Note: The following is a redacted version of the original report published November 10, 2021 [34 pgs].

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Goldman Sachs | Research

Carbonomics

The dual action of Capital Markets transforms the Net Zero cost curve

In this report we examine how **capital markets' deep engagement in sustainability** is driving de-carbonization through a **divergence in the cost of capital of high carbon vs. low carbon investments**. This is having a dual impact on the Carbonomics cost curve, lowering the cost of capital for low carbon developments with good regulatory visibility (driving c.1/3 of renewable power cost deflation over the past decade), while increasing the cost of capital for high-carbon sectors. We identify **a clear mismatch between the limited reach and coordination of carbon prices** (rising from US$2.2/ton in 2020 to US$4.5/ton at present on a global weighted-average basis) **and the implied carbon prices charged by investors** through higher cost of capital for long-term hydrocarbon investments (US$40-80/ton, on our estimates). In our view, this mismatch between global policies and capital allocation is driving a **disjointed de-carbonization process** that leads to **structural underinvestment in key energy, materials, and heavy transport sectors** (reinvesting on average c.40% less of their cash flow vs. 10-year average). This could drive **higher commodity prices** in the long term, raising affordability concerns, but also making de-carbonization technologies comparatively more attractive. The current increases in oil, gas and coal prices (vs. 2020 average) imply an increase of US$80/ton for full-cycle CO_2e emissions from hydrocarbons and have driven two-thirds of the **12% flattening of the 2021 Carbonomics cost curve, compared to 2020**. We believe 'the revenge of the old carbon economy' this year is driving de-carbonization more forcefully than Clean Tech innovation.

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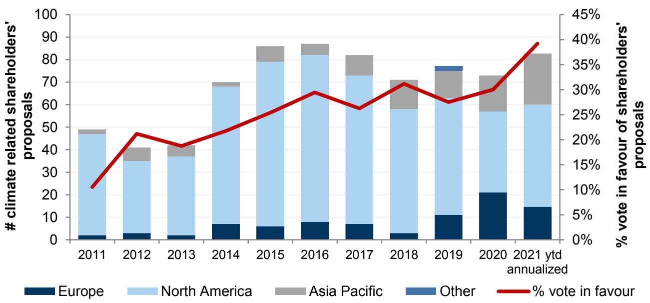
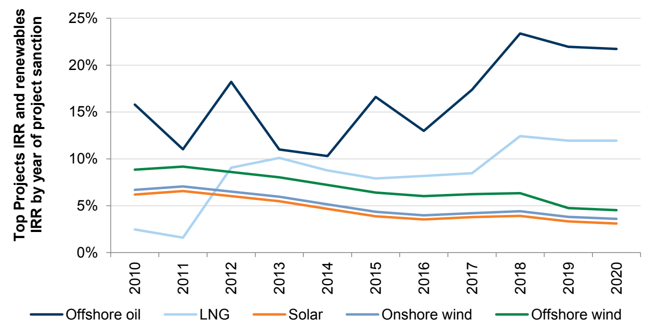
Carbonomics in 12 charts

Exhibit 1: Capital markets' engagement in climate change keeps rising..
Number of climate-related shareholder proposals and % vote in favour



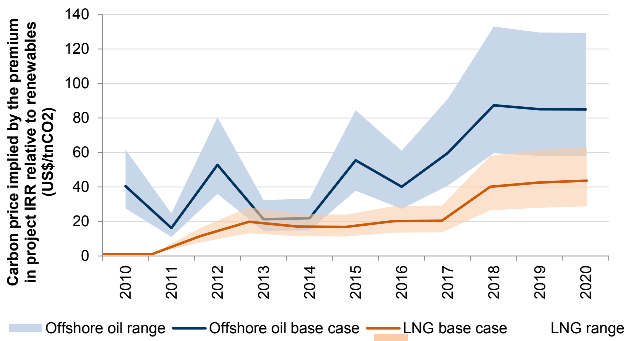
Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 2: ...driving a divergence in the cost of capital of low vs. high-carbon investments...
Top Projects IRR for oil & gas and renewable projects by year of project sanction



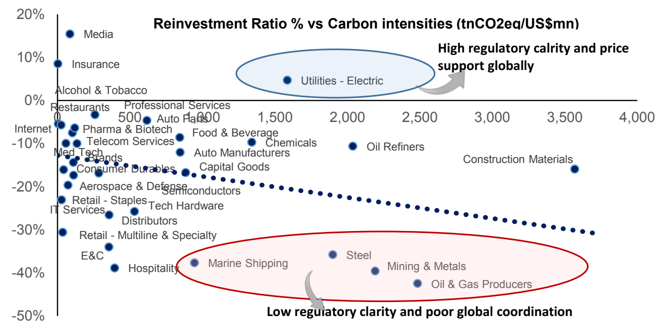
Source: Goldman Sachs Global Investment Research

Exhibit 3: ...implying a US$40-80/ton long-term carbon price for new hydrocarbon developments
Carbon price implied by the IRR premium for offshore oil/LNG projects compared with renewables (US$/tnCO2)



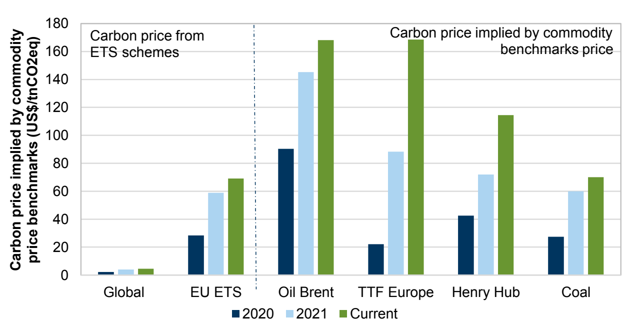
Source: Goldman Sachs Global Investment Research

Exhibit 4: Shareholder pressure and lack of policy coordination engenders structural underinvestment in carbon intensive industries...
Reinvestment Ratio % (2022E vs. 10-yr average) vs. carbon intensities (Scope 1,2,3 emissions intensity per revenue (tnCO2eq/US$mn))



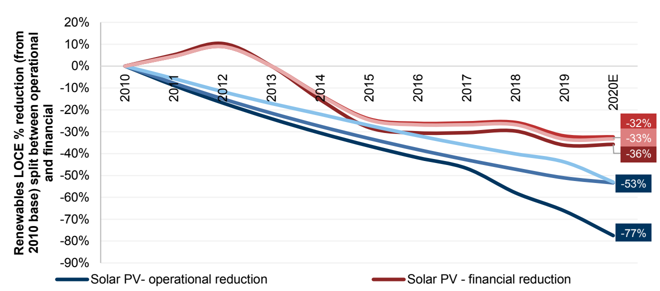
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 5: ...leading to structurally higher commodity prices, impacting consumer behaviours much more deeply than carbon prices...
Carbon price implied by commodity benchmarks vs. ETS markets ($/tnCO2eq)



Source: Thomson Reuters, Bloomberg, Goldman Sachs Global Investment Research

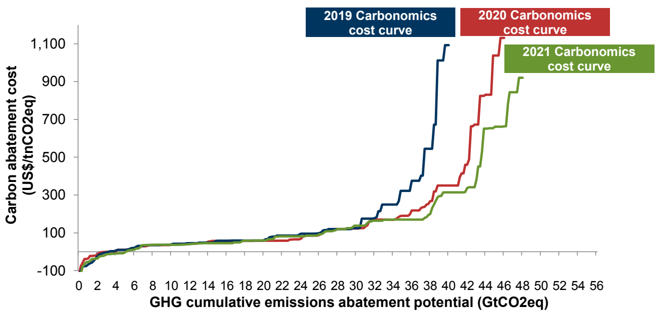
Exhibit 6: ...and fostering rising investments in industries with clear regulatory frameworks (e.g. renewable power)
LCOE % reduction from 2010 split between operational and financial



Source: Goldman Sachs Global Investment Research

Exhibit 7: The Carbonomics cost curve shifted and flattened for the third consecutive year...

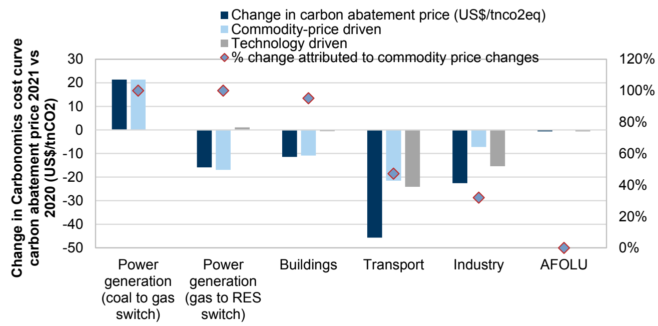
Carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



Source: Goldman Sachs Global Investment Research

Exhibit 8: ...with higher commodity prices contributing c.2/3 of the flattening

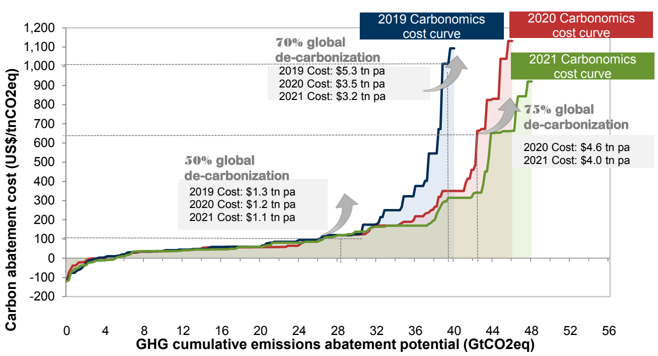
Change in cost curve carbon abatement price of 2021 curve vs. 2020



Source: Goldman Sachs Global Investment Research

Exhibit 9: The incremental cost of net zero carbon continues to improve, lowering the cost of 75% de-carbonization by $0.6 tn pa.

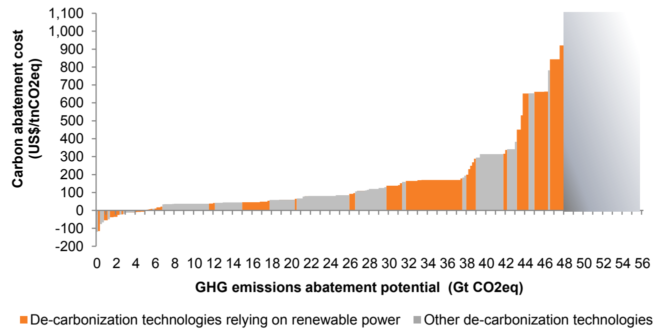
Carbon abatement cost curve for anthropogenic GHG emissions and associated costs for different levels of de-carbonization



Source: Goldman Sachs Global Investment Research

Exhibit 10: Renewable power is vital to the de-carbonization of c.38% of global emissions across sectors...

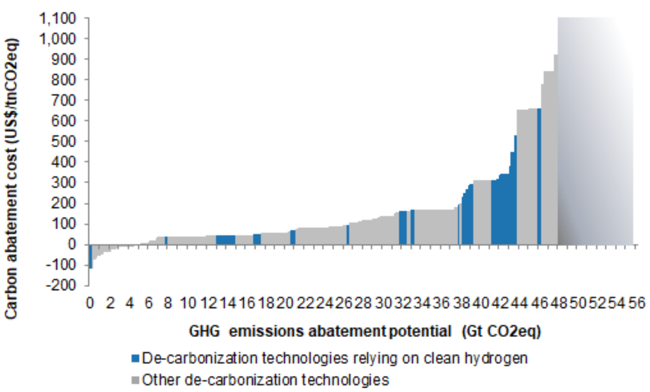
2021 de-carbonization cost curve with technologies relying on renewable power indicated



Source: Goldman Sachs Global Investment Research

Exhibit 11: ...and clean hydrogen has emerged as a key technology, required to de-carbonize c.15% of global emissions across sectors...

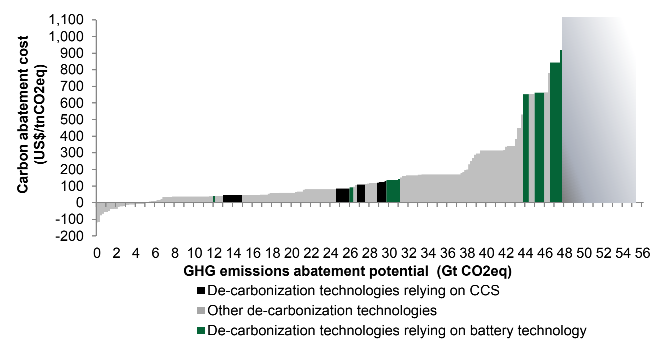
2021 de-carbonization cost curve with technologies relying on clean hydrogen indicated



Source: Goldman Sachs Global Investment Research

Exhibit 12: ...with battery energy storage and CCS also required

2021 de-carbonization cost curve with technologies relying on CCS and battery technologies indicated



Source: Goldman Sachs Global Investment Research

Capital markets are taking a leading role in the climate change debate driving de-carbonization through cost of capital divergence

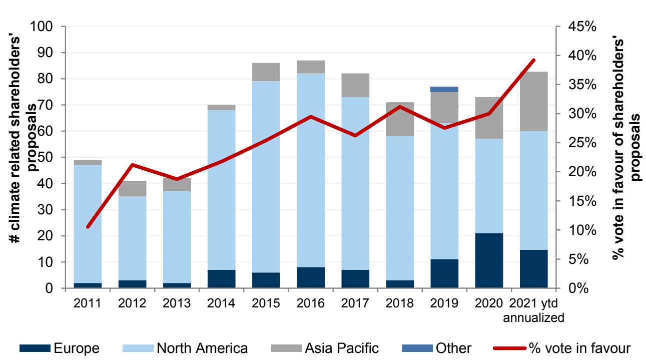
The number of climate-related shareholder proposals continues to increase, with c.40% of investor votes now in support, having more than tripled since 2011

With global GHG emissions on a persistent upward trajectory over the past few years, **investors have emerged with a leading role in driving the climate change debate**, pushing corporate managements towards incorporating climate change into their business plans and strategies. The number of climate-related shareholder proposals (as shown by data from ProxyInsight) has almost doubled since 2011 and the **percentage of investors voting in favour has more than tripled over the same period.** So far, 2021 has been another year of strong shareholder engagement on climate change, with year-to-date climate-related shareholder resolutions exceeding last year's on an annualized basis while the percentage vote in favour has shown a major increase yoy, currently at c.39%, as shown in Exhibit 13. While the 2020 increase in the number of climate-related shareholder resolutions was primarily attributed to the Europe region, 2021 has seen a notable acceleration in the number of these resolutions in North America as well as Asia.

This investor pressure, however, is not uniformly distributed across sectors and shows a clear bias towards energy producers vs. energy consumers, with data since 2014 showing >50% of proposals targeting energy producers (oil & gas, utilities) while only 30% of the proposals target the sectors that account for most of the final energy consumption. As such, the energy sector is one of the most susceptible to the capital markets' focus on the topic of climate change and is one where the largest divergence and impacts can be observed, therefore the sections that follow in this report use it as a primary example.

Exhibit 13: The number of climate-related shareholder resolutions and % vote in favour continues to gain momentum so far in 2021 reaching c.39% globally...

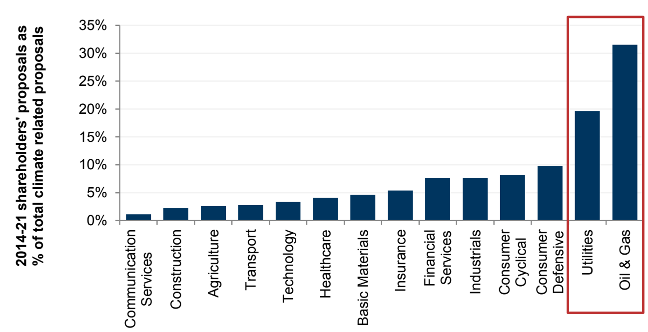
Number of climate-related shareholders' proposals vs. % vote in favour



Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 14: ...with a targeted focus on energy producers (oil & gas, utilities)

% of climate-related shareholder proposals, split by industry, 2014-21



Source: ProxyInsight, Goldman Sachs Global Investment Research

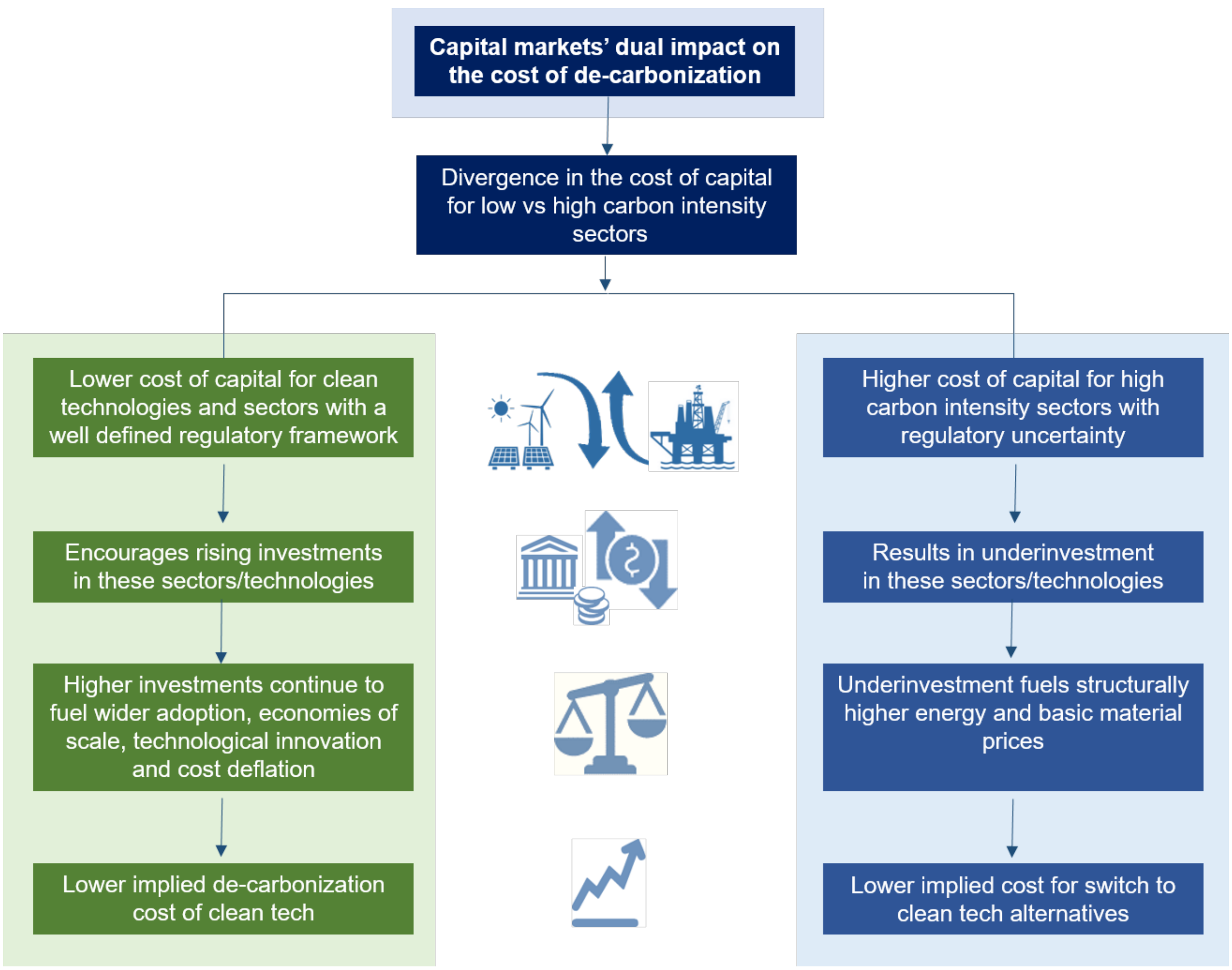
The capital markets' increasing engagement on the topic of climate change is having a dual impact on the cost of de-carbonization and our Carbonomics cost curve

Today >$100 tn of global assets under management have signed up to UN PRI and are implementing ESG metrics as part of their investment process. This wave of "green" investments is driving capital towards de-carbonization technologies through a divergence in the cost of capital of high-carbon vs. low-carbon investments. We view **capital markets' increasing engagement on climate change as having a dual impact on the cost of de-carbonization**:

(a) Higher cost of capital and regulatory uncertainty in more carbon intensive industries is leading to **underinvestment** and the revenge of the old economy**.** This drives **structurally higher commodity prices which can be viewed as an additional carbon tax, encouraging consumer shift into cleaner alternatives.**

(b) Lower cost of capital and wider access to cheap financing is leading to **higher investments in clean technologies** ultimately driving further **technological innovation and cost deflation.**

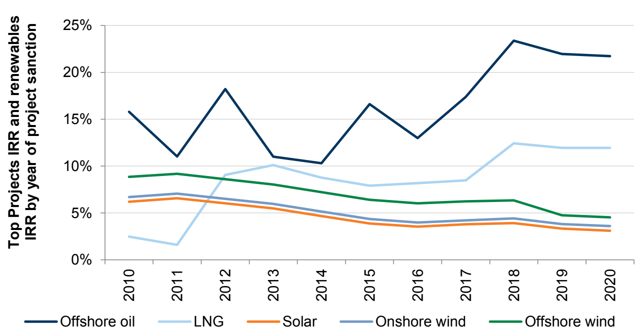
Exhibit 15: Schematic diagram summarizing capital markets' dual impact on the cost of de-carbonization



Source: Goldman Sachs Global Investment Research

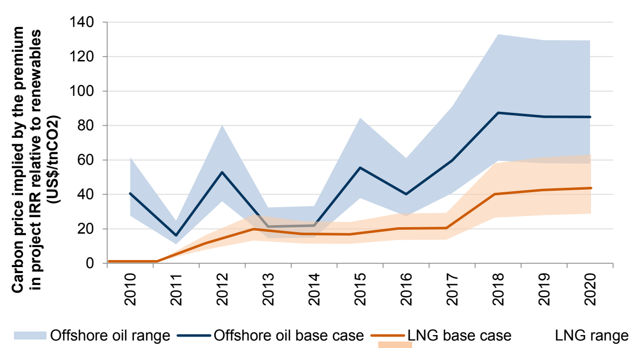
Looking at the energy sector, we estimate that the spread in the cost of capital of hydrocarbon vs. renewable developments has widened by > ten percentage points over the last five years. This is equivalent, on our estimates, to a global carbon tax of $80/tnCO2eq, and is driving a historical turning point in energy investment, with global renewable power spend overtaking oil & gas developments for the first time in history. Uncertainty around future carbon regulation and the lack of global coordination on carbon pricing are impacting investment in several sectors, mostly in energy, materials and heavy transport. On our estimates, there has been a decline in the re-investment ratio (10-year average vs. 2022E) of c.40% in Oil & Gas, Steel, Mining and Marine Shipping: global carbon intensive sectors which suffer from a lack of clear policies around de-carbonization. In contrast, Electric Utilities is an example of a sector where clear de-carbonization incentives and strategies are actually leading to higher investment than in the past, as shown in Exhibit 18. We believe that the continued lack of coordination runs the risk of severe underinvestment in core parts of the 'Old Carbon Economy' that could lead to supply tightness, as we already are starting to experience in parts of the materials, oil & gas and transport industries.

Exhibit 16: Looking at the energy sector, the bifurcation in the cost of capital for hydrocarbon 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



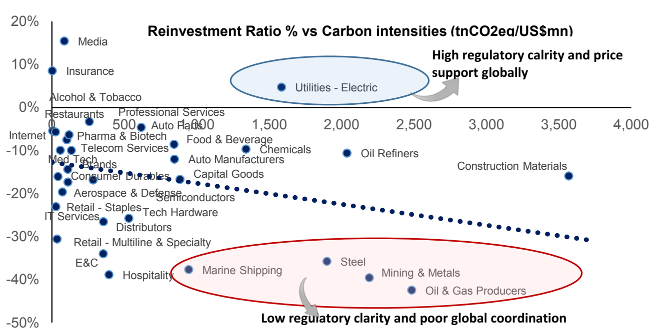
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 17: ...implying a carbon price range of US$80/40 per tn CO2 for offshore oil and LNG projects...
Carbon price implied by the IRR premium for offshore oil and LNG projects compared with renewables (US$/tn CO2)



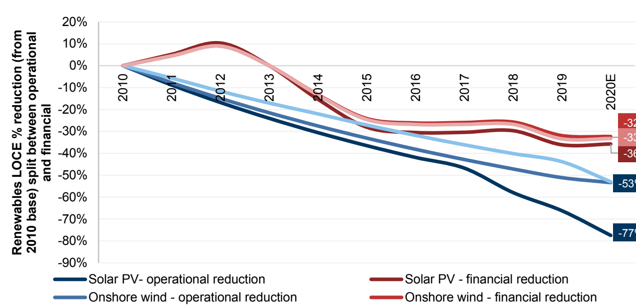
Source: Goldman Sachs Global Investment Research

Exhibit 18: High cost of capital and regulatory uncertainty have led to underinvestment in investment in carbon intensive sectors throughout energy, materials and heavy transport...
Reinvestment Ratio % (2022E vs. 10-year average) vs. carbon intensities (Scope 1,2,3 emissions intensity per revenue (tnCO2eq/US$mn))



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 19: ...yet higher investments in sectors like utilities where we estimate that lower cost of capital and financial innovation have driven 1/3 of the cost deflation in renewables since 2010
LCOE % reduction from 2010 split between operational and financial



Source: Goldman Sachs Global Investment Research

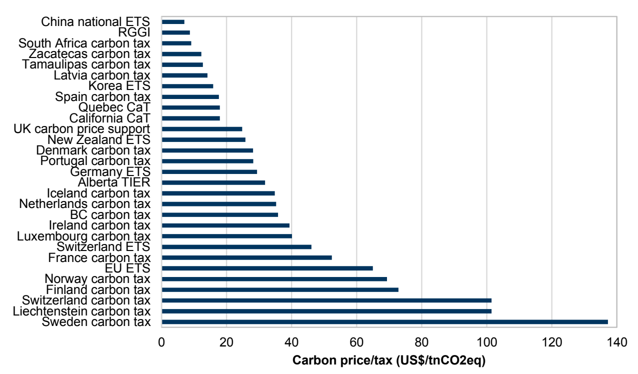
Structural underinvestment in carbon intensive sectors leads to higher commodity prices and indirectly taxes emissions

Carbon pricing a key ingredient for de-carbonization, yet global coordination has so far failed with a global average carbon price of only $5/tnCO2...

We believe that **carbon pricing will be a critical** part of any effort to move to net zero emissions, while incentivizing technological innovation and progress in de-carbonization technologies. The very steep carbon abatement cost curve calls for a growing need for technological innovation, sequestration technologies deployment and effective carbon pricing. The abatement weighted average carbon price implied by our Carbonomics cost curve lies in the range of $100-200/tnCO2 and we believe that **carbon prices should be sufficiently high to incentivize innovation and healthy competition between conservation and sequestration technologies shown on the cost curve**, while in the longer term, such an equilibrium price of carbon is likely to decline on the back of technological innovation and economies of scale.

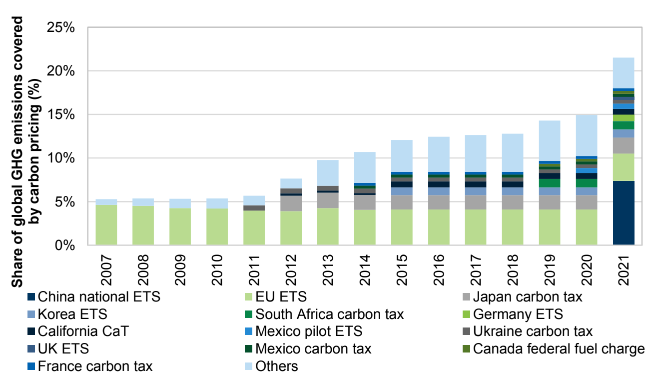
At present, 65 carbon pricing initiatives have been implemented or are scheduled for implementation, covering 45 national jurisdictions worldwide, according to the World Bank Group, mostly through cap-and-trade systems. These initiatives are gaining momentum, with China, the world's largest CO_2 emitter, launching the initial phase of its own ETS roadmap in 2021. These carbon pricing systems have shown varying degrees of success in reducing carbon emissions; yet together, according to the World Bank Group, all of these initiatives (including China) cover only 12 GtCO2eq, representing c.22% of the world's total GHG emissions.

Exhibit 20: The carbon prices associated with global national and sub-national carbon price initiatives (carbon taxes & ETS) show a wide regional variability...
Carbon prices through taxes and ETS (mid 2021)



Source: World Bank Group

Exhibit 21: ...and carbon pricing initiatives cover only up to 25% of global GHG emissions, even with the addition of China by 2021
Carbon pricing initiatives' share of global GHG emissions covered (%)



Source: World Bank Group, Goldman Sachs Global Investment Research

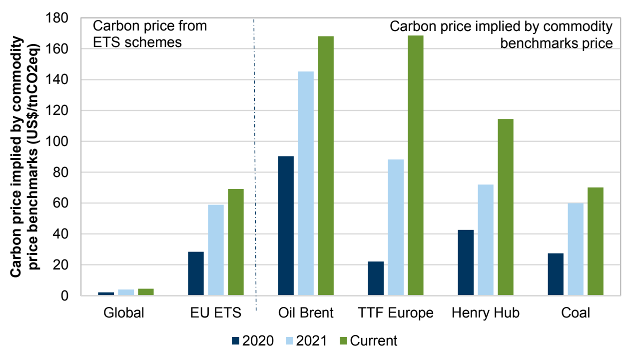
...yet structurally higher commodity prices resulting from higher cost of capital and underinvestment are acting as another potentially more effective form of carbon pricing globally

Despite the lack of global coordination in establishing a global carbon pricing market, with the current global average carbon price being only around $5/tnCO2eq and well below what is required to incentivize a switch to cleaner alternatives, **the impact of capital markets on the old economy,** as described previously, through a higher cost of capital leading to structural underinvestment, **is creating a new form of implied carbon pricing - structurally higher commodity prices.** In the charts that follow we show the carbon price implied by the various commodity price benchmarks globally (Brent oil price, Henry Hub and European TTF natural gas prices, coal prices). This analysis is done by considering the current commodity price environment and the well-to-wheel carbon intensity of the different commodities.

Our results indicate that whilst the global average carbon price is only $5/tnCO2 and the European ETS carbon price around $60/tnCO2, the carbon price implied by the current commodity price environment are well above those levels with Brent and European gas prices (TTF) currently implying a carbon price >$160/tnCO2eq. Moreover, ytd the carbon price implied by commodity price benchmarks has risen by more than $50/tnCO2eq across commodities compared to a c.US$30/tnCO2eq increase in the EU ETS price and c.$1/tnCO2eq change in the global average carbon price.

Exhibit 22: The carbon price implied by the various commodity benchmarks is well above the current global and EU ETS carbon price...

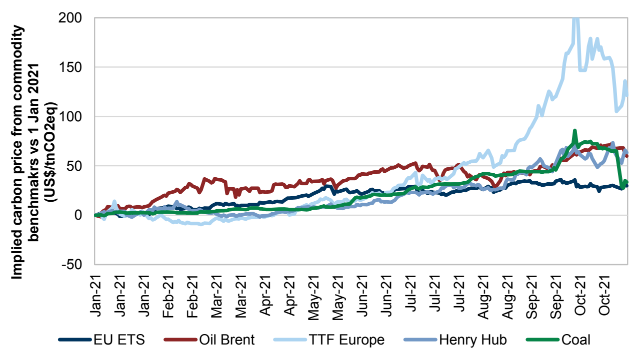
Carbon price implied by various commodity benchmarks and carbon ETS schemes (US$/tnCO2eq)



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

Exhibit 23: ...having increased by >$50/tnCO2 ytd across commodities, vs. a c.US$30/tnCO2 increase in the carbon price of the EU ETS and c.$1-2/tnCO2 increase in the global average carbon price

Ytd change in the carbon price implied by various commodity benchmarks and carbon ETS schemes (US$/tnCO2eq, rebased to 1 Jan 2021)



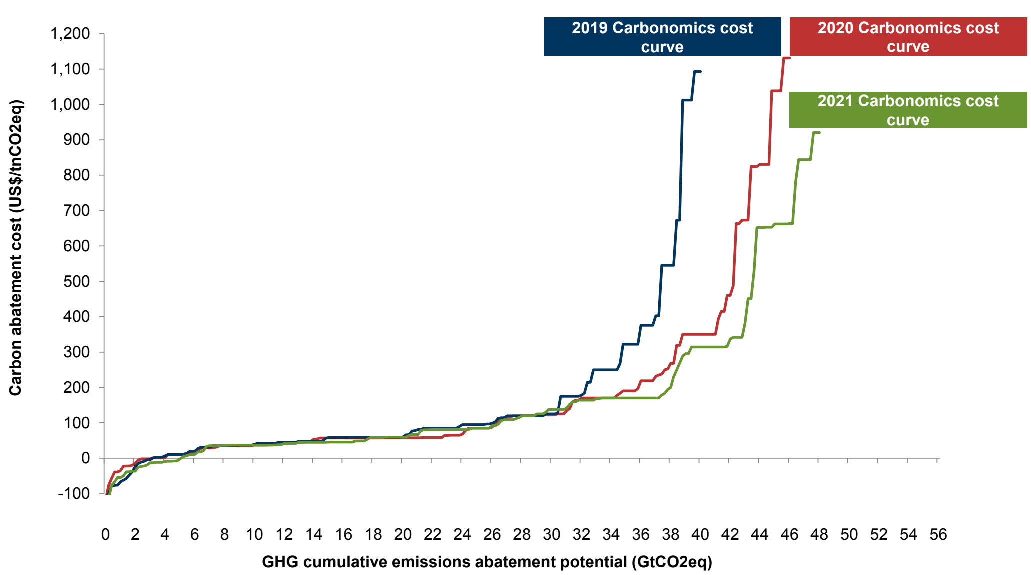
Source: Thomson Reuters Eikon, Bloomberg, Goldman Sachs Global Investment Research

High commodity prices and clean tech investments flatten the Carbonomics cost curve

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**, **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 26 and the transformation of the 2021 Carbonomics cost curve and the comparison to the 2020/2019 comparable Carbonomics cost curves is shown in Exhibit 24.

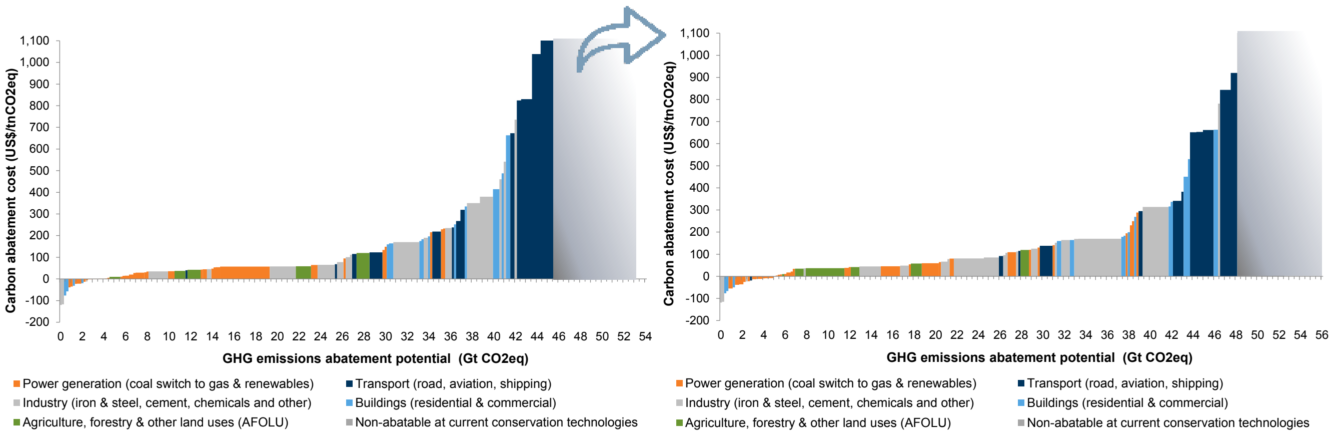
Exhibit 24: The 2021 Carbonomics cost curve flattened for the third consecutive year and shows a notable shift lower for the more costly technologies (upper end of the cost curve) driven by higher commodity pricing and rising clean tech investments

2021 vs 2020/2019 restated 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 25: 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.
- 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.

AFOLU

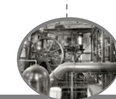
De-carbonization technologies

- **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 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

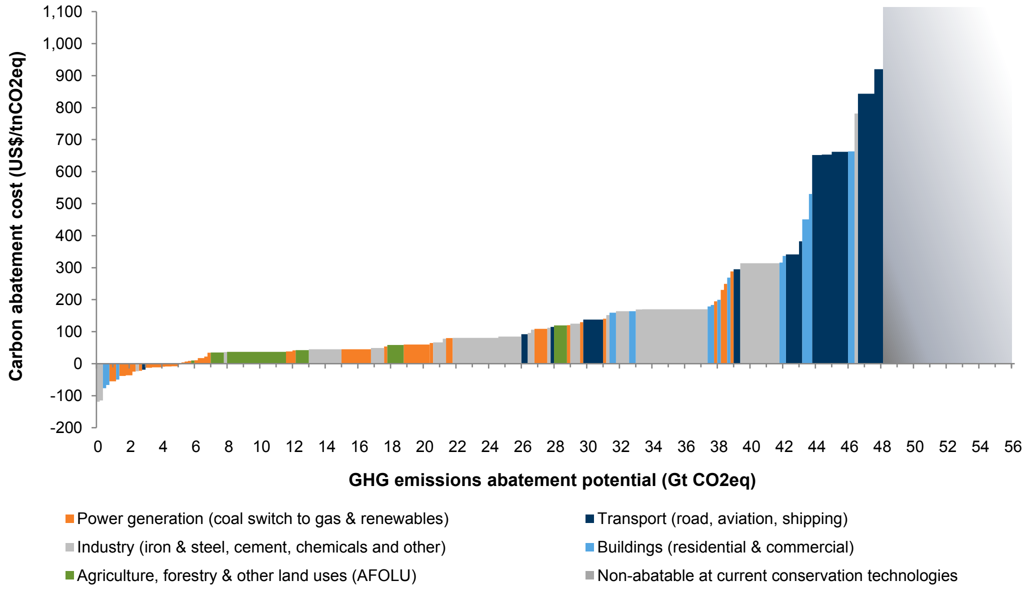
De-carbonization technologies

- **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

Exhibit 26: Capital markets' focus on climate change continues to transform the cost curve of de-carbonization through the dual effect of higher old economy costs and further technological innovation and cost deflation in low carbon technologies.

2021 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



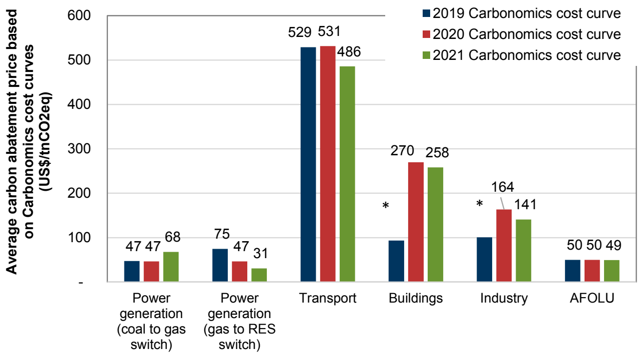
Source: Goldman Sachs Global Investment Research

The Carbonomics cost curve is updated for the third consecutive year, and this year shows a notable shift lower for the higher-cost de-carbonization technologies (upper end of the curve)

Exhibit 24 shows the comparison between the 2021 Carbonomics cost curve and the 2020/2019 comparable cost curves. We note that the 2019 and 2020 published Carbonomics cost curves were re-stated to include process specific carbon capture across both, making them directly comparable with our 2021 cost curve which includes process specific sequestration technologies. As shown in the exhibit, the 2021 Carbonomics cost curve remains broadly similar in level for its lower half (low-cost 50% de-carbonization), yet shows a notable shift lower for the higher-cost de-carbonization technologies (upper 50% of the curve) primarily attributed to the lower abatement carbon cost for transport and industry. This is driven by the dual impact of capital markets outlined in the previous sections of this report with contributions from (a) higher long-term commodity prices (oil, natural gas, coal) reducing the implied cost of the switch to cleaner alternative technologies and (b) the continuation of clean tech cost reduction for existing technologies (such as battery costs) and further de-carbonization additions. Amongst the technologies added in this year's de-carbonization cost curve are FC hydrogen trains in transport, nuclear and hydroelectric plants in power generation, waste heat recovery, scrap steel DRI-EAF and electrification of low temperature heat in industry. These further increase the total potential abatement achievable as shown by the moderate shift of the curve to the right.

Exhibit 27: Transport and industry are the sectors showing the yoy largest reduction in the emissions weighted average carbon abatement cost on our 2021 cost curve...

Average carbon abatement price based on our Carbonomics cost curves ($/tnCO2eq)

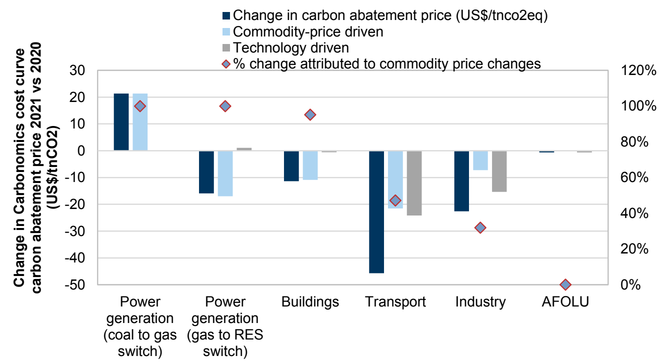


* Buildings and industry lower average cost in 2019 is due to the lower achievable carbon abatement (in the absence of hydrogen technology)

Source: Goldman Sachs Global Investment Research

Exhibit 28: ...as they benefit from both higher commodity prices encouraging low carbon alternatives switch and ongoing technological innovation and economies of scale

Change in Carbonomics cost curve average carbon abatement price 2021 vs. 2020 attributed to commodity price changes and technological cost changes

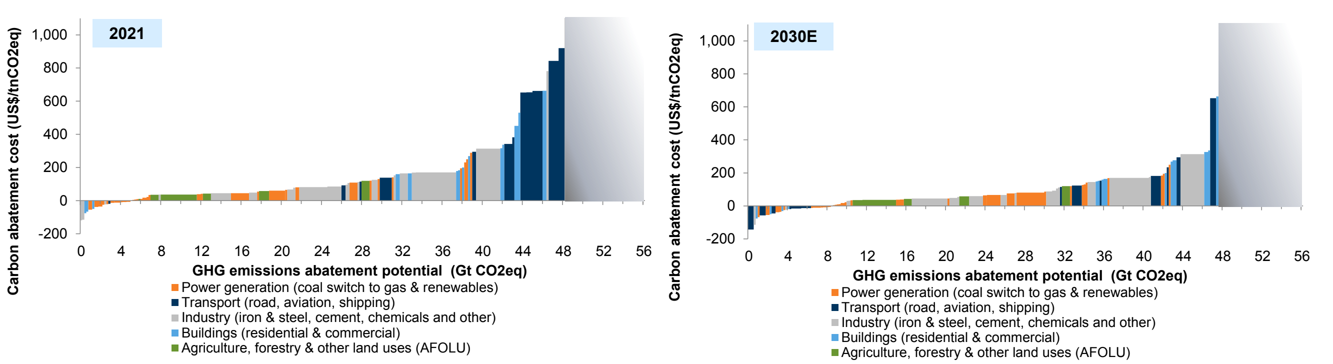


Source: Goldman Sachs Global Investment Research

Our dynamic Carbonomics cost curve is expected to continue transform this decade, driven by cost deflation (especially for batteries, clean hydrogen and CCS)

Our Carbonomics cost curve is dynamic in nature and evolves as the cost underpinning the underlying clean technologies evolve over time. We expect that the shape of the cost curve will transform in a manner similar to what is shown in Exhibit 29 with a notable reduction in the average abatement carbon price for the upper half of the cost curve. This is driven by technological innovation and benefits of scale, particularly for energy storage (batteries and clean hydrogen) as well as carbon capture technologies. This shift in the cost curve should improve further the affordability of net zero by the end of the decade.

Exhibit 29: We estimate that the upper half of the Carbonomics cost curve can continue to transform and fall by 2030, driven by technological innovation and the benefits of scale, mostly in energy storage and carbon capture technologies



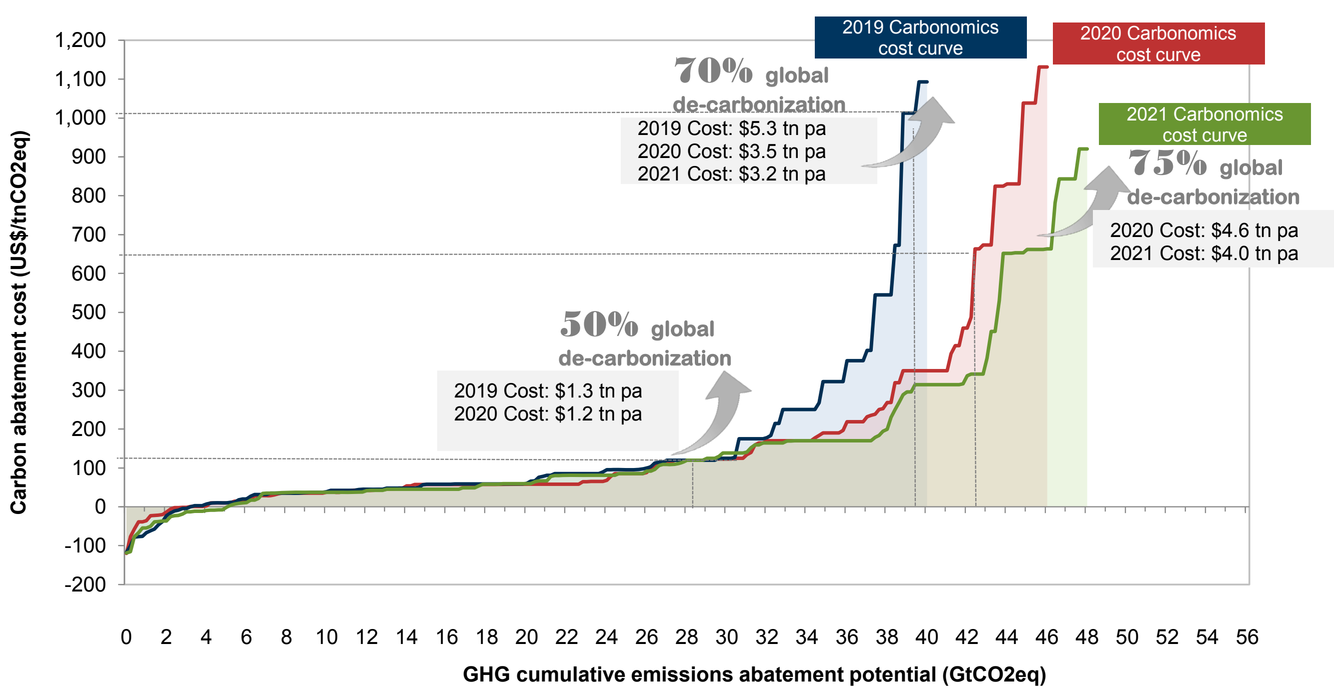
Source: Goldman Sachs Global Investment Research

Evolution of the cost curve improves affordability of net zero

The evolution of the Carbonomics cost curve results, on our estimates, in a c.US$0.5 tn pa reduction in the global cost to reach 75% de-carbonization

The transformation of the cost curve brings with it a **meaningful reduction in the global annual cost to achieve de-carbonization** from existing, large-scale commercially available technologies. As shown in Exhibit 30, the initial c.50% of global anthropogenic GHG emissions, what we classify as **'low-cost de-carbonization'**, can be abated at an **annual cost that is broadly similar yoy**, at c.US$1.1 tn pa based on the 2021 cost curve vs. US$1.2 tn pa based on 2020. Nonetheless, as we move towards 70%-75% de-carbonization, we enter into the **'high-cost de-carbonization'** spectrum, with the three curves – and subsequently the annual cost required to achieve de-carbonization – diverging significantly; we estimate **c.12% global annual cost reduction in the upper part of the cost curve,** from US$4.6 tn in our 2020 cost curve to US$4.0 tn in our updated 2021 cost curve. Overall, this implies **c.US$0.6 tn of annual savings as we approach net zero.** Moreover, for the same total global annual investment, the **evolved cost curve results in c.85% abatement of global GHG emissions (including LULUCF) and c.93% abatement of global CO2 emissions** with the remaining 7% CO2 emissions abatement required for net zero to be achieved through the use of non-specific carbon sequestration - **natural sinks and DACCS offsets.**

Exhibit 30: Evolution of the de-carbonization cost curve results in c.$0.6 tn annual savings on the path to net zero based
2021 vs. 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 phase



Source: Goldman Sachs Global Investment Research

A deep dive into the four key transformational technologies reshaping the cost dynamics of de-carbonization

Looking at the transformation of our conservation de-carbonization cost curve, we note that the **de-carbonization process is evolving from one dimensional (renewable power) to a multi-dimensional ecosystem.** Four technologies are emerging as transformational, having a leading role in the evolution of the cost curve and the path to net zero emissions. Notably, all of these technologies are interconnected:

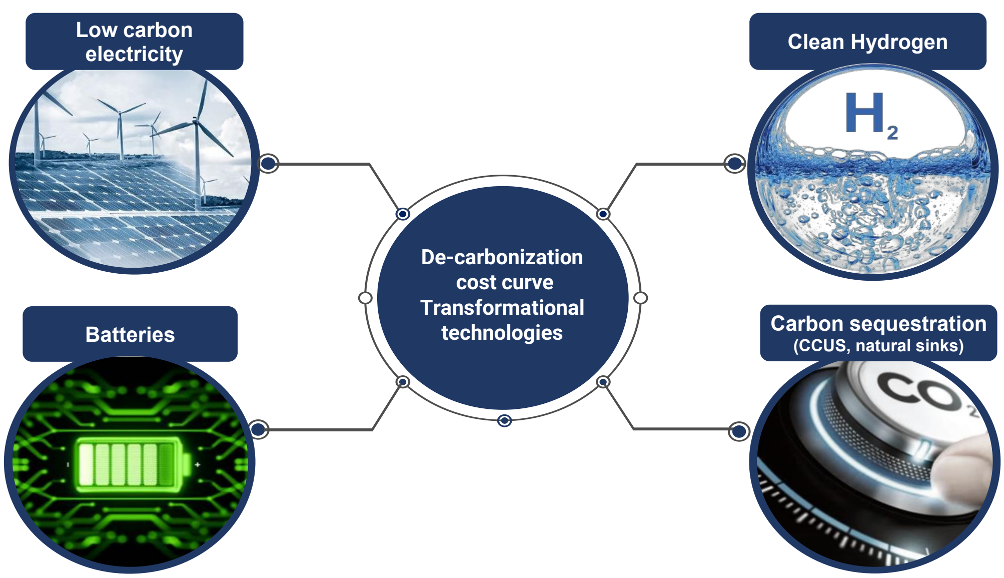
(1) Renewable power: The technology that dominates the 'low-cost de-carbonization' spectrum today and has the potential to support the de-carbonization of c.40% of total global anthropogenic GHG emissions, supporting a number of sectors that require electrification, as well as being critical for the production of clean hydrogen longer term ('green' hydrogen).

(2) 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).

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

(4) 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 identify four transformation technologies that we expect to lead the evolution of the Carbonomics cost curve



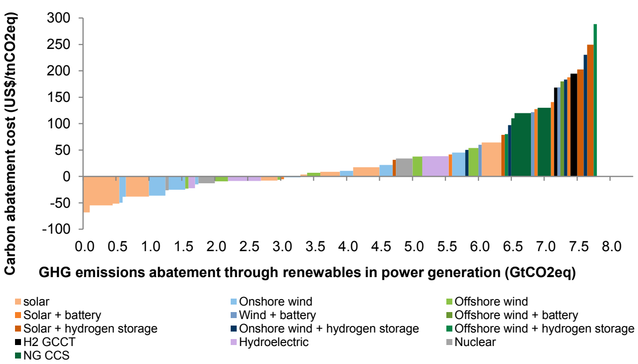
Source: Goldman Sachs Global Investment Research

1) Renewable power: The low-carbon technology dominating 'low-cost de-carbonization'

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 on the back **of lower technology costs observed over the past decade** as the industry benefits from economies of scale and **lower cost of capital.** We estimate that c.38**% of the de-carbonization of global anthropogenic GHG emissions is reliant on access to clean power generation** (as shown in Exhibit 10), including electrification of transport and various industrial processes, electricity used for heating and more. The power generation system is facing a dual challenge on the path to net zero: de-carbonization of its existing mix whilst also growing three-fold on our estimates.

Exhibit 31: De-carbonization through renewable power generation is among the lowest-cost technologies on our de-carbonization cost curve, even when energy storage (batteries and hydrogen) is needed...

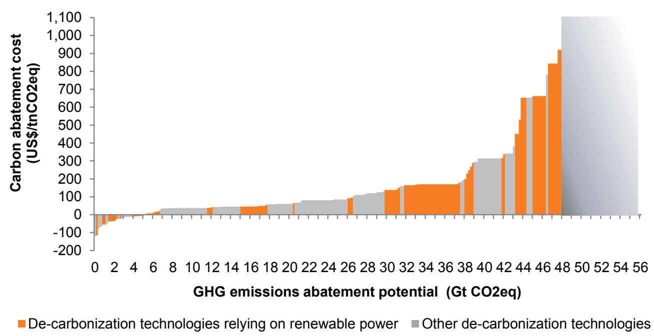
Power generation switch from natural gas to renewables (and storage) de-carbonization cost curve



Source: Goldman Sachs Global Investment Research

Exhibit 32: ...while access to low-carbon power more broadly is vital for the de-carbonization of c.38% of the global anthropogenic GHG emissions across sectors (such as electrification of transport, industry, buildings)

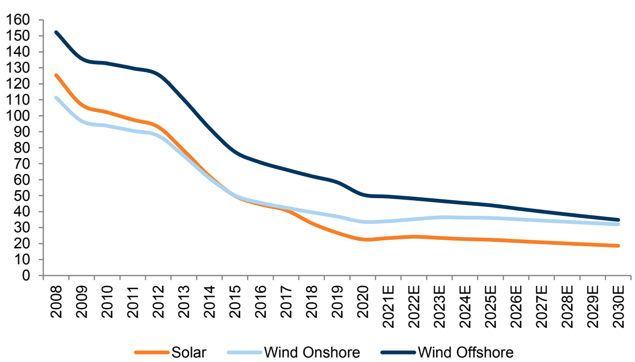
2021 carbon abatement cost curve for anthropogenic GHG emissions, with orange indicating renewable power-reliant technologies



Source: Goldman Sachs Global Investment Research

Exhibit 33: Renewable power LCOEs have decreased by >70% on aggregate across technologies...

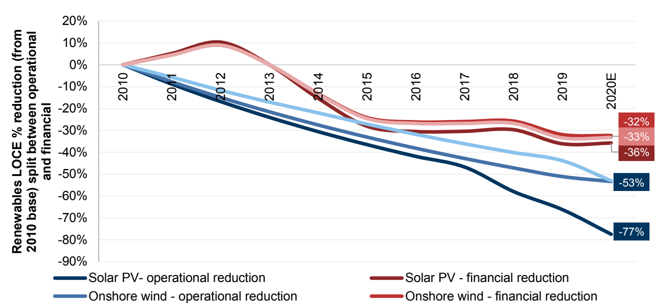
LCOE for solar PV, wind onshore and wind offshore for select regions in Europe (EUR/MWh)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 34: ...on the back of ongoing operational cost reduction from economies of scale and a reduction in the cost of capital for these clean energy developments, contributing c.1/3 of the cost reduction since 2010

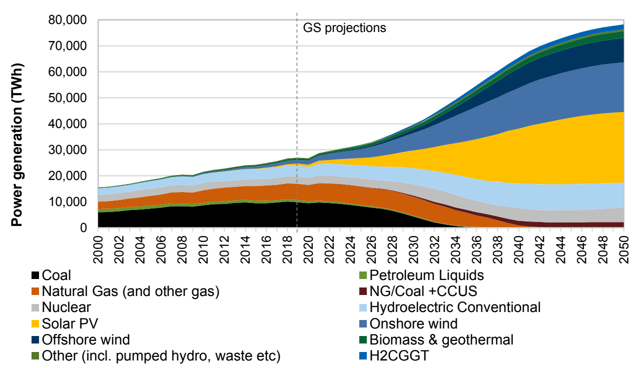
Renewables LCOE % reduction from 2010 base, split between operational and financial (cost of capital)



Source: Goldman Sachs Global Investment Research

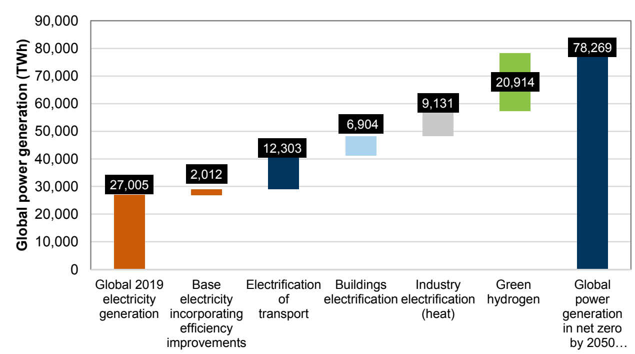
Power generation is the most vital component for any net zero scenario, with the sector currently accounting for c.32% of global anthropogenic CO_2 emissions (incl. AFOLU), making it the most critical area of focus to tackle the net zero challenge. The role of power generation is, in our view, only likely 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, in our GS net zero models, 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.** 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.

Exhibit 35: Based on our global net zero by 2050 path, power generation demand increases three-fold to 2050...
Global electricity generation (TWh)



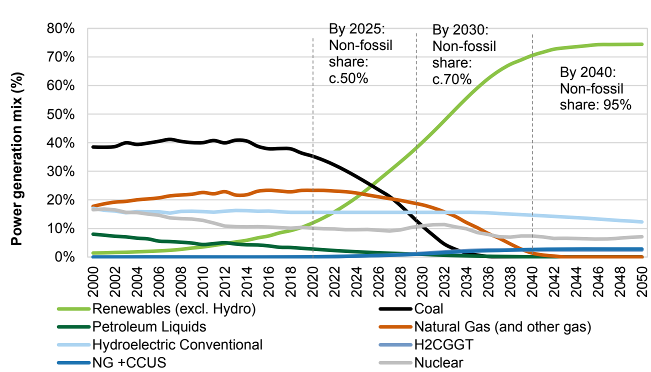
Source: BP Statistical Review, Goldman Sachs Global Investment Research

Exhibit 36: ...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
Global electricity generation bridge to 2050E (TWh)



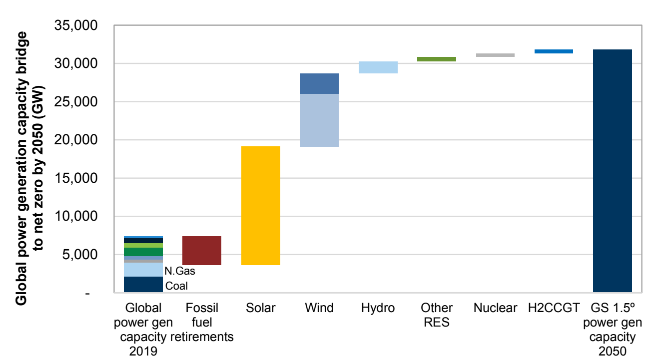
Source: Goldman Sachs Global Investment Research

Exhibit 37: A path consistent with net zero by 2050 requires transformational 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 38: ...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)

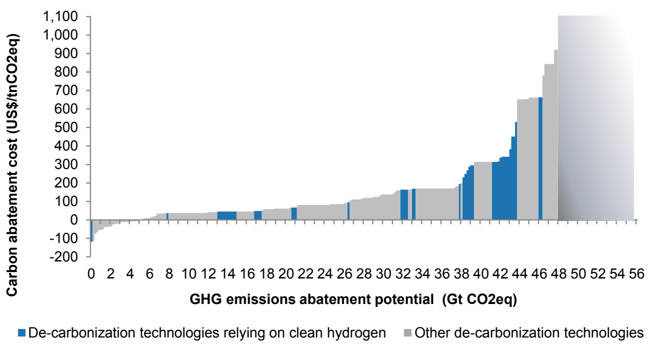


Source: Goldman Sachs Global Investment Research

2) Clean hydrogen: The emerging technology that can transform multiple parts of the Carbonomics cost curve

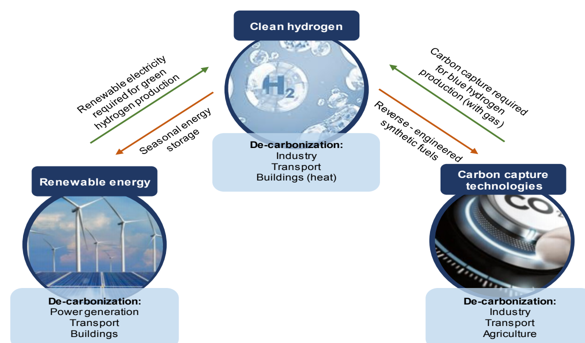
Hydrogen has a critical role to play in any aspiring path targeting carbon neutrality by 2050 in our view, with a wide range of applications across sectors including but not limited to its potential use as an energy storage (seasonal) solution that can extend electricity's reach, industrial energy source 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.15% of current global GHG emissions abatement** 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 39: We estimate that c.15% of global GHG emissions could be abated through technologies that rely on clean hydrogen...



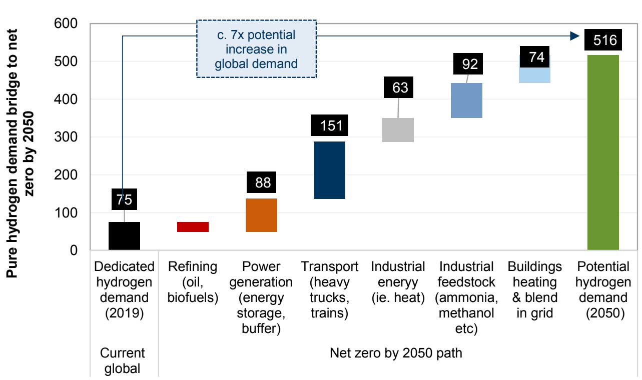
Source: Goldman Sachs Global Investment Research

Exhibit 40: ...with hydrogen forming a key connecting pillar between renewable power and carbon capture



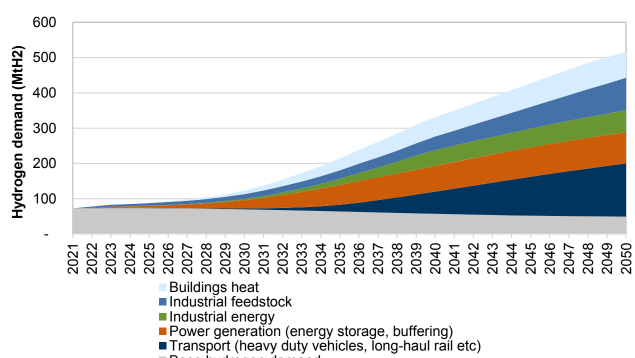
Source: Goldman Sachs Global Investment Research

Exhibit 41: 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 42: ...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.

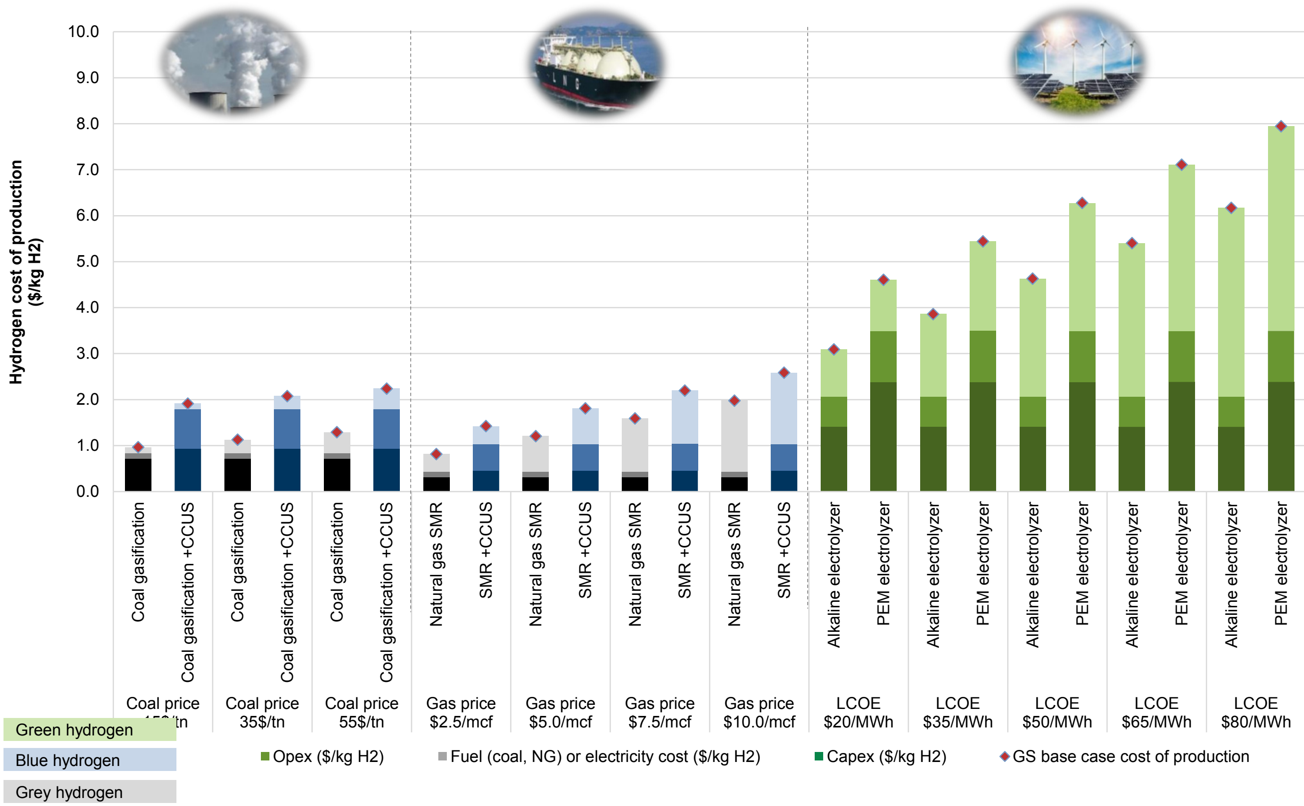
While hydrogen has gone through several waves of interest in the past 50 years, none has translated into sustainably rising investment and broader adoption in energy systems. Nonetheless, the recent focus on de-carbonization and the scaling up and accelerated growth of low-carbon technologies such as 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.

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 43, 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.

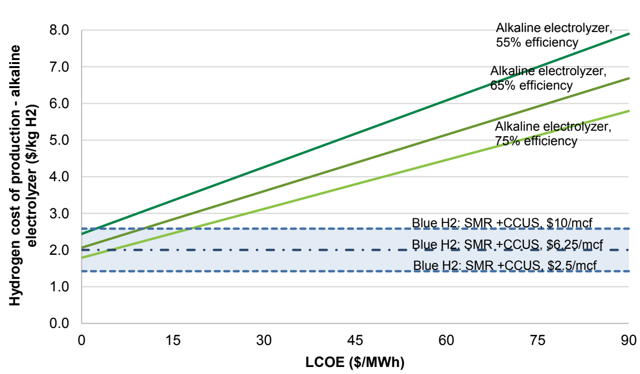
Exhibit 43: 'Blue' and 'green' hydrogen set the stage for de-carbonization, with 'blue' currently having a lower cost of production compared with 'green' hydrogen, but both being more costly than traditional 'grey' hydrogen



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 44: 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)...

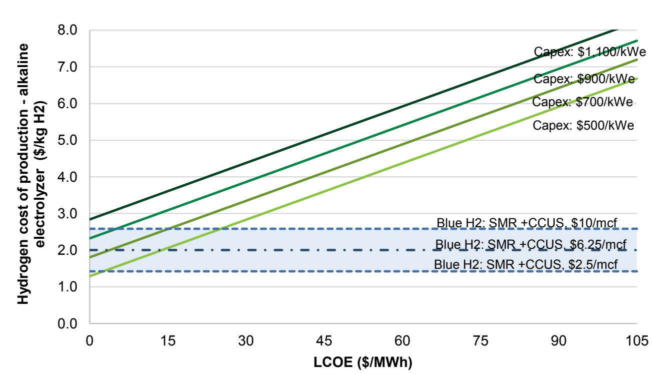
Hydrogen cost of production ($/kg H2) vs LCOE ($/MWh)



Source: Goldman Sachs Global Investment Research

Exhibit 45: ...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)

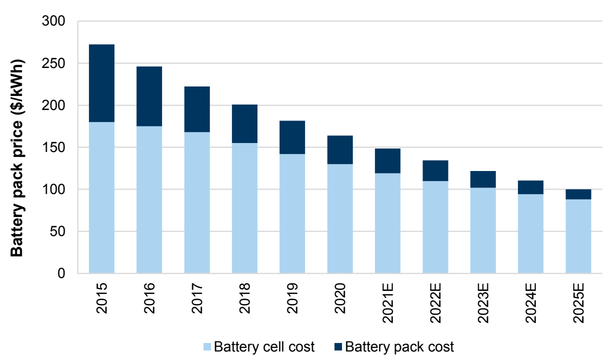


Source: Goldman Sachs Global Investment Research

3) Batteries: A key energy storage technology with a critical role to play in transforming mobility and power grid management

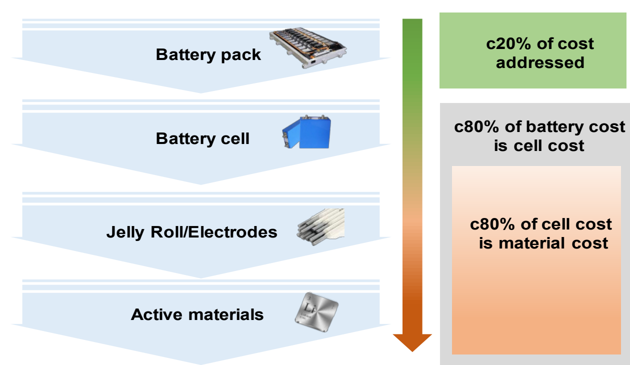
Battery technology and its evolution play a key role in aiding de-carbonization of both transport and power generation. The high focus on electric batteries over the past decade has helped to reduce battery costs by over c.50% in the past five years alone (Exhibit 46) owing to the rapid scale-up of battery 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. Notably, the majority of the reduction in battery cost emissions has come from the battery pack, but c.80% of the remaining cost is dominated by the battery cell, where cost reduction requires further technological innovation.

Exhibit 46: Battery pack costs have fallen materially over the past few years, primarily from battery pack cost reductions...
Lithium-ion battery pack and cell price (US$/kWh, LHS)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 47: ...with the remaining cost reductions required to come from the cell
Battery pack and cell cost breakdown

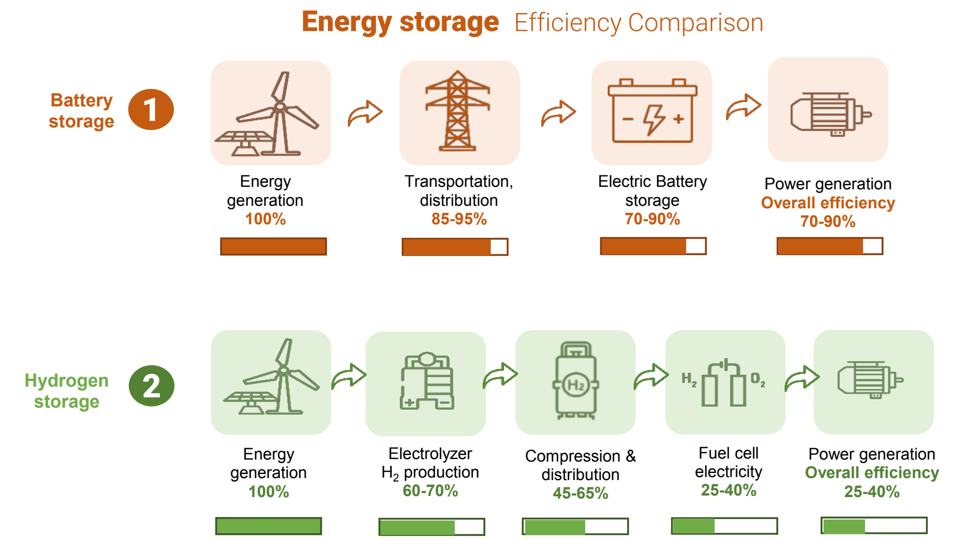


Source: Company data, Goldman Sachs Global Investment Research

Solving the energy storage challenge in power generation: Batteries vs. clean hydrogen

To reach full de-carbonization of power markets, we believe both batteries and hydrogen will play a complementary role to address different challenges. 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 of up to 4-6 hours. Hydrogen on the other hand, and the process of storing energy in chemical form and reconverting it back 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 lifecycle 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 48.

Exhibit 48: While hydrogen could be the key to solving the seasonal storage challenge in power generation, overall energy efficiency remains the weak spot of hydrogen, at c.25%-40% compared with c.70%-90% for batteries



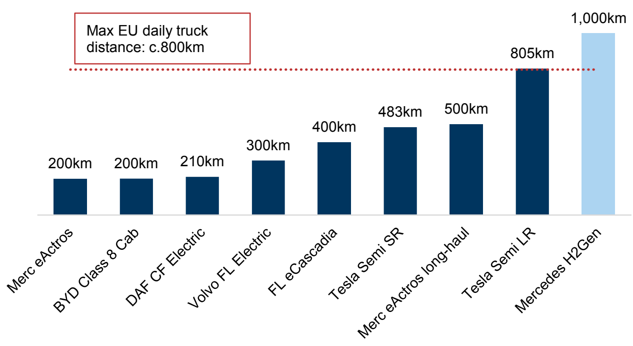
Source: Company data, Goldman Sachs Global Investment Research

Solving the energy storage challenge in transport: Batteries vs clean hydrogen

Hydrogen's key attributes (low weight and high energy per unit mass, short refueling time, zero direct emissions when sourced from renewable energy sources) make it an attractive candidate as a transportation fuel. For all hydrogen applications, the **volume requirement** for on-board storage remains, along with the comparatively low **overall well-to-wheel (or power generation to wheel) efficiency**, the **two key challenges for the use of hydrogen**. Hydrogen in ambient conditions (1 bar atmospheric pressure) has eight times lower energy density than conventional fuels such as natural gas under equivalent conditions, which typically creates the need for compression for use in on-board storage such as in FCEVs.

The exhibits that follow present our **comparative analysis for hydrogen** fuel cell electric vehicles compared to battery electric vehicles (BEVs) and gasoline internal combustion engine vehicles (ICE). Exhibit 50 shows that for a fully loaded (or fully charged) average passenger vehicle, compressed hydrogen FCEVs screen attractively compared with Li-battery EVs on a weight per unit of output energy basis (tank-to-wheel). The cost per unit energy output however for FCEVs, as well as the comparatively low energy efficiency of fuel cell systems remain the two key disadvantages for hydrogen. The cost per unit of energy output for FCEVs becomes more competitive when considering long-haul heavy transport, as their long range implies less frequent refueling is required and as large capacity (>350kWh) batteries in EVs remain costly and still in early development. This makes **FCEVs attractive for long-haul transport applications such as buses and trucks yet battery EVs remain the clear preferred choice for LDVs**.

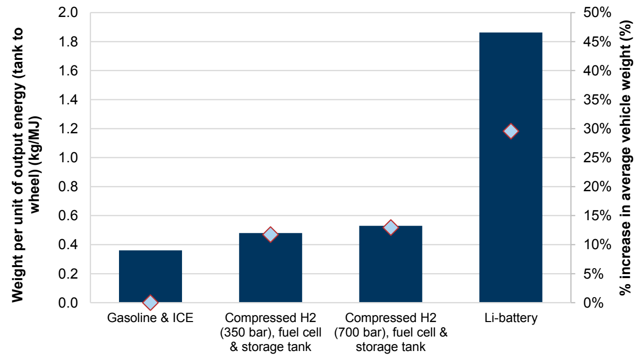
Exhibit 49: Hydrogen provides both faster refueling times and a range advantage, particularly useful for long-haul truck applications, less so for short-haul passenger transport
ZEV Class 8 trucks and range (km)



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

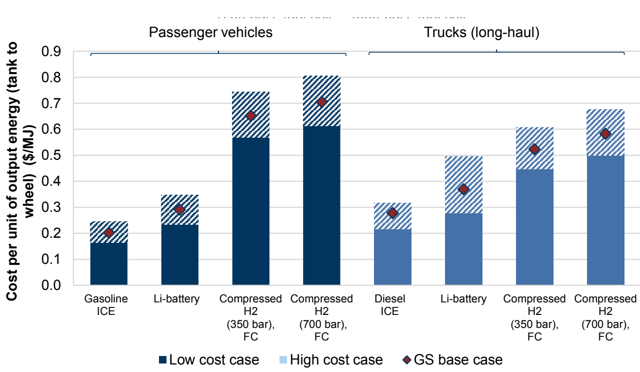
Source: Transport & Environment, EU, Goldman Sachs Global Investment Research

Exhibit 50: 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



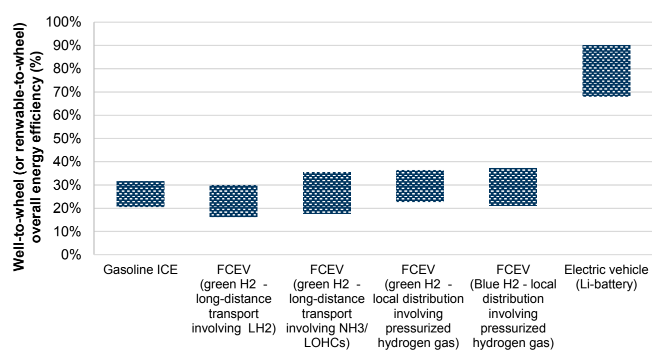
Source: US Department of Energy, EIA, Goldman Sachs Global Investment Research

Exhibit 51: 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 52: However, the low overall efficiency of FCEVs remains their key weakness when compared with electric vehicles
Well-to-wheel (or renewable-to-wheel) energy efficiency (%)



Source: Company data, Goldman Sachs Global Investment Research

4) Carbon capture: A largely under-invested technology coming back after a 'lost decade'

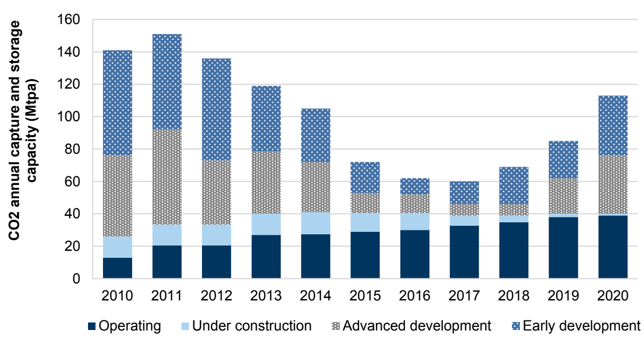
CCUS technologies can be an **effective route to global de-carbonization for industrial and power sources**: they can be used to reduce emissions from coal and gas power generation particularly for young assets, as well as across industrial processes with emissions characterized as 'harder to abate' such as iron & steel, cement and chemicals. CCUS encompass a range of technologies and processes that are designed to capture the majority of CO_2 emissions from large industrial point sources and then to provide long-term storage solutions or utilization.

We have incorporated process-specific carbon capture technologies in our Carbonomics cost curves. According to our GS paths for carbon neutrality by 2050, **CCUS across sectors can contribute to annual CO2 abatement of c.7.2 GtCO2 by 2050**, as shown in Exhibit 54 below. The single largest contributor to 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.

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 interest has returned 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 exceeding 40 Mtpa, as shown in Exhibit 53.

Exhibit 53: The pipeline of large-scale CCS facilities is regaining momentum after a 'lost decade'

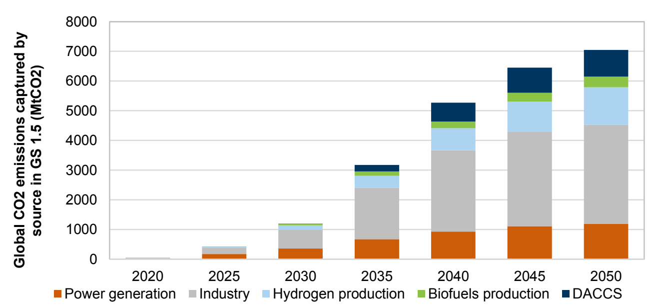
Annual CO2 capture & storage capacity from large-scale CCS facilities



Source: Global CCS Institute Status Report 2020

Exhibit 54: Our GS 1.5 path highlights the importance of CCUS, with 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)



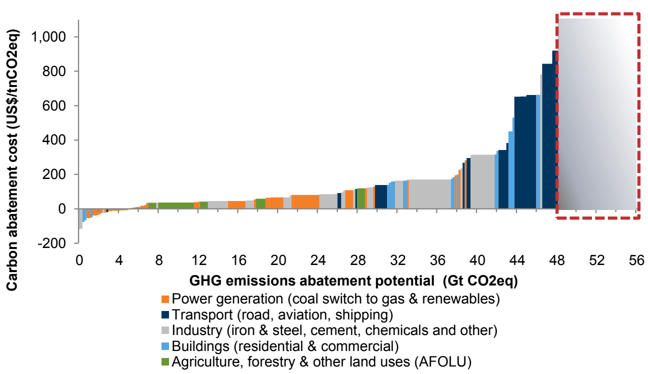
Source: Goldman Sachs Global Investment Research

The importance of carbon offsets: The last key component to full emissions abatement

We consider carbon offsets (natural sinks and non-process specific carbon capture - direct air carbon capture known as DACCS) as a critical tool for net zero to be plausible, as shown in Exhibit 55.

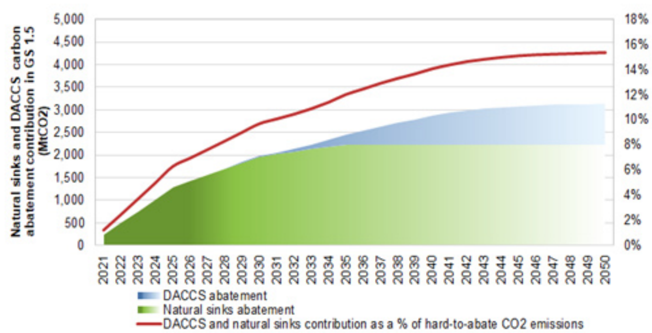
We also incorporate natural sinks and DACCS into our global net zero models (GS 1.5, GS<2.0 and GS 2.0). This is particularly the case for the path to global net zero for harder-to-abate sectors in the absence of further technological innovation. We estimate that natural sinks and DACCS' contribution 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. Voluntary offsets remain one of the only global carbon markets today offering useful tool for global collaboration of the de-carbonization challenge.

Exhibit 55: Carbon offsets (natural sinks and DACCS) are the key remaining component for global net zero across GHG emissions...
Carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



Source: Goldman Sachs Global Investment Research

Exhibit 56: ...which we estimate are particularly important for harder-to-abate sector emissions



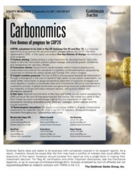
Source: Goldman Sachs Global Investment Research

Related Research

[Taking the Temperature of European Corporates: An Implied Temperature Rise (ITR) toolkit]

27 Oct 2021

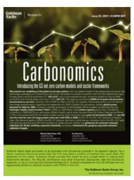
In this report we leverage our Carbonomics Net Zero Paths to gauge the implied temperature rise (ITR) of corporate de-carbonization strategies through the lenses of >110 corporates in the 15 most carbon intensive sectors of the European market. In collaboration with GS SUSTAIN, we test different ITR tools in order to determine a methodology that takes into account each corporate's growth outlook, technological readiness and positioning on the de-carbonization cost curve.



Five themes of progress for COP26

24 Sep 2021

COP26, scheduled to be held in the UK between Oct 31 and Nov 12, is a historical opportunity to accelerate the de-carbonization pledges laid out by COP21 (the Paris agreement) in 2015. The negotiations are likely to focus on climate change-related topics, including ambitious emission reduction targets by country to keep 1.5 degrees of global warming within reach, a framework for global carbon markets including the implementation of Article 6 (Article 6 of the Paris Climate Agreement is designed to enable voluntary international co-operation on climate action.



Introducing the GS net zero carbon models and sector frameworks

23 Jun 2021

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°).

China net zero: The clean tech revolution

20 Jan 2021

China's pledge to achieve net zero carbon by 2060 represents two-thirds of the c.48% of global emissions from countries that have pledged net zero, and could transform China's economy, starting with the 14th Five-Year Plan. We model the country's potential path to net zero by sector and technology, laying out US$16 tn of clean tech infrastructure investments by 2060 that could create 40 mn net new jobs and drive economic growth.

Innovation, Deflation and Affordable De-carbonization

13 Oct 2020

Net zero is becoming more affordable as technological and financial innovation, supported by policy, are flattening the de-carbonization cost curve. We update our 2019 Carbonomics cost curve to reflect innovation across c.100 different technologies to de-carbonize power, mobility, buildings, agriculture and industry.

The Rise of Clean Hydrogen

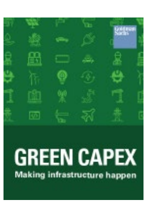
8 Jul 2020

Clean hydrogen is gaining strong political and business momentum, emerging as a major component in governments' net zero plans such as the European Green Deal. This is why we believe that the hydrogen value chain deserves serious focus after three false starts in the past 50 years. In this report we analyze the clean hydrogen company ecosystem, the cost competitiveness of green and blue hydrogen in key applications and its key role in Carbonomics: the green engine of economic recovery.

The Net Zero Guide: Transition tools for corporates and investors

15 Oct 2021

Net zero commitments from corporates and investors have rapidly increased in recent years, with two-thirds of the largest 167 global emitting corporates (responsible for over 80% of global industrial emissions) (CA100+) and over US$88tn in assets having committed to net zero. Despite significant pressure to develop a net zero transition strategy continuing to mount, particularly in the lead up to the 26th UN Climate Change Conference (COP26) this year, existing frameworks are nascent and still evolving.



Green Capex: Making infrastructure happen

11 Oct 2021

We believe Green Capex will be the dominant driver of global infrastructure over the next decade, with $6 trillion of investment needed annually to decarbonize the world, address water needs and shore up transportation and other critical systems.

Stock Implications:

Investing in Green Capex: Themes and stocks to own (Oct 11 2021)

Appendix: De-carbonization cost curve in detail

Exhibit 57: 2021 Carbonomics cost curve with carbon abatement price range (US$/tnCO2eq) and abatement potential (GtCO2eq) by technology in each sector

2021 Carbonomics cost curve - carbon abatement technologies	Industry	Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
Power generation - switch from coal to gas		(US$/tnCO2 eq)	(US$/tnCO2 eq)	(US$/tnCO2 eq)	(GtCO2eq)
Switch from coal to gas - North America (ex-US)	Power generation	-39	-49	-29	0.04
Switch from coal to gas - US	Power generation	-12	-14	-9	0.40
Switch from coal to gas -CIS	Power generation	-12	-14	-9	0.24
Switch from coal to gas -Middle East	Power generation	60	45	74	0.01
Switch from coal to gas -Asia Pacific (low gas price)	Power generation	60	45	74	1.20
Switch from coal to gas -Latin America	Power generation	60	45	74	0.05
Switch from coal to gas -Europe	Power generation	60	45	74	0.26
Switch from coal to gas -Africa	Power generation	80	60	100	0.17
Switch from coal to gas -Other Europe	Power generation	80	60	100	0.14
Switch from coal to gas -Asia Pacific (high gas price)	Power generation	81	61	101	2.74
Coal CCS	Power generation	109	85	135	0.70
Power generation - switch from gas to renewables and other clean tech					
Solar low cost scenario, high gas price	Power generation	-68	-82	-55	0.07
Solar low cost scenario, medium gas price	Power generation	-55	-66	-44	0.36
Solar base cost scenario, high gas price	Power generation	-52	-62	-41	0.07
Onshore wind low cost scenario, high gas price	Power generation	-50	-60	-40	0.05
Onshore base low cost scenario, high gas price	Power generation	-39	-46	-31	0.05
Solar base cost scenario, medium gas price	Power generation	-38	-46	-31	0.36
Onshore wind low cost scenario, medium gas price	Power generation	-36	-44	-29	0.25
Nuclear, high gas price	Power generation	-26	-32	-21	0.05
Onshore wind medium cost scenario, medium gas price	Power generation	-25	-30	-20	0.25
Offshore wind low cost scenario, high gas price	Power generation	-23	-27	-18	0.04
Hydroelectric, high gas price	Power generation	-22	-27	-18	0.09
Solar+battery low cost scenario, high gas price	Power generation	-19	-23	-15	0.01
Onshore high low cost scenario, high gas price	Power generation	-15	-18	-12	0.05
Nuclear, medium gas price	Power generation	-13	-15	-10	0.27
Offshore wind low cost scenario, medium gas price	Power generation	-9	-11	-8	0.20
Hydroelectric, medium gas price	Power generation	-9	-10	-7	0.47
Solar low cost scenario, low gas price	Power generation	-8	-9	-6	0.29
Offshore wind high cost scenario, high gas price	Power generation	-6	-8	-5	0.04
Solar + hydrogen storage low cost scenario, medium gas price	Power generation	-5	-6	-4	0.05
Onshore wind high cost scenario, medium gas price	Power generation	-2	-2	-1	0.25
Onshore wind +battery low cost scenario, high gas price	Power generation	0	0	0	0.01
Solar high cost scenario, high gas price	Power generation	4	3	5	0.07
Offshore wind high cost scenario, medium gas price	Power generation	7	6	8	0.20
Solar base cost scenario, low gas price	Power generation	9	7	11	0.29
Onshore wind low cost scenario, low gas price	Power generation	11	9	13	0.20
Onshore wind +battery low cost scenario, medium gas price	Power generation	13	10	16	0.04
Solar high cost scenario, medium gas price	Power generation	17	14	21	0.36
Solar + hydrogen storage low cost scenario, high gas price	Power generation	18	15	22	0.02
Onshore base low cost scenario, low gas price	Power generation	22	17	26	0.20
Solar + hydrogen storage low cost scenario, medium gas price	Power generation	32	25	38	0.08
Nuclear, low gas price	Power generation	34	27	41	0.22
Onshore wind + hydrogen storage low cost scenario, high gas price	Power generation	37	29	44	0.01
Offshore wind low cost scenario, low gas price	Power generation	38	30	45	0.16
Hydroelectric, low gas price	Power generation	38	31	46	0.37
Solar+battery low cost scenario, low gas price	Power generation	42	33	50	0.04
Offshore wind +battery low cost scenario, high gas price	Power generation	42	34	51	0.00
Onshore high low cost scenario, low gas price	Power generation	45	36	54	0.20
Onshore wind + hydrogen storage low cost scenario, medium gas price	Power generation	50	40	60	0.06
Offshore wind high cost scenario, low gas price	Power generation	54	43	65	0.16
Offshore wind +battery low cost scenario, medium gas price	Power generation	56	44	67	0.02
Onshore wind +battery low cost scenario, low gas price	Power generation	60	48	72	0.03
Solar high cost scenario, low gas price	Power generation	64	51	77	0.29
Offshore wind + hydrogen storage low cost scenario, high gas price	Power generation	67	53	80	0.01
Solar + hydrogen storage low cost scenario, low gas price	Power generation	79	63	94	0.07
Offshore wind + hydrogen storage low cost scenario, medium gas price	Power generation	80	64	96	0.03
Onshore wind + hydrogen storage low cost scenario, low gas price	Power generation	97	78	117	0.04
Offshore wind +battery low cost scenario, low gas price	Power generation	103	82	123	0.02
Onshore wind +battery high cost scenario, high gas price	Power generation	108	87	130	0.01

Source: Goldman Sachs Global Investment Research

2021 Carbonomics cost curve - carbon abatement technologies	Industry	Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
NG CCS, low case	Power generation	110	88	132	0.05
NG CCS, base case	Power generation	120	96	144	0.25
Onshore wind +battery high cost scenario, medium gas price	Power generation	122	97	146	0.04
Offshore wind + hydrogen storage low cost scenario, low gas price	Power generation	127	102	153	0.02
Solar+battery high cost scenario, high gas price	Power generation	127	102	153	0.01
NG CCS, high case	Power generation	130	104	156	0.20
Solar+battery high cost scenario, medium gas price	Power generation	141	113	169	0.05
Offshore wind +battery high cost scenario, high gas price	Power generation	166	133	200	0.00
Hydrogen CGGT, low gas price	Power generation	168	135	202	0.08
Onshore wind +battery high cost scenario, low gas price	Power generation	169	135	203	0.03
Onshore wind + hydrogen storage high cost scenario, high gas price	Power generation	170	136	204	0.01
Offshore wind +battery high cost scenario, medium gas price	Power generation	180	144	216	0.02
Offshore wind+ hydrogen storage high cost scenario, medium gas price	Power generation	183	147	220	0.06
Solar+battery high cost scenario, low gas price	Power generation	188	150	225	0.04
Solar + hydrogen storage high cost scenario, high gas price	Power generation	189	151	227	0.02
Hydrogen CGGT, medium gas price	Power generation	195	156	234	0.10
Solar + hydrogen storage high cost scenario, medium gas price	Power generation	203	162	243	0.08
Offshore wind +battery high cost scenario, low gas price	Power generation	227	181	272	0.02
Offshore wind + hydrogen storage high cost scenario, high gas price	Power generation	228	182	274	0.01
Onshore wind + hydrogen storage high cost scenario, low gas price	Power generation	230	184	277	0.04
Offshore wind + hydrogen storage high cost scenario, medium gas price	Power generation	242	193	290	0.03
Solar + hydrogen storage high cost scenario, low gas price	Power generation	250	200	299	0.07
Hydrogen CGGT, high gas price	Power generation	282	225	338	0.02
Offshore wind + hydrogen storage high cost scenario, low gas price	Power generation	289	231	346	0.02
Transport					
Switch aircraft to one of highest efficiency	Transport	-19	-68	54	0.17
City Buses to electric buses	Transport	92	77	107	0.33
LNG fuel in shipping	Transport	115	68	162	0.17
Switch to electric trucks, short-haul	Transport	138	123	153	1.08
Marine biofuels	Transport	235	215	254	0.02
Biofuels on road transport	Transport	268	179	357	0.10
Switch to electric trucks, medium-haul	Transport	291	276	307	0.15
Clean ammonia fuel-run ships	Transport	295	226	369	0.34
Hydrogen FCEV truck, heavy long-haul	Transport	342	314	383	0.92
Hydrogen FC rail	Transport	383	150	615	0.12
Diesel vehicle to EV, urban	Transport	652	345	997	0.52
Aviation biofuels	Transport	653	594	752	0.62
Gasoline vehicle to EV, urban	Transport	662	454	896	0.99
Gasoline vehicle to EV, rural	Transport	844	623	1,129	0.94
Diesel vehicle to EV, rural	Transport	920	594	1,342	0.50
Industry & industrial waste					
Efficiency gains & plastics recycling	Industry & waste	-119	-143	-95	0.07
Secondary production through scrap/recycling in aluminium	Industry & waste	-115	-138	-92	0.19
Energy & process efficiency through recycling and BAT in pulp & paper	Industry & waste	-23	-28	-19	0.10
Efficiency gains in ammonia production	Industry & waste	37	29	44	0.06
Ammonia CCS	Industry & waste	45	34	60	0.09
Efficiency industrial gains - low cost (incl. waste to heat recovery)	Industry & waste	45	32	59	3.61
Steel production switch from BF-BOF to scrap EAF (circular economy)	Industry & waste	49	39	59	0.73
Other chemicals CCS	Industry & waste	55	0	0	0.00
Other petrochemical process efficiency gains	Industry & waste	67	47	87	0.57
Other material & energy efficiency improvements in cement (ie. BAT)	Industry & waste	78	62	94	0.15
Cement CCS	Industry & waste	85	65	115	1.46
Switch to electrolysis-derived hydrogen process in ammonia production	Industry & waste	96	58	135	0.20
Reducing clinker to cement ratio in cement	Industry & waste	106	85	127	0.26
Switch to charcoal/biomass as fuel and feedstock in traditional steel process	Industry & waste	106	85	128	0.02
Switch to natural gas DIR-EAF in iron & steel (switch from BF-BOF)	Industry & waste	112	90	134	0.13
Steel CCS	Industry & waste	125	100	150	0.59
Switch to hydrogen or biogas DIR-EAF in iron & steel (switch from BF-BOF)	Industry & waste	164	98	230	0.91
Switch to clean hydrogen as feedstock in petrochemicals	Industry & waste	169	135	203	0.25
Industrial manufacturing electrification (ie. electrification of heat)	Industry & waste	170	119	221	4.01
Fuel switch to biomass & waste in cement	Industry & waste	235	188	282	0.14
Al CCUS	Industry & waste	250	175	325	0.03
Efficiency industrial gains other high cost	Industry & waste	314	220	408	2.40
Switch to biogas or biomass as a feedstock in ammonia process	Industry & waste	559	447	671	0.03
Switch to biogas or biomass as a feedstock in petrochemicals	Industry & waste	781	625	938	0.14

Source: Goldman Sachs Global Investment Research

2021 Carbonomics cost curve - carbon abatement technologies	Industry	Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
Buildings		(US$/tnCO2 eq)	(US$/tnCO2 eq)	(US$/tnCO2 eq)	(GtCO2eq)
LED and increased efficiency - commercial	Buildings	-77	-96	-58	0.16
LED and increased efficiency, residential	Buildings	-67	-83	-50	0.13
Insulation (cavity and wall) - commercial buildings	Buildings	-58	-72	-43	0.09
Insulation (cavity wall) for new residential	Buildings	-50	-63	-38	0.06
HVAC smart systems/efficiency gains - commercial	Buildings	-48	-60	-36	0.05
HVAC Systems/thermostat & smart meters for residential new	Buildings	-42	-52	-31	0.03
HVAC Systems/thermostat & smart meters residential retrofit	Buildings	-32	-40	-24	0.06
Insulation (cavity wall) - residential retrofit	Buildings	-20	-25	-15	0.11
Heat pumps - water heating - commercial	Buildings	140	105	174	0.15
Renewable heat (solar thermal, PV) - water heating - commercial	Buildings	149	112	186	0.07
Heat pumps - commercial buildings	Buildings	152	114	190	0.23
BACS systems/efficiency gains/BAT appliances residential	Buildings	159	120	199	0.28
Heat pumps - water heating (ground source heat pump), residential	Buildings	164	123	205	0.32
Renewable heat (solar thermal, PV) - water heating, residential	Buildings	175	131	219	0.14
Heat pumps (air to air), residential, new	Buildings	179	134	224	0.14
BACS systems - commercial	Buildings	183	138	229	0.08
Heat pumps (air to air), residencial retrofit	Buildings	200	150	249	0.22
Heat pumps running on energy seasonally stored via hydrogen - commercial	Buildings	269	202	336	0.18
Heat pumps running on energy seasonally stored via hydrogen - residential	Buildings	316	237	395	0.11
Heat pumps running on energy seasonally stored via hydrogen - residential, retrofit	Buildings	337	253	421	0.22
Hydrogen boiler (switch from gas boiler) - commercial	Buildings	451	338	564	0.36
Hydrogen boiler (switch from gas boiler) - residential	Buildings	531	398	663	0.22
Hydrogen boiler (switch from gas boiler) - residential, retrofit	Buildings	663	498	829	0.50
Agriculture, Forestry and Other Land uses (AFOLU)					
Reduce conversion of savvanas and natural grasslands	Agriculture, forestry & other land uses	10	6	14	0.07
Reduce conversion/draining and burning of peatlands	Agriculture, forestry & other land uses	35	21	49	0.84
Reduce deforestation, forest degradation	Agriculture, forestry & other land uses	37	22	52	3.60
Improved cropland management practices	Agriculture, forestry & other land uses	42	25	59	0.88
Improved grazing land management practices	Agriculture, forestry & other land uses	58	35	81	1.00
Improved livestock management practices	Agriculture, forestry & other land uses	120	72	167	0.80

Non process-specific sequestration routes		Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
		(US$/tnCO2 eq)	(US$/tnCO2 eq)	(US$/tnCO2 eq)	(GtCO2eq)
Low cost natural sinks (reforestation, afforestation, agroforestry)	Natural sinks	13	0	25	2.0
Medium cost natural sinks (reforestation, afforestation, agroforestry)	Natural sinks	38	20	55	1.4
High cost natural sinks (reforestation, afforestation, agroforestry)	Natural sinks	75	50	100	3.2
DACCS	DACCS	287	125	549	*almost infinite*

Source: Goldman Sachs Global Investment Research

Disclosure Appendix

Reg AC

We, Michele Della Vigna, CFA and Zoe Clarke, 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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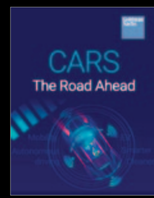

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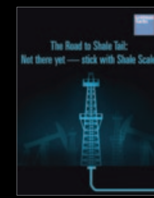

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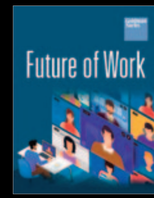

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