization, dominated by transportation, move lower on the cost curve as batteries resume their deflationary trend. Lower raw material costs and simpler cell-to-vehicle integration bring the target 3-yr payback in sight by mid-decade

Carbon abatement cost change in the 2023 Carbonomics cost curve vs 2022 by technology (US$/tnCO2)



Source: Goldman Sachs Global Investment Research

Evolution of the cost curve with lower end impacted by lower commodity prices, inflation and interest rates, while higher end benefits from lower battery prices

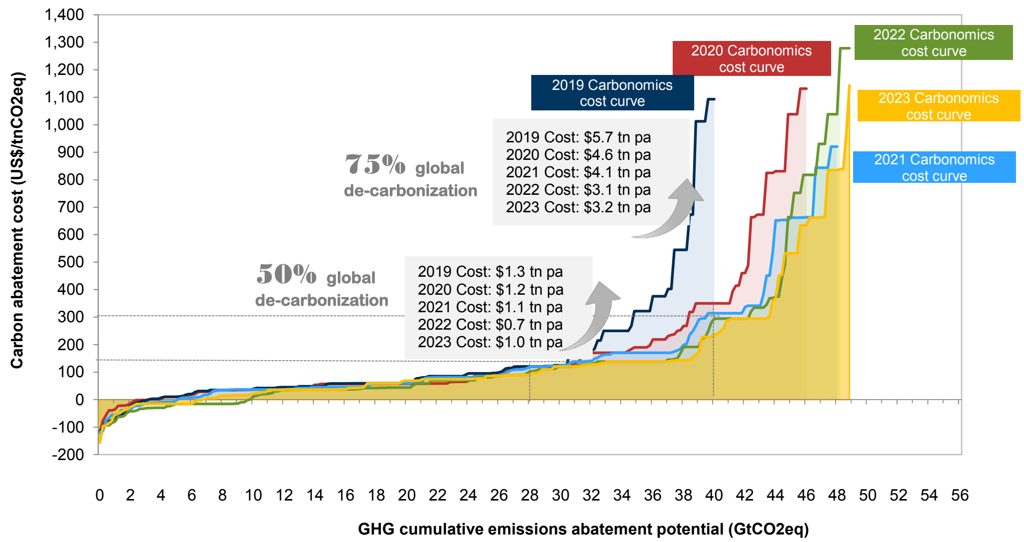
The evolution of the Carbonomics cost curve results, on our estimates, in higher costs to reach 75% de-carbonization but a decrease in the cost of achieving the remaining 25% de-carbonization

The transformation of the cost curve brings with it a **change in the global annual cost to achieve de-carbonization** from existing, large-scale commercially available technologies. As outlined in the previous section of this report, a combination of lower energy prices and higher clean tech costs (inflation) has a negative impact on the Carbonomics cost curve, while lower battery prices in EVs have a positive impact on overall cost. This results in the 2023 Carbonomics cost curve getting flatter with the lower end of the curve moving higher but the higher end moving lower.

As shown in Exhibit 17, the initial c.50% of global anthropogenic GHG emissions, what we classify as **'low-cost de-carbonization'**, can be now abated at an **annual cost that is $0.3 trn pa higher**, at c.$1.0 trn pa based on the 2023 cost curve vs. $0.7 trn pa based on 2022, largely driven by lower energy prices (c.50%), cost inflation (c.30%) and higher interest rates (c.20%) impacting primarily such sectors as power generation. The cost of achieving 75% of global anthropogenic GHG emissions is at c.$3.2 tn pa in 2023, c.$0.1 tn pa higher than $3.1 tn in 2022, with lower battery prices being offset by clean tech inflation, higher interest rates and lower energy prices. At the same time, as we move towards 100% de-carbonization, we enter into the 'high-cost de-carbonization' spectrum, with the 2023 Carbonomics cost curve resulting in **significant cost savings — c.$0.6tn pa —** to abate the last 25% of emissions, with lower battery prices in EVs driving the savings for transportation sector.

Exhibit 17: The evolution of the de-carbonization cost curve this year results in flat yoy costs for 75% de-carbonization...

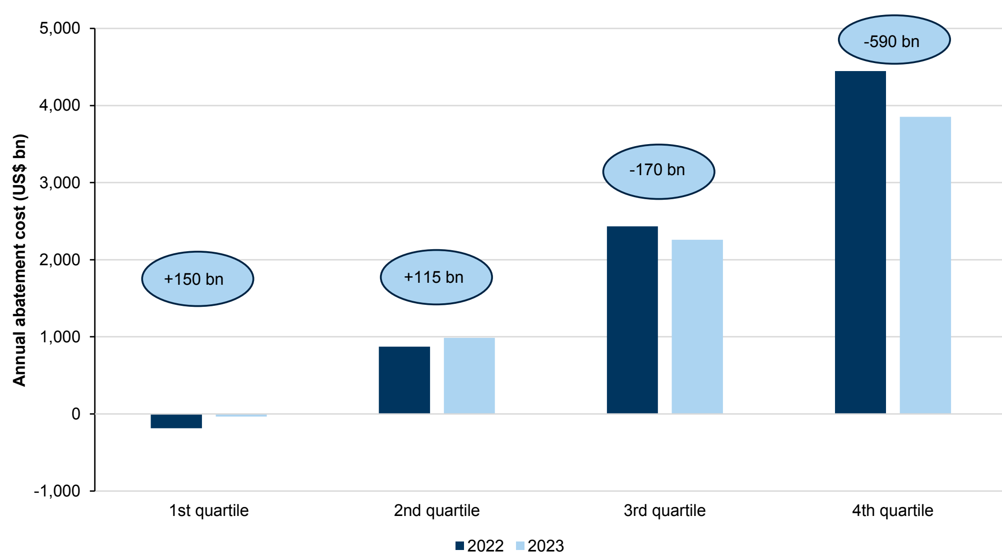
2023 vs. 2022/2021/2020/2019 Carbonomics cost curve for anthropogenic GHG emissions - comparison of the cumulative area under each curve, based on current technologies, assuming economies of scale for technologies in pilot



Source: Goldman Sachs Global Investment Research

Exhibit 18: ...but a significant decrease for the remaining 25% of emissions

2023 Carbonomics cost curve for anthropogenic GHG emissions - comparison of the annual abatement cost for each quartile



Source: Goldman Sachs Global Investment Research

Power generation: lower gas prices, cost inflation and higher interest rates shift cost curve to the left

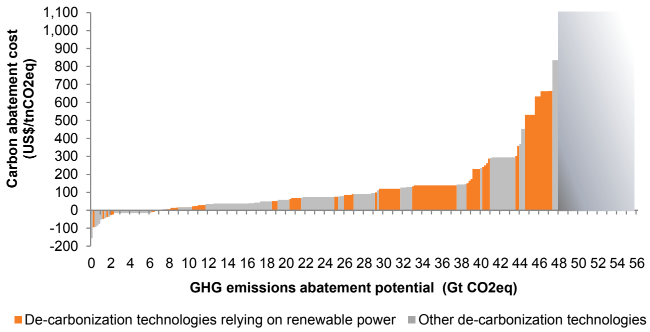
Renewable power has transformed the landscape of the energy industry and represents one of the most economically attractive opportunities in our de-carbonization cost curve. We estimate that c.35% of the de-carbonization of global anthropogenic GHG emissions is reliant on access to clean power generation, including electrification of transport and various industrial processes, electricity used for heating and more. This year, we see **power generation** switch from natural gas to renewables (and storage) **de-carbonization cost curve moving significantly to the left** on cost inflation and higher funding costs in renewable power leading to an increase in Levelized Cost of Energy (LCOE) for solar and wind yoy, and lower gas prices, primarily in Europe and Asia, at the same time:

- The weighted average cost of capital (WACC) for new renewable power projects increased to 6-6.5% in 2023 from 4-4.5% in 2022, driven by the increase in risk-free rates in Europe in the US;
- Higher equipment costs in renewable energy, though cost inflation has been most prominent in offshore wind, while in solar module prices have been decreasing. Overall, higher interest rates and cost inflation led to the increase in LCOE of renewable power generation (solar, wind) in Europe by c. 11% yoy and c.42% vs the trough observed in 2020;
- Increased LCOE in other renewable generation: primarily, hydro (largely owing to the development of more challenging and remote sites) and nuclear power;
- Gas prices eased from 2022 peaks as supply concerns retreated, leading to c.30% decline in the back end of TTF forward curve, increasing competitiveness of gas versus renewables.

Overall, on our estimates, these factors contributed to the increase in the weighted-average carbon abatement cost in power generation by c.3 times in 2023 yoy — from \$20/t in 2022 to \$66/t in 2023, with c.35% of the increase driven by cost inflation, 40% by lower gas prices and c.25% by higher interest rates, on our estimates. At the same time, CO2 cost for power generation remains the lowest on the Carbonomics cost curve.

Exhibit 19: Access to low-carbon power more broadly is vital for the de-carbonization of c.35% of the current global anthropogenic GHG emissions across sectors (such as electrification of transport, industry, buildings)

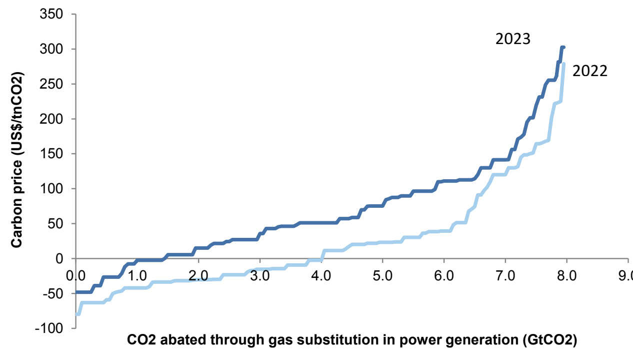
2023 conservation carbon abatement cost curve for anthropogenic GHG emissions, with orange indicating renewable power-reliant technologies



Source: Goldman Sachs Global Investment Research

Exhibit 20: We see power generation switch from natural gas to renewables (and storage) de-carbonization cost curve moving significantly to the left on cost inflation and higher funding costs in renewables and lower gas prices

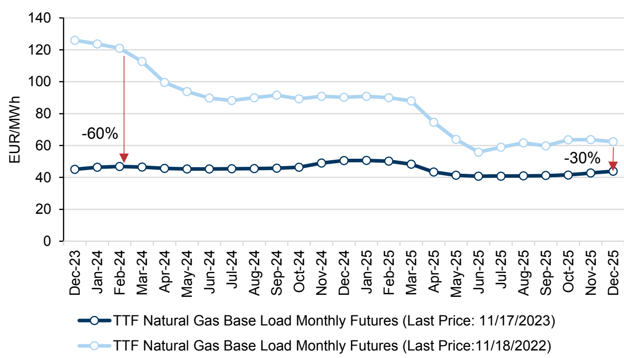
Power generation switch from natural gas to renewables (and storage) de-carbonization cost curve 2023 vs 2022



Source: Goldman Sachs Global Investment Research

Exhibit 21: Back end of TTF forward curve decreased by c.30% in the last year

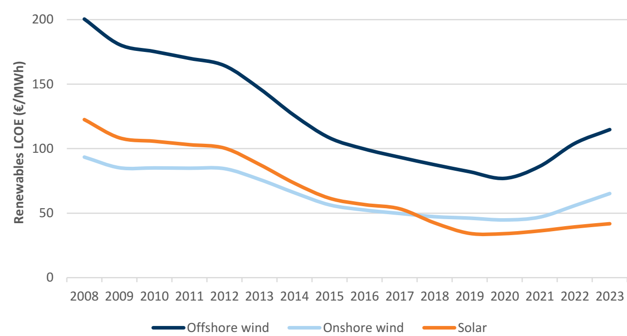
TTF forward curve Nov'23 vs Nov'22, EUR/MWh



Source: Bloomberg

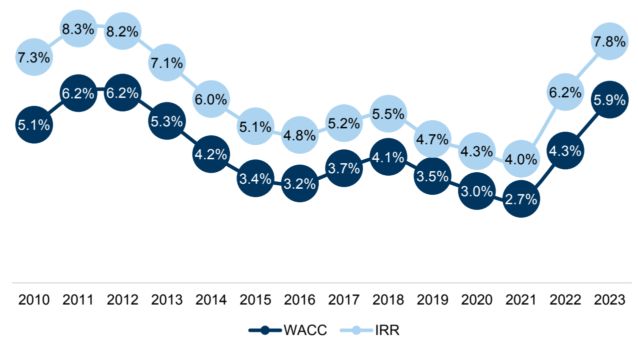
Exhibit 22: Renewable power LCOEs have increased across technologies...

LCOE for solar PV, wind onshore and wind offshore for select regions in Europe (EUR/MWh)



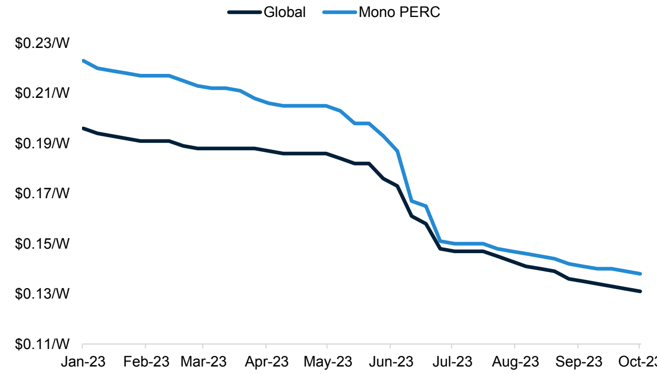
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 23: ...on the back of increased financing costs and costs inflation
RES WACC and IRR in Europe,%



Source: IRENA, Goldman Sachs Global Investment Research

Exhibit 24: Cost inflation in renewables has been most prominent in offshore wind, while solar module prices have come down YTD
Module prices (US$/W)

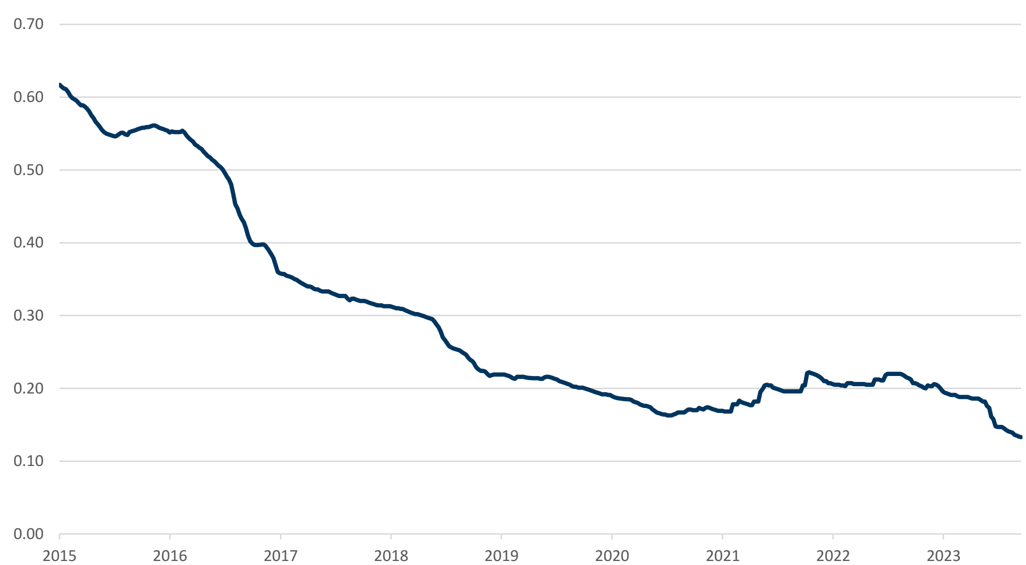


Source: PVinsights, Goldman Sachs Global Investment Research

Cost inflation and higher cost of capital most prominent in offshore wind, while solar still offers the most attractive economics

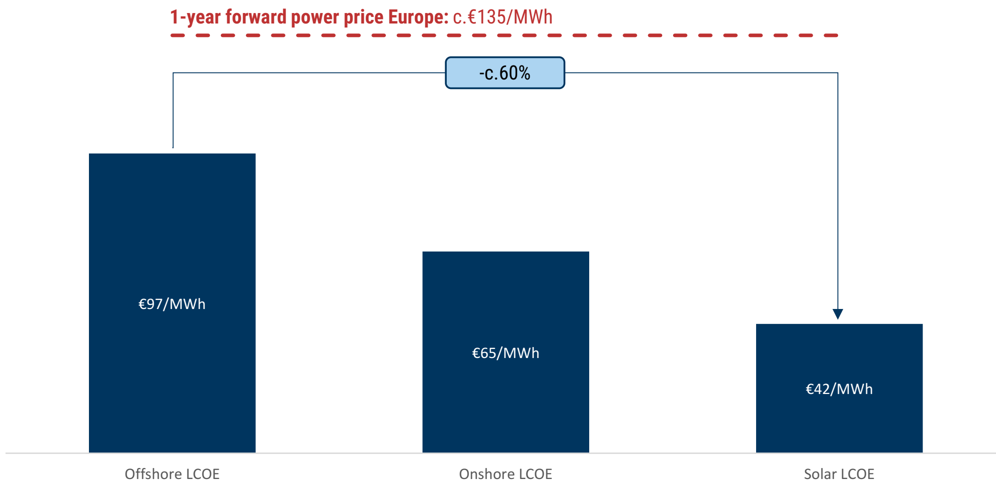
Solar power generation has been relatively less prone to cost inflation with solar module prices declining significantly since last summer. The ongoing decline in equipment costs, and somewhat stickier PPA prices, suggest better economics for solar: we estimate the solar LCOE at c.€40/MWh in Europe, which is less than half the cost of offshore wind, as a reference, and nearly one quarter of the current forward curves for 2024. Better relative competitiveness against other renewable technologies, and its high deflationary impact in the context of current power prices (especially in Europe), suggest that solar could gain incremental market share from other technologies.

Exhibit 25: Solar module prices have declined significantly since last summer
Global average solar module cost ($/W)



Source: PV Insights

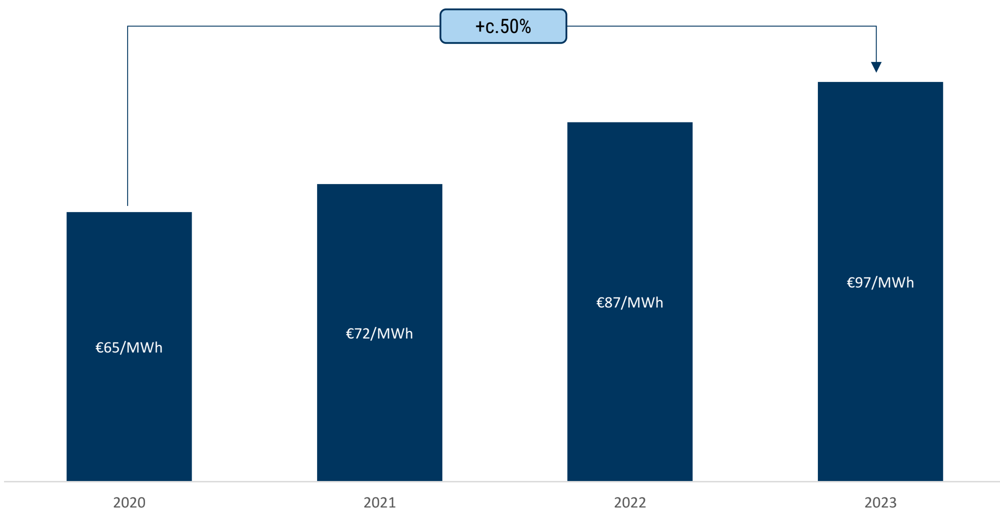
Exhibit 26: Solar is currently significantly cheaper than wind
RES LCOE and Germany 1-year forward power price (€/MWh)



Source: Bloomberg, Goldman Sachs Global Investment Research

Meanwhile, the steep cost inflation has been most prominent in **offshore wind** (especially in the US, owing to an under-developed supply chain) which could precede a setback to growth and a slowdown in future developments, according to our European utilities team. Examples of this include the recent UK auction (which attracted no participants), the cancellation of the Rhode Island tender and of projects by Vattenfall (UK) and Iberdrola (Massachusetts), and by ongoing delays in New York. Since its inception in the late 1990s, the offshore wind industry has benefited from a major improvement in economics. In Europe, we estimate that between 2008 and 2020, the LCOE for offshore wind dropped by -65%, from c.€200/MWh to a trough of c.€65/MWh. Yet, following a steep, 20-year decline in costs, the more recent cost inflation of raw materials, and an unprecedented spike in funding costs, have led to a strong increase in offshore's levelized costs. We estimate that LCOE of offshore wind in Europe and the US increased by c.10% in 2023 yoy: in Europe — from €87/MWh in 2022 to €97/MWh in 2023, in the US — from $120/MWh in 2022 to $133/MWh in 2023, with the latest New York auction has seen most offshore developers asking for price revisions in a range of $140-190/MWh.

Exhibit 27: The cost of offshore wind has increased significantly since 2020
Europe Offshore wind LCOE evolution, 2020-23E (€/MWh)



Source: Goldman Sachs Global Investment Research

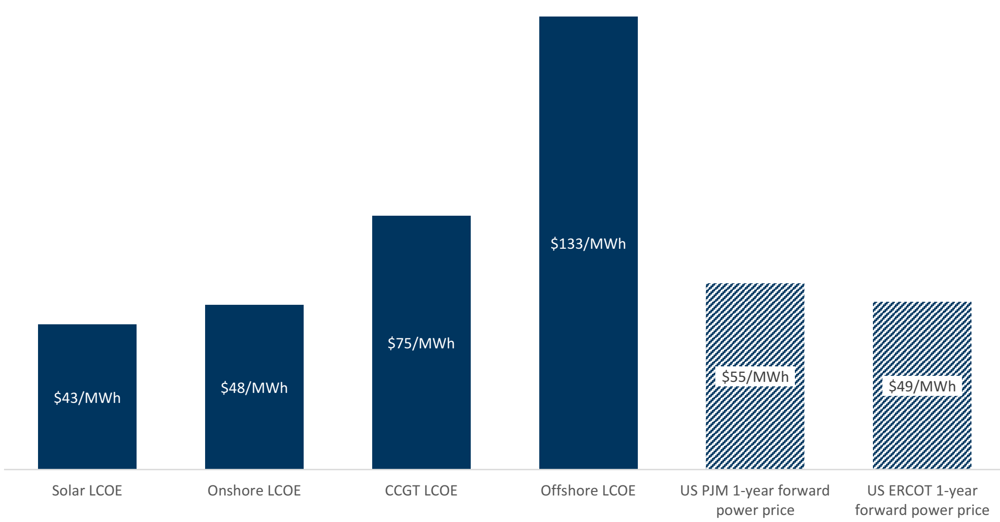
US offshore economics particularly under pressure

(i) Execution delays owing to permitting.

(ii) No full protection against cost inflation.

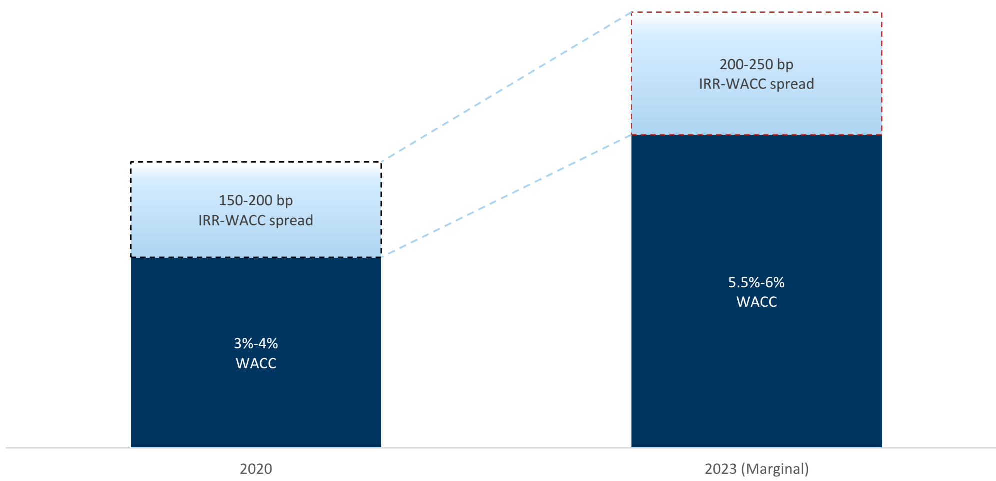
(iii) Harder supply chain bottlenecks.

Exhibit 28: In the US, offshore wind is a standout, from a cost perspective
US LCOE 2023E and 1-year forward power prices ($/MWh)



Source: Goldman Sachs Global Investment Research, SNL

Exhibit 29: Current marginal projects seem to imply a +c.50 bp IRR over WACC spread vs 2020
IRR breakdown: IRR-WACC spread and WACC (bp)



Source: Goldman Sachs Global Investment Research

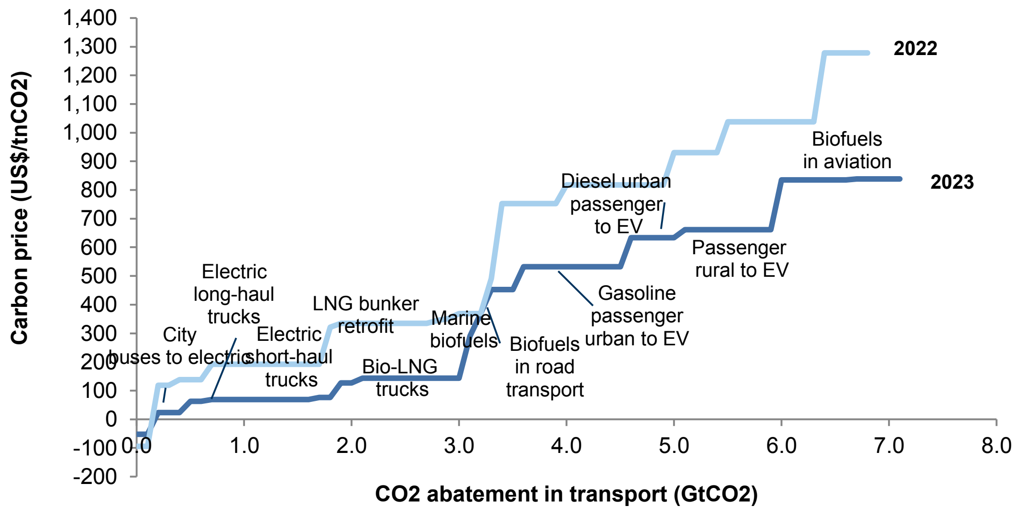
Transport: cost deflation and technological innovation

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.30% of the global final energy consumption and c.15% of the net GHG emissions. This year, we see the transportation de-carbonization cost curve shifting downwards significantly driven by cost deflation and technological innovation observed in EV batteries leading to the decrease in the carbon price of technologies dependent on EVs. At the same time with lower gasoline and jetfuel prices some technologies like SAF become relatively more expensive.

Overall, on our estimates, these factors contributed to the **decrease in the weighted-average carbon abatement cost in transport by 30% in 2023 yoy — from $600/tnCO2eq in 2022 to $422/tnCO2eq in 2023**, **with the decrease attributed to material deflation in battery costs partly being offset by lower jet fuel and gasoline prices on our estimates.**

Exhibit 30: Transportation de-carbonization cost curve shifting downwards significantly driven by cost deflation and technological innovation observed in EV batteries leading to the decrease in carbon price of technologies dependant on EVs. At the same time with lower gasoline and jetfuel prices some technologies like SAF become relatively more expensive.

2023 vs 2022 Carbon abatement cost curve for anthropogenic GHG emissions in transport sector, based on current technologies and associated costs



Source: Goldman Sachs Global Investment Research

Exhibit 31: Price assumptions used in the transport sector

Technology		New Price	Old Price	(%) change	Conservation de-carbonization pathways
Transport					
Biofuel	Marine biofuel ($/bl)	160	190	-16%	Marine biofuels from ULFSO
	ULFSO/Diesel marine ($/bl)	100	100	0%	
	Biodiesel/ethanol ($/bl)	160	225	-29%	Biofuels on road transport
	Gasoline price ($/bl)	95	115	-17%	
	Sustainable Aviation Fuel ($/bl)	350	320	9%	Biofuel blending aviation
	Kerosene/Jet fuel ($/bl)	115	130	-12%	
	Bio-LNG ($/gl)	3.9			Bio-LNG trucks
Electric Vehicle	Diesel US, retail ($/gl)	4.0	3.7	8%	Diesel urban to EV Gasoline urban to EV Truck to EV short haul City Buses to EV
	Diesel EU, retail ($/gl)	6.0	7.0	-14%	
	Gasoline US, retail ($/gl)	3.5	3.5	0%	
	EV Battery pack ($/kWh)	120	160	-25%	
	Electric cost EU ($/kWh)	0.40	0.40	0%	
	Electric cost US ($/kWh)	0.15	0.15	0%	
LNG	LNG delivered ($/mcf)	12	12	0%	LNG retrofit shipping
	Bunker fuel ($/bbl)	100	90	11%	
Hydrogen	Green ammonia ($/tn)	700	550	27%	Ammonia ship switch from diesel in marine
	Hydrogen Battery ($/KWh)	120	160	-25%	FC hydrogen trains
	Green Hydrogen ($/kg)	6.0	6.0	0%	Hydrogen long-haul truck -FCEV

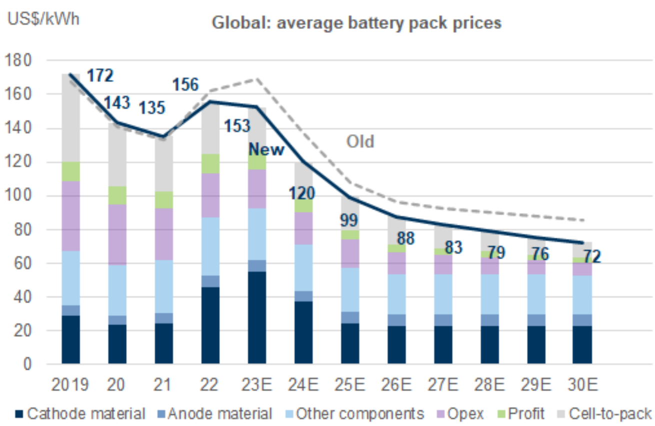
Source: Goldman Sachs Global Investment Research

Battery cost deflation and EV economies of scale to drive down EV costs...

Battery technology and its evolution play a key role in aiding de-carbonization of both transport and power generation. The high focus on electric batteries over the past decade has helped to reduce battery costs by over c.30% in the past five years alone owing to the rapid scale-up of battery manufacturing for passenger electric vehicles (EVs). Nonetheless, the technology is currently not readily available at large, commercial scale for long-haul transport trucks, shipping and aviation, and it remains at early stages for long-term battery storage for renewable energy.

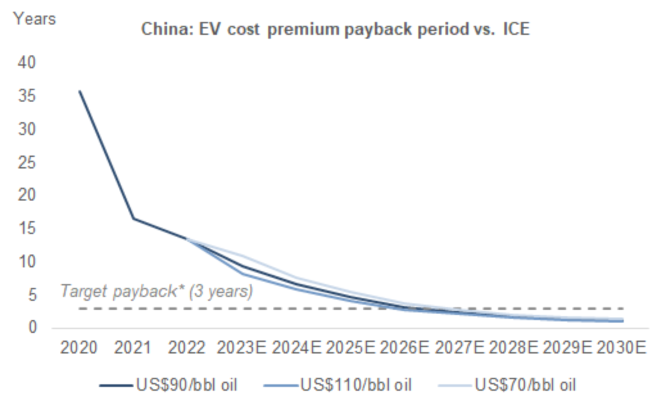
Battery cost deflation and EV economies of scale to drive down EV costs. Looking ahead, we expect declining battery prices (Exhibit 32), as well as EV economies of scale to help narrow the cost gap between EVs and ICEs towards 2030E. As a rule of thumb, we see an EV premium payback period of around 3 years (i.e. the number of years needed for fuel savings from cheaper electricity vs. gasoline to cover the EV cost premium over an ICE) as a threshold for a new powertrain to be widely accepted by consumers, given the case of Toyota Prius. We expect this 3-year target could be reached around mid-decade for EV makers in China, as well as in ex-China markets like the US (Exhibit 33-Exhibit 25).

Exhibit 32: We expect battery prices to decline meaningfully from here



Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Global Investment Research

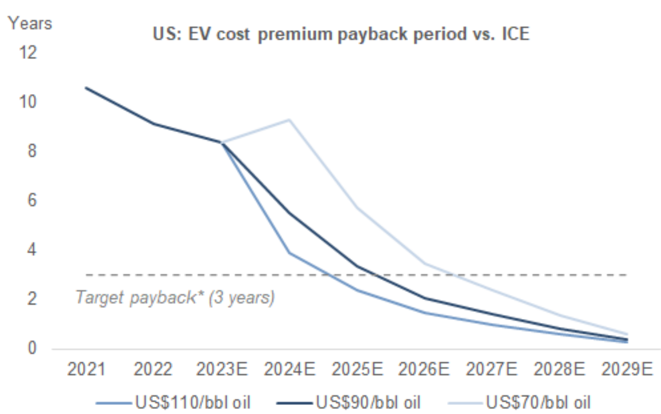
Exhibit 33: The target payback of 3 years could be achieved around mid-decade for BEV makers in China...



*Toyota Prius achieved a breakthrough in sales after shortening the payback period to 3 years.

Source: Company data, Goldman Sachs Global Investment Research

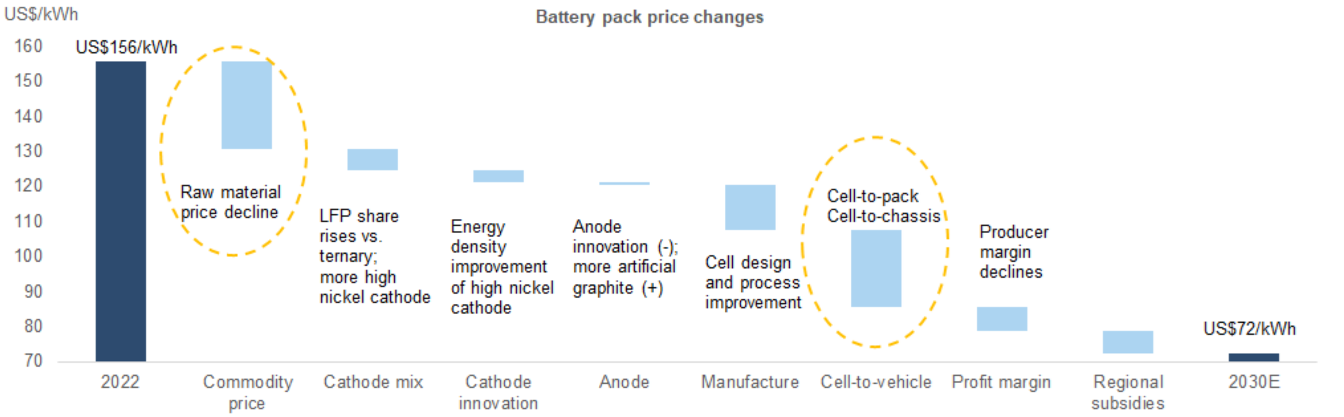
Exhibit 34: ...as well as in ex-China markets like the US



Source: Company data, Goldman Sachs Global Investment Researc

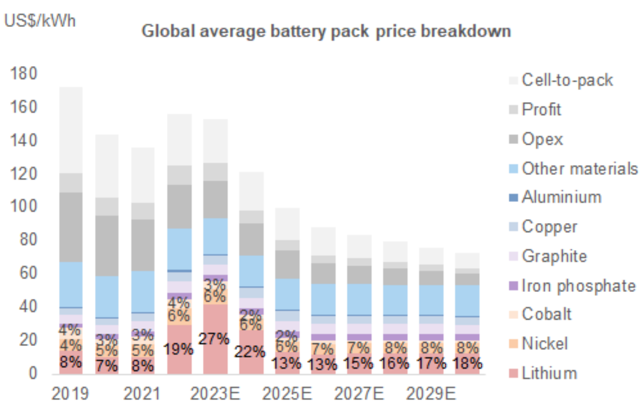
Increased visibility to lower battery costs. In our view, the main drivers for a decline in battery prices from here include lower lithium and other raw material costs and simpler cell-to-vehicle integration (e.g. cell-to-pack, cell-to-chassis, Exhibit 35-Exhibit 37). Our APAC Natural Resources and Clean energy team, lowered 2030E battery pack prices from US$86/kWh to US$72/kWh (Exhibit 32), mainly due to a lowered cell-to-pack premium (2030E from US$19/kWh to US$9/kWh). The cell-to-pack premium in China has been dropping quickly over the past 3 years to US$15-20/kWh currently from c.US$30/kWh at 2021, with the industry estimate at US$10-15/kWh for 2025E.

Exhibit 35: The main drivers for declines in battery prices include lower raw material costs and simpler cell-to-vehicle integration



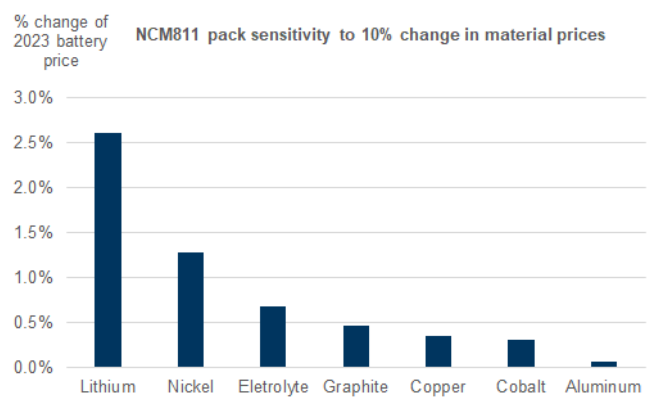
Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Global Investment Research

Exhibit 36: Reduced raw material costs to contribute to lower battery prices



Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Global Investment Research

Exhibit 37: Further medium-term downside for lithium prices to meaningfully reduce battery prices

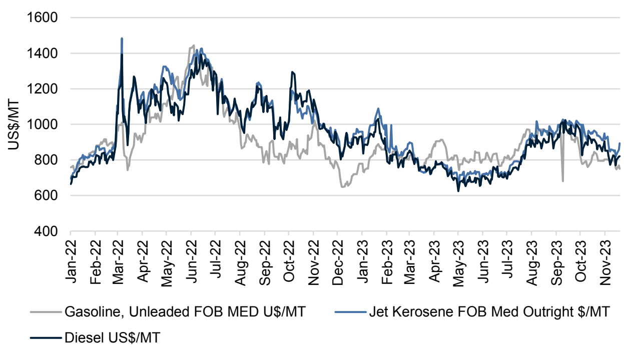


Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Global Investment Research

...while with lower gasoline and jet fuel prices we see technologies like SAF becoming relatively more expensive

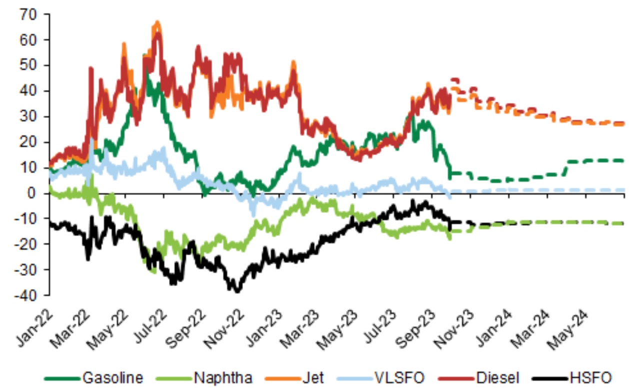
Our analysis focuses on the direct cost the average energy consumer pays in Europe and US and includes the total cost of fuel at the pump (gasoline, diesel for passenger road transport), natural gas final energy consumption in residential buildings and final electricity consumption for residential buildings but also for transport electrification. In 2023, we observed a decrease in gasoline, diesel and jet fuel prices compared to the high levels observed in 2022, thus we see some de-carbonization technologies like SAF relatively more expensive. We do not include e-SAF technology in our cost-curve, since we estimate that at the current level of renewable electricity, CCUS and electrolyzer costs **e-SAF levelized production cost in the range of $9-18/gallon, 3-6 times more expensive than conventional jet fuel.**

Exhibit 38: We have observed a decrease in oil products prices in 2023 compared to 2022...
Oil products prices, US$/MT



Source: Thomson Reuters Eikon

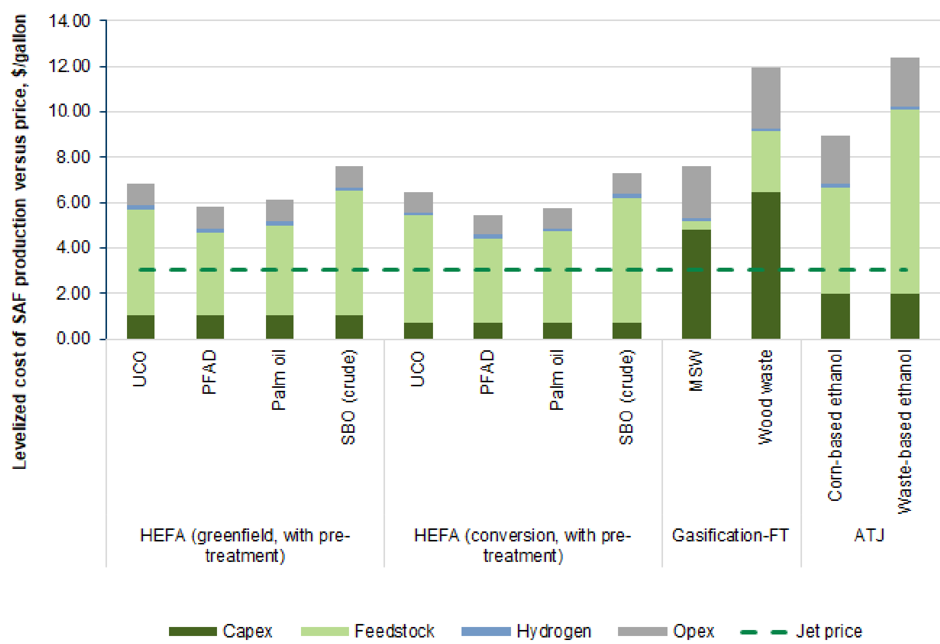
Exhibit 39: ...and we expect prices to stay at the lower levels vs 2022
NW European product cracks (vs Brent, USD/bbl)



VLSFO = Very Low Sulphur Fuel Oil; HSFO = High Sulphur Fuel Oil

Source: Platts, ICE, Goldman Sachs Global Investment Research

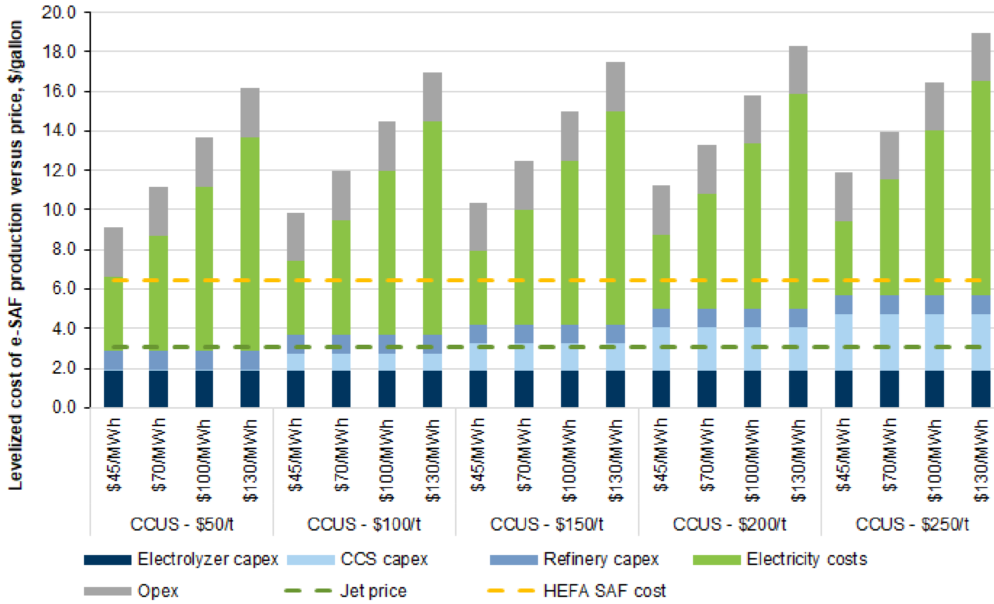
Exhibit 40: SAF production costs: production pathways are more diverse, yet HEFA remains the most cost effective method
SAF Levelized production cost, $/gallon



Source: Company data, Goldman Sachs Global Investment Research

Power-to-Liquid: We estimate e-SAF levelized production cost in the range of $9-18/gallon, 3-6 times more expensive than conventional jet fuel. Synthetic fuel production cost is 50-60% of the green electricity cost for green hydrogen production. We use $50-100/MWh LCOE of electricity in 2023 across different modes of power generation (solar, onshore wind, offshore wind). Capex comprises c.30% of levelized production cost, consisting of capex for the carbon capture unit (either from industrial source or direct air capture), electrolyzer equipment and refinery equipment consisting of the gasification-FT reactor. We use a $50-250/t LCOE of carbon capture with the lower range being attributed to sourcing CO2 from an industrial source (power gen, natural gas processing), and the higher range attributable to direct air carbon capture (DAC). For electrolyzer capex, we use our 2023 GS estimate of $700/t for an alkaline electrolyzer which is currently the most cost effective one. FT refining equipment contributes c.$300/t to SAF production cost. **Overall, we estimate e-SAF levelized production cost in the range of $9-18/gallon, 3-6 times more expensive than conventional jet fuel.** We estimate c.50% cost reduction for renewable electricity, CCUS and electrolyzer cost needed to reach cost parity with HEFA SAF by 2030.

Exhibit 41: We estimate e-SAF LCOE in the range of $9-18/gallon, 3-6 times more expensive than conventional jet fuel
Levelized production cost of e-SAF, $/gallon (2023)



Source: Goldman Sachs Global Investment Research

Renewable gases as a critical pillar for energy security, affordability and sustainability

Renewable gases such as biogas and biomethane are critical, under-appreciated pillars for energy security, affordability and sustainability.

Biogas is a mixture of methane, CO2 and small amounts of other gases produced by the anaerobic digestion of organic matter in an oxygen-free environment. The precise composition of biogas relies on the type of feedstock and the production pathway. Examples of these include biodigesters, landfill gas recovery systems, and wastewater treatment plants. The methane content of biogas typically ranges between c.45% to 75% by volume (according to the IEA), with most of the remainder being CO2. Biogas can be used in this form directly to produce electricity and heat or as an energy source for cooking.

Biomethane is a near-pure source of methane that is produced either by "upgrading" biogas or through the gasification of solid biomass followed by methanation; since it is indistinguishable from the regular natural gas stream, it can be transported and used wherever gas is consumed, but without adding to emissions. The deployment of biomethane to replace natural gas does not require any additional investments to develop new infrastructure, since the existing gas infrastructure can be used for biomethane. Depending on the feedstock used, biomethane can have even negative emissions, meaning that CO2 is actually removed from the atmosphere.

Renewable gases can be used to help to abate emissions in multiple sectors, including power generation, transport, buildings, industry and agriculture. Almost two-thirds of biogas production in 2018 was used in power generation (with an approximately equal split between electricity-only facilities and co-generation facilities). Around c.30% was consumed in buildings, mainly in the residential sector for cooking and heating, with the remaining 9% upgraded to biomethane and blended into the natural gas grid or used as a transport fuel.

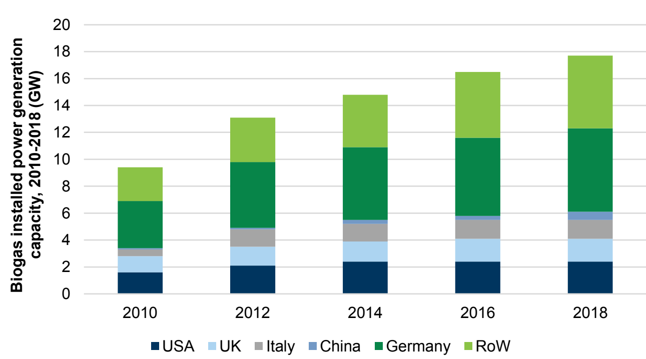
With this report we complement our Carbonomics cost curve with several de-carbonization technologies, relying on bioenergy, specifically biogas and biomethane.

Power generation is the biggest consumer of biogas

Biogas can be used directly to produce electricity or it can be upgraded to biomethane and fed into the existing gas infrastructure, making it possible to offer dynamic electricity production that can accomondate fluctuations in electricity demand. The relatively high cost of biogas and biomethane production compared to the natural gas prices means a carbon price of using renewable natural gas instead of conventional natural gas for power generation at 59-112 US$/tnCO2eq depending on the gas prices.

Exhibit 42: Germany is the leader in terms of biogas installed power generation capacity

Biogas installed power generation capacity, GW



Source: IEA

Heating in buildings

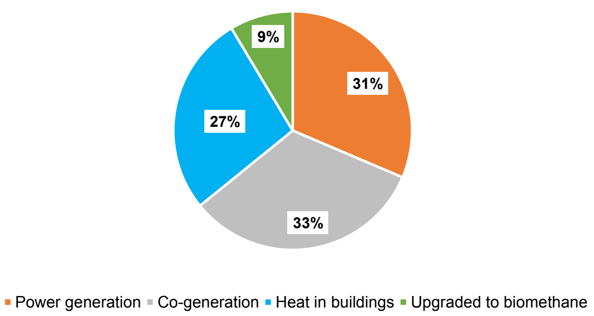
Buildings, both residential and commercial (including services and public), account for c.30% of final energy consumption globally, with the energy mix currently dominated by electricity and natural gas (primarily for heating). We see potential in renewable gases as one of the solutions for the de-carbonization of the buildings sector. Biogases can provide heat for residential and commercial buildings either directly on-site or off-site with distribution via a district heating grid. This can be done through a range of appliances, for instance, once injected into the gas grid, biomethane can fuel end use appliances such as **highly efficient gas boilers and gas or hybrid heat pumps**. Central combined heat and power generation (CHP) units can be run on biomethane and provide heat through a district heating network. One of the main advantages of using renewable gas as a de-carbonization technology is the absence of additional costs for the adopting of infrastructure or appliances to make them biomethane-appropriate, since biomethane can act as a natural gas substitute, transported through the natural gas network and used in existing heating appliances or district heating facilities. We estimate a carbon price of biomethane fueled appliances such as biogas boilers, used for heating of new residential and commercial buildings, at around c.206 and 175 US$/tnCO2eq respectively.

Transport

Biomethane is an effective way to abate emissions in transport, which represents 15% of total global emissions. Biomethane can be used as a renewable alternative to fossil fuels in gas vehicles and LNG vessels, with little to no change required to existing CNG and LNG-fuelled engines. Similar to renewable gas adoption in buildings, biomethane can be directly injected into the natural gas grid and then supplied to the already existing network of CNG and LNG filling stations, which means that biomethane deployment in order to substitute conventional fuels does not require any additional investments and time to develop new infrastructure. Liquefied biomethane can be used, for example, in heavy-duty road transport, which is difficult to electrify. Transition from diesel heavy-duty trucks to bio-LNG trucks will lead to incremental upfront costs, since price of the bio-LNG vehicle is third higher than conventional-fuel trucks. We estimate the carbon price of switching from long-haul diesel trucks to bio-LNG trucks at around c.127 US$/tnCO2eq under current diesel cost price of 4 US$/gallon.

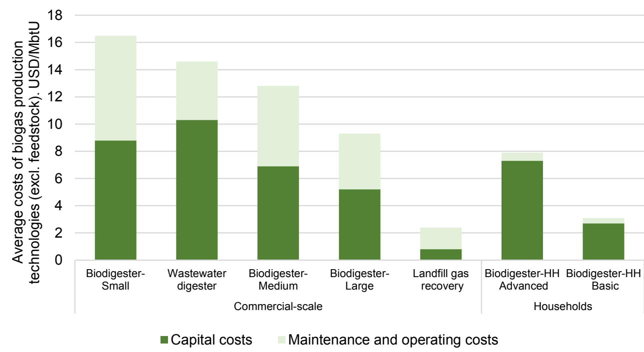
At the current level of biogas and biomethane technology development, using these types of renewable energy sources is still more expensive than conventional fuels, leading to the carbon abatement costs of de-carbonization technologies relying on the bioenergy mainly positioned at the higher end of the cost curve. However, RNG is also seeing strong regulatory momentum and returns in both Europe and the US now. Specifically, biogas has already become profitable in the US, benefiting from D3 RIN and ITC proposed by US IRA. EU countries also have different country-level incentives put in place which make biomethane production profitable.

Exhibit 43: Power generation and Buildings are the biggest consumers of biogas across all sectors currently
Biogas consumption by end use, 2018



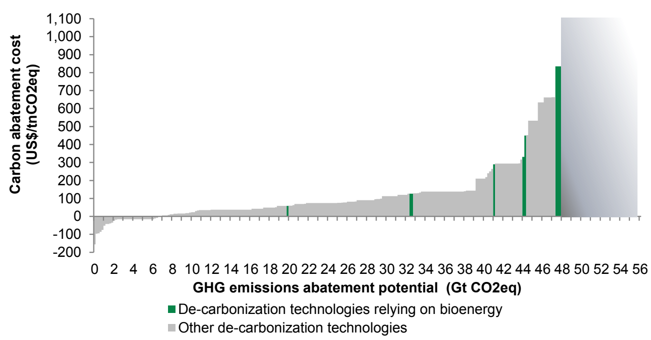
Source: IEA

Exhibit 44: Under the curent level of costs of biogas production...
Average costs of biogas production technologies, USD/Mbtu



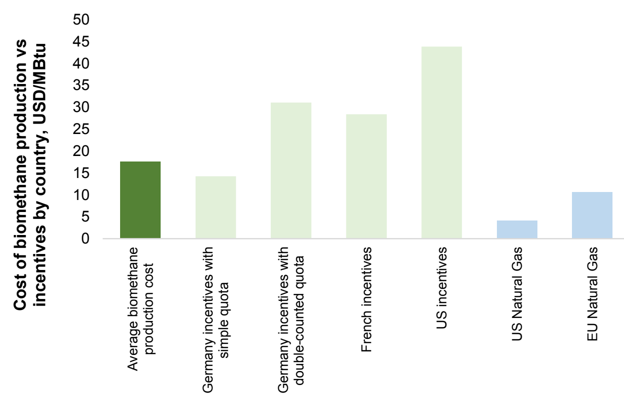
Source: IEA

Exhibit 45: ...carbon abatement prices of de-carbonization technologies relying on the bioenergy are mainly positioned at the higher end of the of the cost curve...
2023 carbon abatement cost curve for anthropogenic GHG emissions, with green indicating bioenergy-reliant technologies



Source: Goldman Sachs Global Investment Research

Exhibit 46: ...however, RNG is also seeing a strong regulatory momentum and returns in both Europe and US now, making it cost-efficient vs conventional fuels
Comparison of biomethane production costs with incentives by country



Source: Goldman Sachs Global Investment Research, IEA

Disclosure Appendix

Reg AC

We, Michele Della Vigna, CFA, Alberto Gandolfi, Nikhil Bhandari, Anastasia Shalaeva, Yulia Bocharnikova and Quentin Marbach, 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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