Goldman Sachs

Carbonomics

Innovation, Deflation and Affordable De-carbonization

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, and draw three key conclusions:

1) low-cost de-carbonization technologies (mostly renewable power) continue to **improve consistently through scale**, reducing the lower half of the cost curve by 20% on average vs. our 2019 cost curve;

2) **clean hydrogen emerges as the breakthrough technology** in the upper half of the cost curve, lowering the cost of de-carbonizing emissions in more difficult sectors (industry, heating, heavy transport) by 30% and increasing the proportion of abatable emissions from 75% to 85% of total emissions; and

3) **financial innovation and a lower cost of capital** for low-carbon activities have driven around one-third of renewables cost deflation since 2010, highlighting the importance of shareholder engagement in climate change, monetary stimulus and stable regulatory frameworks.

The result of these developments is very encouraging, **shaving US$1 tn pa from the cost of the path towards net zero** and creating a broader connected ecosystem for de-carbonization that includes renewables, clean hydrogen (both blue and green), batteries and carbon capture.

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PM Summary: The green engine of economic recovery gains speed through technological and financial innovation

We update our 2019 Carbonomics cost curve to reflect technological innovation, manufacturing efficiency through scale and lower cost of capital

In our deep-dive de-carbonization report published in 2019, *Carbonomics: The future of energy in the Age of Climate Change*, we introduced our inaugural estimate of the carbon abatement cost curve. The Carbonomics cost curve shows the reduction potential for anthropogenic GHG emissions through >100 different applications of GHG conservation technologies across all key emitting sectors globally: power generation, industry, mobility, buildings and agriculture. **In this report, we update the inaugural Carbonomics cost curve to reflect four key changes** that we have witnessed over the past 12 months: 1) **cost deflation** in low-carbon technologies that are being developed at global scale, such as solar, wind and electric vehicles; 2) **positive momentum in global de-carbonization policies** following the net zero target embraced by some of the world's largest economies; 3) the consequent **revitalization of high-cost technologies** that are pivotal for net zero, such as clean hydrogen and carbon capture; and 4) the **falling cost of capital for low-carbon projects** with a sound regulatory framework, as a consequence of expansionary monetary policy and investors' rising focus on de-carbonization and climate change.

Technological and financial innovation are flattening the de-carbonization cost curve, lowering the cost of net zero by $1 tn pa

The transformation of the cost curve through technological and financial innovation, supported by policy, is flattening the de-carbonization cost curve, improving the affordability of net zero. The lower half of the cost curve is dominated by renewable power and technologies already at scale. We estimate that **the annual cost of 50% de-carbonization has been reduced by c.20%**, from US$1.2 tn pa based on the initial 2019 cost curve of de-carbonization, to US$1.0 tn pa based on the latest updated 2020 cost curve. **Two-thirds of this cost deflation was driven by improved manufacturing efficiency through global scale and one-third by lower cost of capital**. As we move higher on the abatement cost curve towards 70% de-carbonization, we encounter the harder-to-abate emissions in need of material technological innovation, and the cost curve takes on an exponential shape. This part of the cost curve has seen the greatest improvement year on year, mainly thanks to renewed policy support for clean hydrogen, resulting in c.30% global annual cost reduction, on our estimates, from US$2.9 tn to US$2.0 tn (**for 70% de-carbonization** through conservation – we look at carbon sequestration separately), **c.US$1 tn of annual savings** as we aim for net zero by 2050. Effectively, the 2020 cost curve results in a maximum c.85% de-carbonization through conservation vs c.75% de-carbonization achieved at the same cost based on the 2019 cost curve, contributing an additional c.10% of de-carbonization potential. This transformation of the high end of the Carbonomics cost curve is the result of technologies such as the addition of clean hydrogen in different industrial applications including iron & steel, petrochemicals (ammonia, methanol) and high-temperature heat, the addition of clean ammonia and hydrogen for shipping and long-haul road transport, respectively, the addition of energy storage (batteries for intraday, hydrogen for seasonal) for power generation, enabling the full uptake of renewables, the addition of hydrogen blending for the de-carbonization of buildings' heating systems, and more.

Clean hydrogen emerges as the breakthrough technology in the upper half of the cost curve

We estimate that c.35% of the de-carbonization of global anthropogenic GHG emissions is reliant on access to clean power generation, with the second most scalable (and complementary) technology being clean hydrogen. **Clean Hydrogen addresses the tougher to de-carbonize emissions (industry, heating, heavy transport) that make up 20% of global GHG emissions,** and extends the proportion of abatable emissions (through conservation) from 75% to 85% of the total. As we outlined in our in-depth report *Carbonomics: The rise of clean hydrogen*, clean hydrogen could unlock de-carbonization in some of the harder-to-abate sectors including: long-haul transport (trucks), seasonal storage that enables the full uptake of renewables in power generation, high-temperature heat for industrial combustion and other industrial applications (such as iron & steel, petrochemicals), heating for buildings, and more. **Clean hydrogen cost competitiveness is also closely linked to cost deflation and large-scale developments in renewable power and carbon capture** (two key technologies to produce it)**, creating three symbiotic pillars of de-carbonization**. 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. Hydrogen is very versatile, both in its production and consumption: it is light, storable, has high energy content per unit mass and can be readily produced at an industrial scale. The key challenge comes from the fact that hydrogen (in its ambient form as a gas) is the lightest element and so has a low energy density per unit of volume, making long-distance transportation and storage complex and costly.

Financial innovation and lower cost of capital for low-carbon activities has driven c.1/3 of renewables cost deflation since 2010

Shareholder engagement in climate change, monetary stimulus and stable regulatory frameworks have been key drivers behind a falling cost of capital for low-carbon projects. **The ongoing downward trajectory of the cost of capital has been a key driver of the overall affordability and competitiveness of clean energy**. We estimate that the reduction in the cost of capital has contributed about one-third of the >70% reduction in LCOEs of renewable power technologies, along with the cost deflation that renewable energy has enjoyed over the past decade, benefiting from economies of scale. **In contrast, financial conditions keep tightening for long-term hydrocarbon developments**, creating higher barriers to entry, lower activity, and ultimately lower oil & gas supply in our view. This has created an unprecedented divergence in the cost of capital for the supply of energy, where the continuing shift in allocation away from hydrocarbon investments has led to **hurdle rates of 10-20% for long-cycle oil & gas developments compared with c.3-5% for renewable power investments** in the

OECD. With global GHG emissions on a persistent upward trajectory over the past decade, 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 tripled over the same period. So far, 2020 has been, despite the outbreak of COVID-19, another year of strong shareholder engagement on climate change, with the year-to-date climate-related shareholder resolutions exceeding last year's on an annualized basis (the most notable increase coming from Europe). Similarly, the percentage vote in favour of such resolutions has increased yoy, currently at c.30%. This investor pressure, however, is not uniformly distributed across sectors and shows a clear bias towards energy producers vs. energy consumers: data since 2014 shows 50% of proposals target energy producers (oil & gas, utilities, coal) while only 30% of the proposals target the sectors that account for most of the final energy consumption.

We estimate that global investors are already pricing in c.US$80/ton carbon pricing in the cost of capital of new long-term oil projects

We estimate that the divergence in the cost of capital for high-carbon vs. low-carbon investments implies a carbon price of US$40-80/ton, well above most carbon pricing schemes. We calculate the implied carbon price by leveraging our Top Projects database of the most important oil & gas projects in the world. We estimate the projects' "well to wheel" carbon intensity (scope 1+2+3) and charge each project the cost of carbon in full (we assume the producer takes the full economic hit from carbon pricing, without passing on any of the cost to the consumer through higher oil and gas prices). We calculate the IRR sensitivity by oil & gas field to different CO_2 prices and work out the carbon price that would bring the IRR of the project in line with the IRR of low-carbon projects (renewables) that were developed in the same year. We estimate that the IRR sensitivity of oil and LNG projects is 14-32 bps for each US$1/ton of carbon pricing, with an average of 21 bps. We make two critical assumptions in this analysis: (1) we assume that the carbon cost associated with the use of the oil & gas produced (scope 3) is fully paid by the producers and not by the final consumer of those hydrocarbons; and (2) we consider the different risk profile of renewables vs. hydrocarbon developments given the implicit incentive for renewables provided by governments, and include its value in the implied carbon price. Our results indicate that **the IRR premium for long-cycle offshore oil and LNG projects relative to renewables implies a carbon price in the range of US$60-130/tn CO_2 (US$80/tnCO_2 on average) for offshore oil and US$30-60/tn$CO_2$ (US$40/ton on average) for LNG. The capital markets are therefore implying a materially higher cost of carbon than the global average carbon price of c.US$3/tn CO_2.**

Carbon sequestration also has a key role to play to achieve affordable net zero

We envisage **two complementary paths to enable the world to reach net zero emissions: conservation and sequestration**. The former refers to all technologies enabling the reduction of gross greenhouse gases emitted and the latter refers to natural sinks and carbon capture, usage and storage technologies (CCUS) that reduce net emissions by subtracting carbon from the atmosphere. While the conservation cost curve has larger scope for low-cost de-carbonization opportunities and a smaller range of uncertainty, it steepens exponentially beyond 50%. **The sequestration cost curve, on the other hand, offers fewer low-cost solutions and has greater cost uncertainty, but provides tremendous long-term potential if a commercially feasible solution for Direct Air Carbon Capture is developed**. We believe that carbon sequestration can be an attractive competing technology for sectors in which emissions are harder or more expensive to abate, with industry being a prominent example. The merged cost curve of de-carbonization that incorporates both conservation and sequestration initiatives shows that 100% net de-carbonization is achievable and that the overall cost would be lower than by following the conservation route alone. The merged cost curve indicates that >60% of the current global anthropogenic GHG emissions can be abated at an implied carbon price of <US$100/tn$CO_2$, consisting mostly of renewable power and natural sinks. **Conservation technologies overall contribute c.70% of total abatement, with natural sinks and carbon capture contributing the remaining c.30% of total abatement, on our estimates.**

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Carbonomics: Innovation, Deflation and Affordable De-carbonization in numbers

Our updated 2020 Carbonomics cost curve of de-carbonization is **flattening**, leading to **c.20%** reduction in the annual cost to achieve 50% global de-carbonization...

...and **c.30%** in the annual cost to achieve 70% de-carbonization, translating into c.**$1 tn of annual global savings** on the path to Net Zero.

Our latest 2020 Carbonomics cost curve leads to **c.85%** global de-carbonization through current conservation technologies **vs c.75%** de-carbonization achieved at the **same cost** based on last year's cost curve.

Clean hydrogen emerges as a key transformational technology addressing the harder-to-decarbonize emissions (industry, heating, heavy long-haul transport) making **up c.20%** of global GHG emissions.

Access to renewable power is vital, with **c.35%** of global de-carbonization reliant upon it...

...and we estimate that the renewable energy technologies have experienced **>70%** deflation over the past decade...

...with financial innovation and lower cost of capital contributing to **c.1/3** of the cost reduction on our estimates.

In contrast, financial conditions keep tightening for hydrocarbon developments, leading to hurdle rates of **>20%** for long-cycle oil developments...

...compared with **c.3-5%** for renewable power investments.

This divergence in the cost of capital for high- vs low-carbon investments implies a carbon price of **$40-80/tnCO2**, on our estimates.

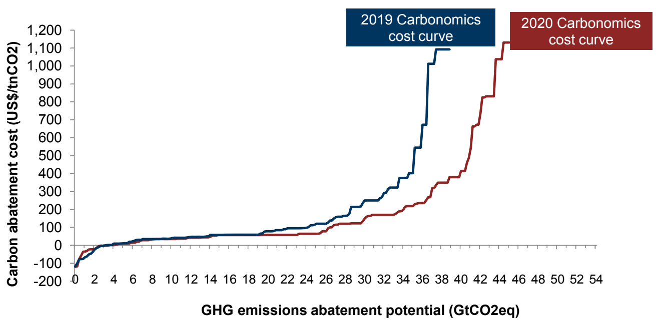
Carbon sequestration is a key complementary path to achieve affordable Net Zero, with a reduction of **c.$3 tn pa** to achieve Net Zero through a combination of sequestration and conservation technologies vs relying solely on conservation technologies for c.85% de-carbonization...

...with the merged conservation-sequestration de-carbonization cost curve indicating that **>60%** of current global anthropogenic GHG emissions are abatable at an implied carbon price **<$100/tnCO2eq**...

..with conservation contributing to **c.70%** of total abatement and sequestration **c.30%**.

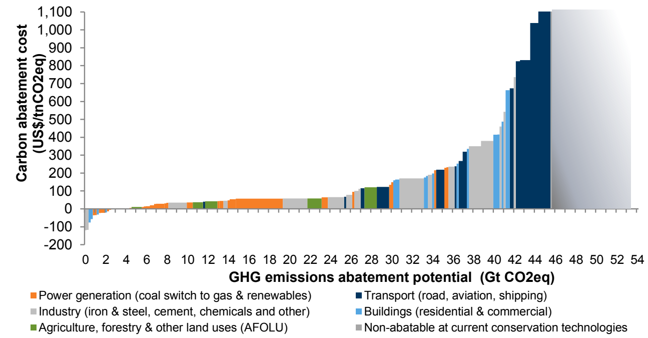
Carbonomics in 12 charts

Exhibit 1: Technological and financial innovation are flattening the de-carbonization cost curve...
Conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



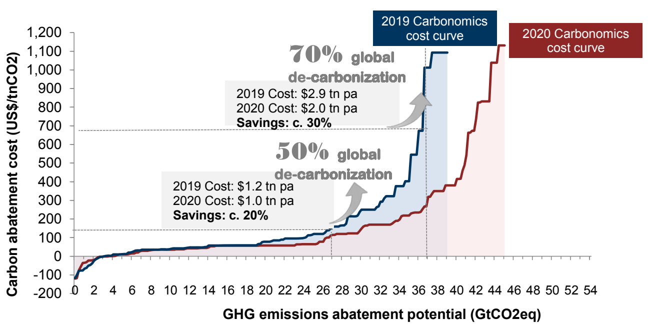
Source: Goldman Sachs Global Investment Research

Exhibit 2: ... improving the affordability of net zero carbon...
Conservation carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



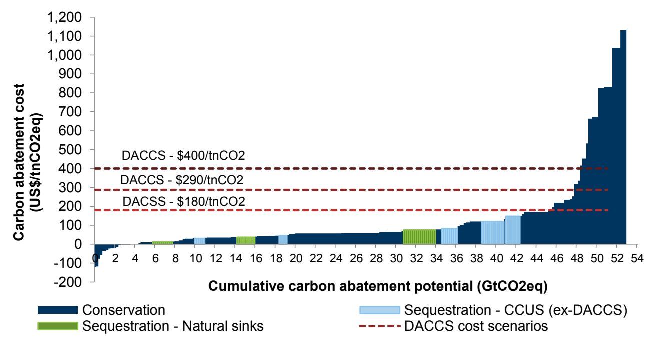
Source: Goldman Sachs Global Investment Research

Exhibit 3: ...by lowering the cost of 70% carbon abatement by $1 tn pa.
Conservation carbon abatement cost curve for anthropogenic GHG emissions and associated costs for different levels of de-carbonization



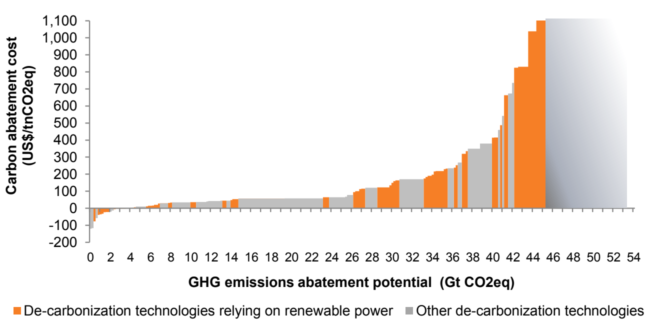
Source: Goldman Sachs Global Investment Research

Exhibit 4: The merged cost curve of abatement and sequestration shows close to 20% cost saving to net zero
Merged de-carbonization cost curve combining both conservation and sequestration technologies



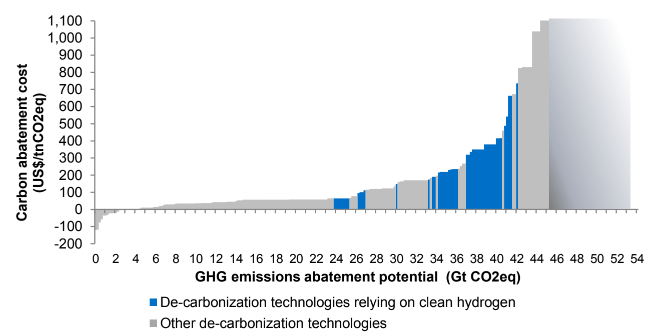
Source: Goldman Sachs Global Investment Research

Exhibit 5: Renewable power is vital for the de-carbonization of c.35% of global emissions across sectors...
2020 conservation de-carbonization cost curve with technologies relying on renewable power indicated



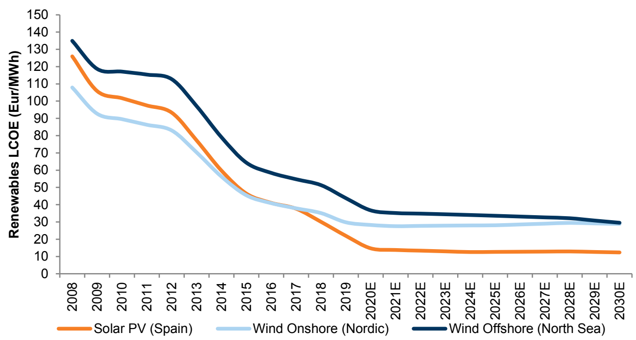
Source: Goldman Sachs Global Investment Research

Exhibit 6: ...and clean hydrogen emerges as a key technology, required to de-carbonize c.20% of global emissions across sectors.
2020 Conservation de-carbonization cost curve with technologies relying on clean hydrogen indicated



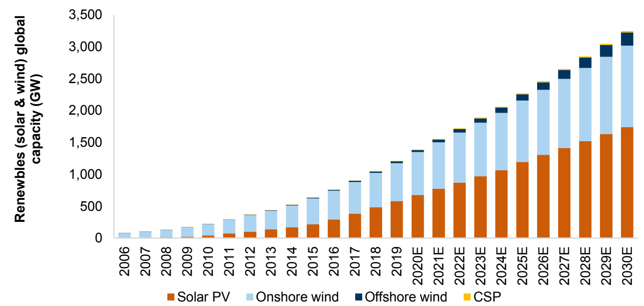
Source: Goldman Sachs Global Investment Research

Exhibit 7: Scale fosters cost deflation: Renewable power costs have decreased by >70%...
LCOE for solar PV, wind onshore and wind offshore with select regions in Europe (EUR/MWh)



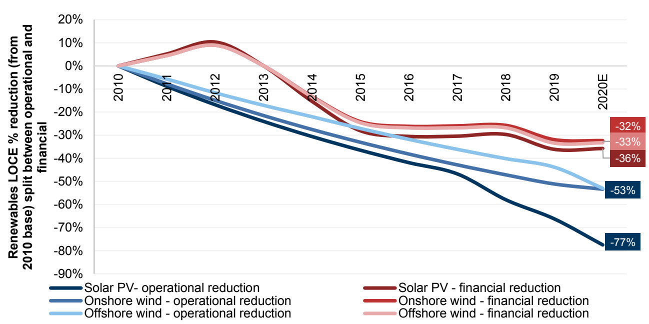
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 8: ...on the back of economies of scale and technological innovation...
Global renewables (solar & wind) installed capacity (GW)



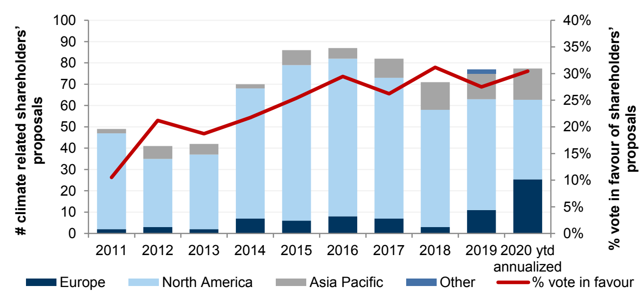
Source: IRENA, Company data, Goldman Sachs Global Investment Research

Exhibit 9: ...while financial innovation and a lower cost of capital have driven c.1/3 of renewables cost deflation since 2010.
LCOE % reduction from 2010 split between operational and financial



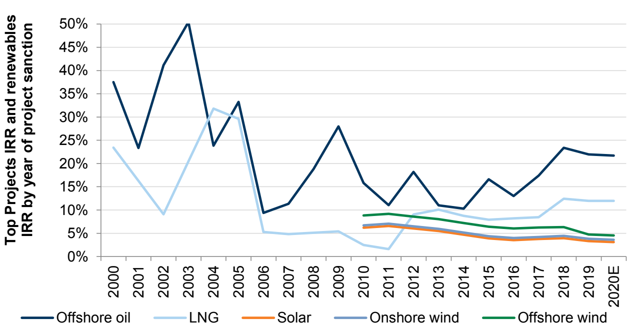
Source: Goldman Sachs Global Investment Research

Exhibit 10: Investor engagement in climate change keeps rising...
Number of climate-related shareholders' proposals vs. % vote in favour



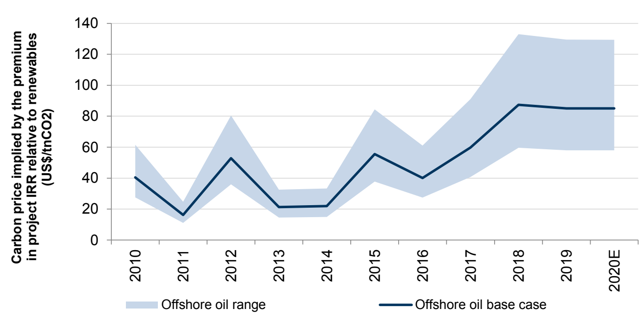
Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 11: ...driving an unprecedented divergence in the cost of capital...
Top Projects IRR for oil & gas and renewable projects by year of project sanction



Source: Goldman Sachs Global Investment Research

Exhibit 12: ...and an implied carbon price of US$80/tnCO2 for new long-cycle oil developments.
Carbon price implied by the IRR premium for offshore oil projects compared to renewables (US$/tnCO2)



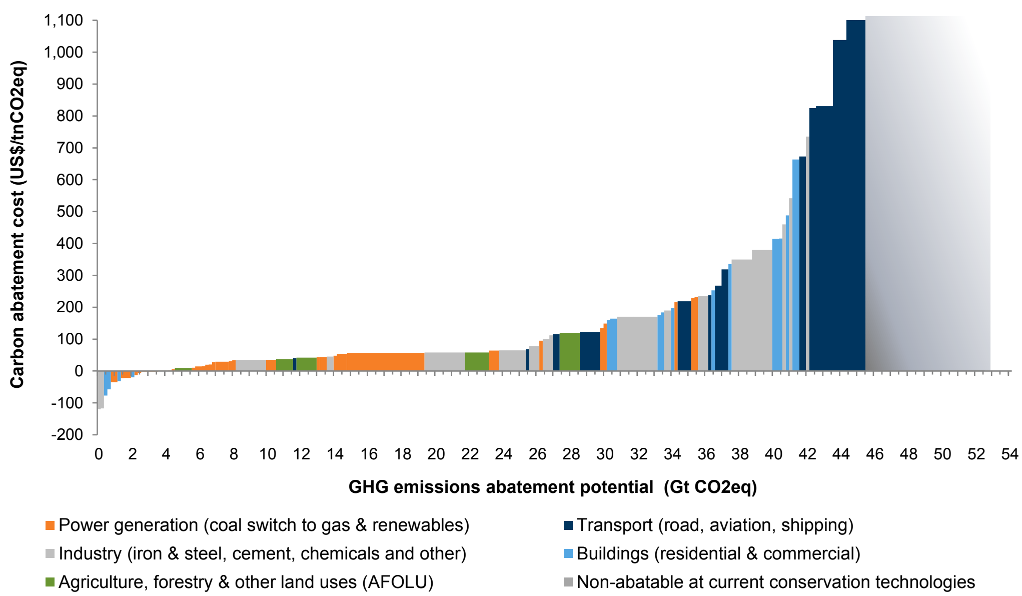
Source: Goldman Sachs Global Investment Research

The cost curve of de-carbonization is transforming along with technological innovation and acceleration in low-carbon investments

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 primarily comprises conservation 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 (we examine carbon sequestration technologies in a different cost curve – Exhibit 18) across all key emission-contributing industries globally: power generation, industry and industrial waste, transport, buildings and agriculture. In this report, **we update the inaugural de-carbonization cost curve**, now **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 cost curve from its original publication to the newly updated one is summarized in Exhibit 15.

Exhibit 13: The cost curve of de-carbonization has transformed, with new technology additions and cost deflation in others expanding the total GHG emissions abatement potential while widening the range of low-cost investment opportunities

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



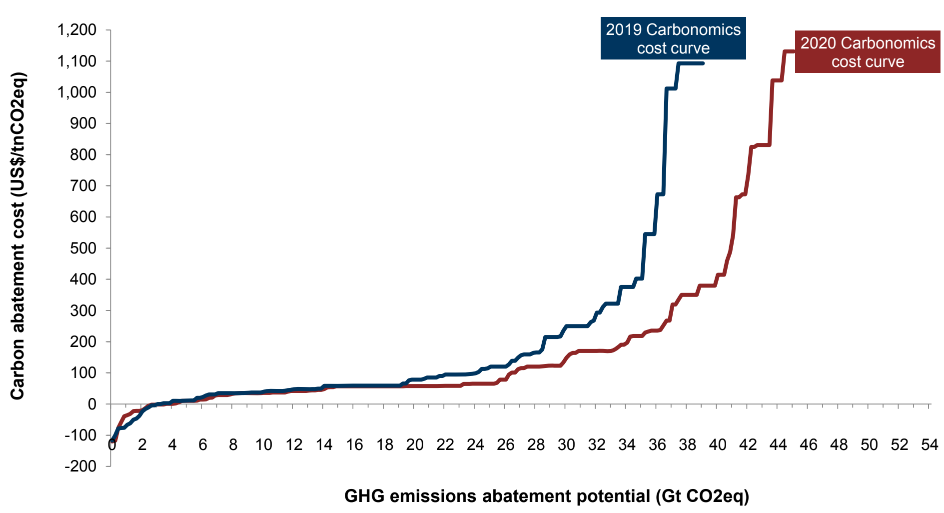
Source: Goldman Sachs Global Investment Research

As shown in Exhibit 14, **the wealth of relatively low-cost de-carbonization opportunities has increased even further with the transformation of the cost curve,** resulting in an overall higher proportion of abatable emissions under current technologies and a flattening of the cost curve**.** This is in line with our view, as we highlight in our report *Carbonomics: The green engine of economic recovery*, that **the recovery that is likely to follow the COVID-19 crisis** will see an **acceleration of low-cost opportunities for de-carbonization**. In fact, such areas of investment could act as a further catalyst for increased investment and employment, a key focus for governments in the coming months.

Moreover, we note that while in our original de-carbonization cost curve, an estimated c.25% of anthropogenic GHG emissions remained non-abatable (through carbon conservation) under the commercial technologies then available at large scale, this **proportion has decreased to c.15% on the updated de-carbonization cost curve**, as more technologies reach commercial scale and find their way into our cost curve analysis. A notable example of this is clean hydrogen, which, as we outlined in our deep-dive report *Carbonomics: The rise of clean hydrogen*, could unlock de-carbonization in some of the harder-to-abate sectors including*:* long-haul heavy transport, seasonal storage that enables the full uptake of renewables in power generation, high-temperature heat for industrial combustion, other industrial applications (such as iron & steel and petrochemicals), and heating systems for buildings.

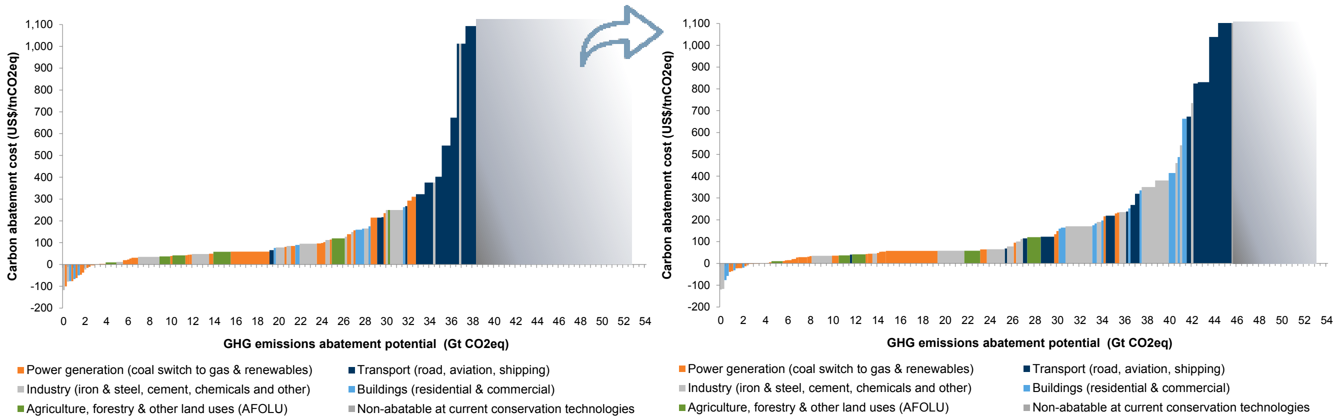
Exhibit 14: The updated Carbonomics cost curve has shifted notably to the right, as more de-carbonization technologies emerge (such as clean hydrogen) while others continue on a cost deflationary path (low-carbon electricity)

2020 vs 2019 Conservation carbon abatement cost curve 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 15: Summary of key technologies considered in the construction of the de-carbonization cost curve, along with the new technological additions in our 2020 cost curve vs 2019



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, biojet) remain the sole commercially available de-carbonization route longer term.
- **Shipping/marine:** LNG ships a technological option for ships meeting a threshold size, marine biofuels another viable technology, with clean ammonia run ships the key 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.

2020 Cost curve technology additions

- Clean hydrogen FCEVs for long-haul heavy trucks
- Switch to most efficient aircraft in aviation
- Clean ammonia-run ships

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 achieve full de-carbonizaation 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.

2020 Cost curve technology additions

- Clean hydrogen-based seasonal storage for full uptake of renewables in power generation
- Hydrogen and biogas based CGGTs

AGRICULTURE

De-carbonization technologies

- **Improved land management 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.

BUILDINGS

De-carbonization technologies

- **Heating**: Hydrogen and renewable electricity-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.

2020 Cost curve technology additions

- Clean hydrogen for heating (including switch from conventional gas boilers to hydrogen boilers)
- Heat pumps run on renewable electricity supported by hydrogen seasonal storage

INDUSTRY & WASTE

De-carbonization technologies

- **Industrial combustion/ heating:** Across major emitting industrial sectors, c. 40% of emissions are associated with the use of energy, primarily through industrial combustion (heat) processes. Switch from coal, natural gas to biomass, biogas or hydrogen are the key technologies in de-carbonizing energy-related emissions in industry.
- **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.
- **Petrochemicals:** Clean hydrogen (either blue or green) could aid the de-carbonization of process/raw material-related emissions.
- **Efficiency**: Across all industrial processes, improvements in efficiency & recycling have the potential to aid de-carbonization.

2020 Cost curve technology additions

- Hydrogen for full de-carbonization of iron & steel
- Clean hydrogen as a raw material for ammonia and petrochemicals production (ie. methanol)
- Hydrogen for high temperature heat/combustion

Source: IPCC, Goldman Sachs Global Investment Research

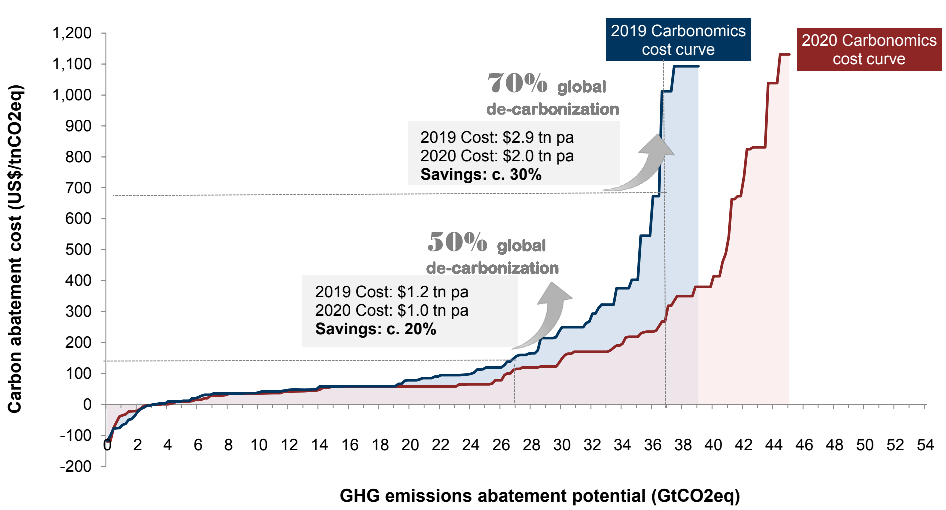
The transformation of the cost curve: Flatter and more comprehensive

The evolution of the Carbonomics cost curve results, on our estimates, in a c.US$1 tn pa reduction in the global cost to reach 70% 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 16, 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 has decreased by c.20%**, from c.US$1.2 tn pa based on the initial 2019 cost curve of de-carbonization, to c.US$1.0 tn pa based on the latest updated 2020 cost curve. More importantly, as we move towards 70% de-carbonization, we enter into the **'high-cost de-carbonization'** spectrum, with the two curves – and subsequently the annual cost required to achieve de-carbonization – diverging significantly; we estimate **c.30% global annual cost reduction in the upper part of the cost curve,** from US$2.9 tn in our 2019 cost curve to US$2.0 tn in our updated 2020 cost curve. Overall, this implies **c.US$1 tn of annual savings as we approach net zero by 2050.** Moreover, for the same total global annual investment, the evolved cost curve results in c.85% de-carbonization vs c.75% de-carbonization achieved based on the 2019 de-carbonization cost curve, with this year's cost curve evolution effectively contributing an additional c.10% of de-carbonization potential.

Exhibit 16: The evolution of the de-carbonization cost curve results in c.20% reduction in global 'low-cost de-carbonization' and c.30% in global 'high-cost de-carbonization', translating into c.$1 tn annual savings on the path to net zero

2020 vs 2019 conservation carbon abatement 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

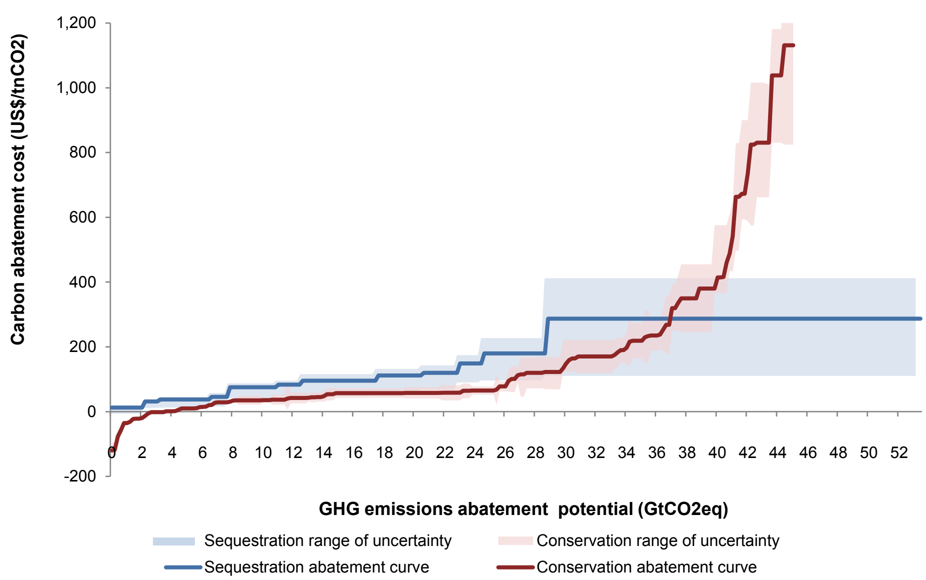
The role of carbon sequestration

Conservation efforts alone are unlikely to reach net zero carbon in the absence of carbon sequestration

We envisage two complementary paths to enable the world to reach net zero emissions: conservation and sequestration. The former refers to all technologies enabling the reduction of gross greenhouse gases emitted (already presented in the conservation cost curve of the previous section) and the latter refers to natural sinks and carbon capture, usage and storage technologies (CCUS) that reduce net emissions by subtracting carbon from the atmosphere. The need for technological breakthroughs to unlock the potential abatement of the **c.15% of total current anthropogenic emissions that cannot at present be abated** through existing conservation technologies **makes the role of sequestration a critical piece of the puzzle in solving the climate change challenge and leading the world to net zero carbon** emissions at the lowest possible cost. The cost curves for sequestration and conservation are both presented in Exhibit 17 below. While the conservation cost curve has larger scope for low-cost de-carbonization opportunities and a smaller range of uncertainty, it steepens exponentially beyond 50%. The sequestration cost curve, on the other hand, offers fewer low-cost solutions and has greater cost uncertainty, but provides tremendous long-term potential if a commercially feasible solution for Direct Air Carbon Capture is developed. We believe that carbon sequestration can be an attractive competing technology for sectors in which emissions are harder or more expensive to abate, with industry being a prominent example.

Exhibit 17: The path to de-carbonization will be driven by technological innovation and economies of scale for both conservation and sequestration initiatives

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



Source: Goldman Sachs Global Investment Research

The carbon sequestration cost curve

As part of our analysis, we have constructed a carbon abatement cost curve for sequestration (Exhibit 18), although we see a greater range of uncertainty in these technologies, given their under-invested state and the largely pilot nature of the CCUS plants. **Carbon sequestration** efforts can be broadly classified into three main categories:

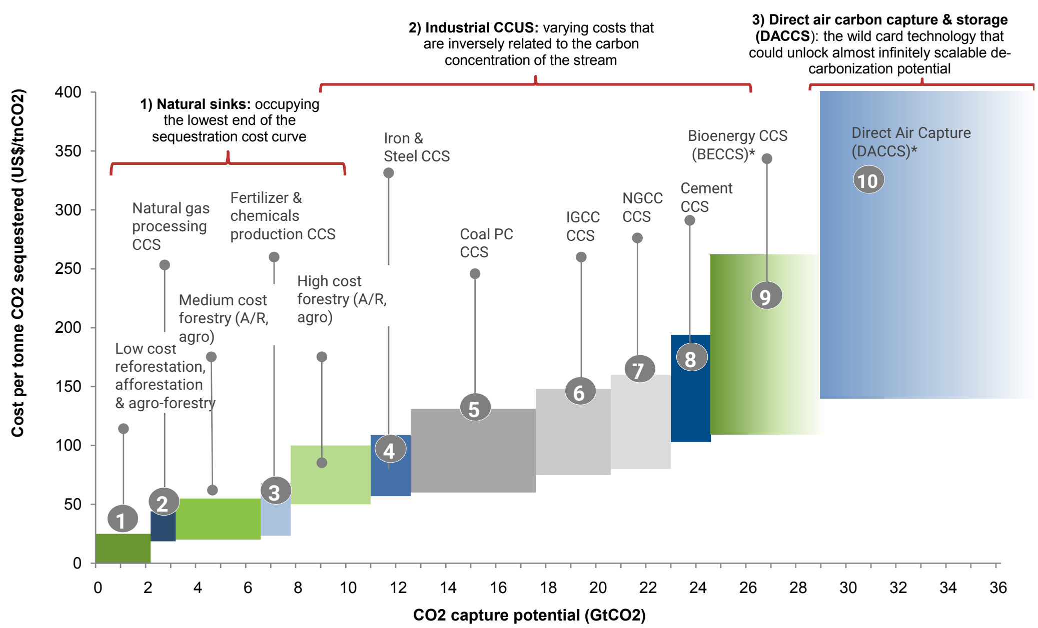
1) Natural sinks, encompassing natural carbon reservoirs that can remove carbon dioxide. Efforts include reforestation, afforestation and agro-forestry practices.

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

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

Exhibit 18: The carbon sequestration curve is less steep vs. the conservation curve but has a higher range of uncertainty given the limited investment to date and the largely pilot nature of these technologies

Carbon sequestration cost curve (US$/tnCO2eq) and the GHG emissions abatement potential (GtCO2eq)



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

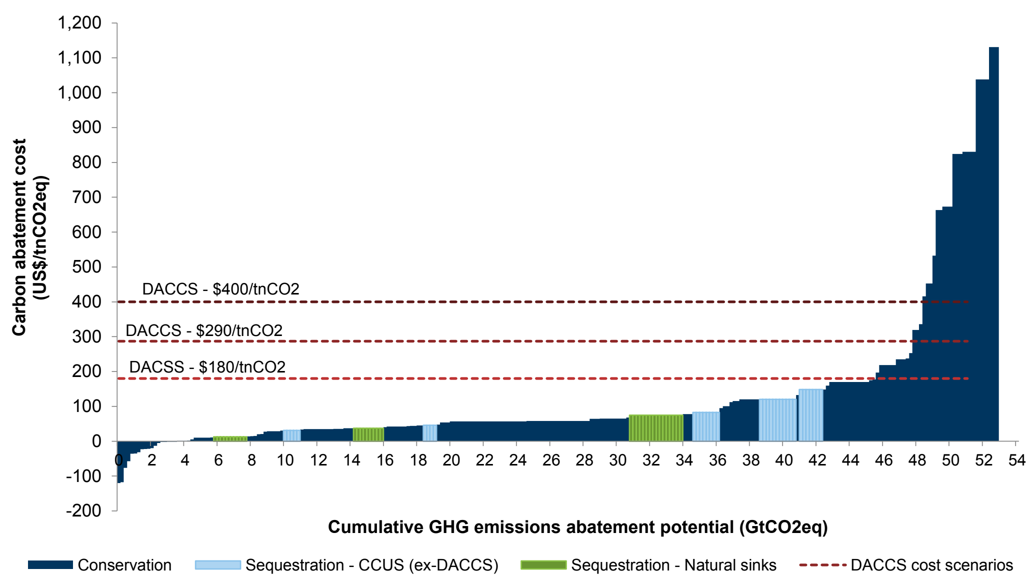
Source: IPCC, Global CCS Institute, Goldman Sachs Global Investment Research

Carbon sequestration is a vital part of achieving net zero carbon, helping to unlock the last 15% of de-carbonization and offering an alternative to high-cost carbon conservation

In the exhibit below, we present the **merged cost curve of de-carbonization that incorporates both conservation** (Exhibit 13) **and sequestration** (Exhibit 18) **initiatives**. We exclude from the merged cost curve the technology of direct air carbon capture (DACCS), as in theory this technology could unlock almost infinite de-carbonization potential, ultimately determining the carbon price required to reach net zero. Instead, we present three cost scenarios for DACC below using straight cut-off lines. Our results indicate that >60% of the current global anthropogenic GHG emissions can be abated at an implied carbon price of <US$100/tn$CO_2$ (mostly from low-carbon electrification and natural sinks). Conservation technologies overall contribute c.70% of total abatement, with natural sinks and carbon capture contributing the remaining c.30% of total abatement.

Exhibit 19: The merged cost of de-carbonization (including all conservation and sequestration approaches), indicates that >60% of emissions can be abated at a price <US$100/tnCO2, comprising mostly low-cost clean alternatives in power generation and natural sinks

Total conservation and sequestration abatement cost curve of de-carbonization for anthropogenic GHG emissions, based on current technologies and associated costs

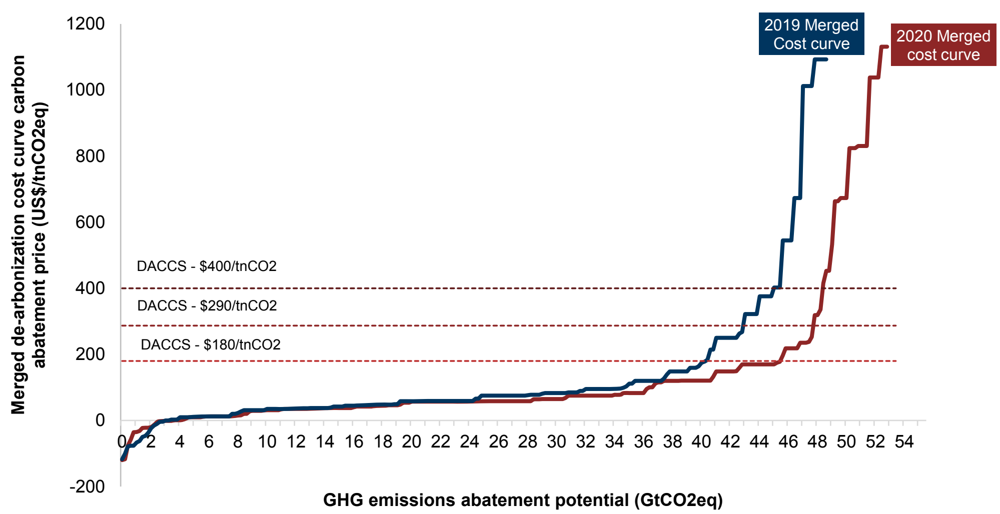


Source: Goldman Sachs Global Investment Research

We also compare the resulting merged 2020 global de-carbonization cost curve (which incorporates both conservation and sequestration technologies) with the one resulting from our previous Carbonomics cost curve update (2019). Considering the total investments for global de-carbonization, for the merged cost curve (represented by the area under each of the two curves in Exhibit 20), and assuming DACCS sets the net zero carbon price (with technologies above it therefore being substituted by DACCS), we **conclude that the combined conservation and sequestration path to net zero results in c.US$4.8 tn of annual investments required to achieve full de-carbonization** (at today's costs – which are likely to move lower in the coming years on the back on continued clean tech innovation). **In contrast**, **following a path relying solely on conservation technologies results in c.US$7.7 tn pa of required investments for only c.85% global de-carbonization.** This reinforces our view that carbon sequestration is vital to unlock affordable full de-carbonization potential.

Exhibit 20: The merged cost of de-carbonization (including both conservation and sequestration) has also meaningfully shifted lower, and offers a cheaper alternative to pure conservation

Total conservation and sequestration abatement cost curve of de-carbonization for anthropogenic GHG emissions, based on current technologies and associated costs



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:

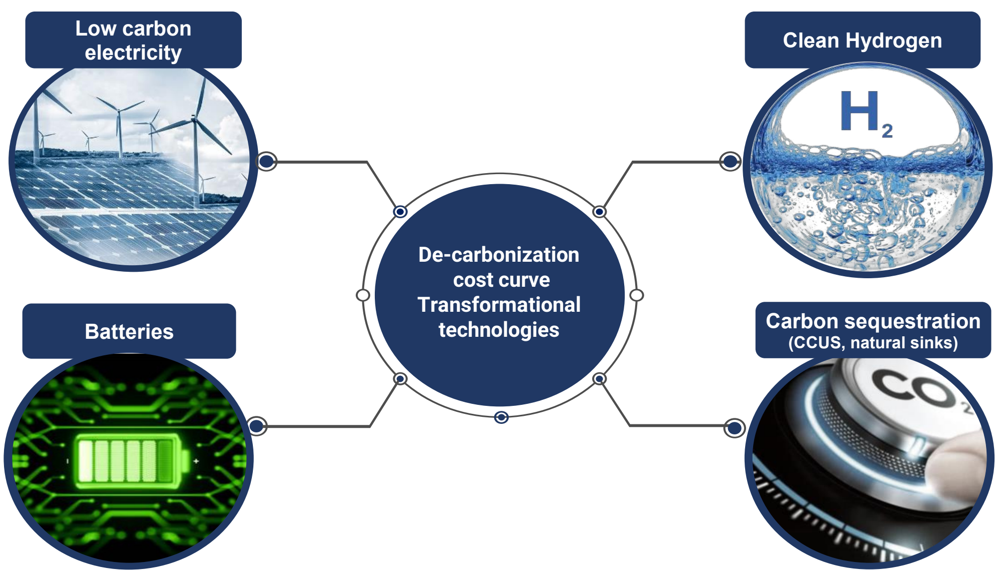
(a) Renewable power: The technology that dominates the 'low-cost de-carbonization' spectrum today and has the potential to support the de-carbonization of c.35% of total global anthropogenic GHG emissions, supporting a number of sectors that require electrification, as well as being critical for the production of clean hydrogen longer term ('green' hydrogen).

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

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

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

We identify four transformation technologies that we expect to lead the evolution of the cost curve of de-carbonization



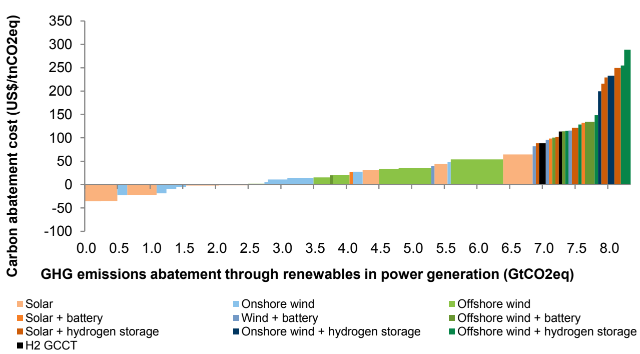
Source: Goldman Sachs Global Investment Research

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 (as shown in Exhibit 21) on the back **of lower technology costs** as the industry benefits from economies of scale and **lower cost of capital.** We estimate that c.**35% of the de-carbonization of global anthropogenic GHG emissions is reliant on access to clean power generation** (as shown in Exhibit 22), including electrification of transport and various industrial processes, electricity used for heating and more.

Exhibit 21: 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...

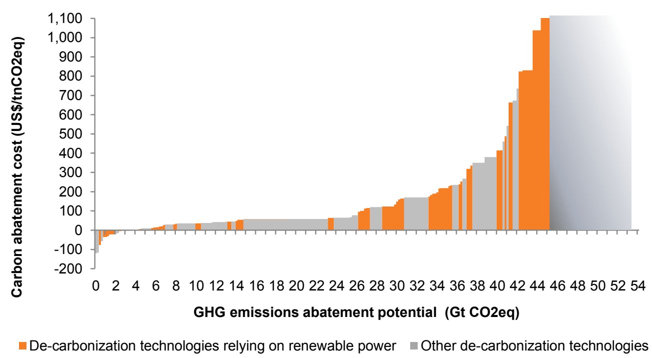
Power generation switch from natural gas to renewables (and storage) de-carbonization cost curve



Source: Goldman Sachs Global Investment Research

Exhibit 22: ...while 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)

2020 conservation carbon abatement cost curve for anthropogenic GHG emissions, with orange indicating renewable power-reliant technologies

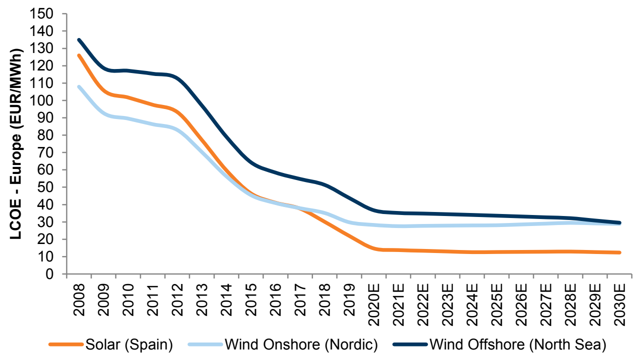


Source: Goldman Sachs Global Investment Research

The bifurcation in the cost of capital for high-carbon vs low-carbon energy has contributed c.1/3 of the reduction in overall costs for renewable power...

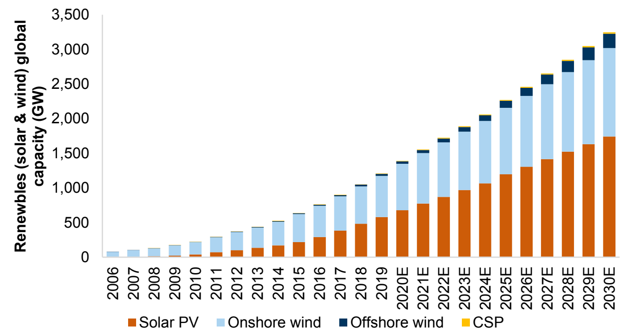
We note that along with the operational cost reduction that renewable energy has enjoyed over the past decade owing to economies of scale, the ongoing downward trajectory of the cost of capital for these low-carbon energy developments has also made a meaningful contribution to the overall affordability and competitiveness of clean energy. We show in Exhibit 25 how the **reduction in the cost of capital has contributed c.1/3 of the reduction in LCOEs of renewable technologies since 2010**. In contrast, financial conditions keep tightening for long-term hydrocarbon developments, creating higher barriers to entry, lower activity, and ultimately lower oil & gas supply, in our view. This has created an unprecedented divergence in the cost of capital for the supply of energy, as we show in Exhibit 26, with the continuing shift in allocation away from hydrocarbon investments leading to hurdle rates of 10-20% for long-cycle oil & gas developments compared with c.3-5% for the regulated investments in Europe.

Exhibit 23: 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)



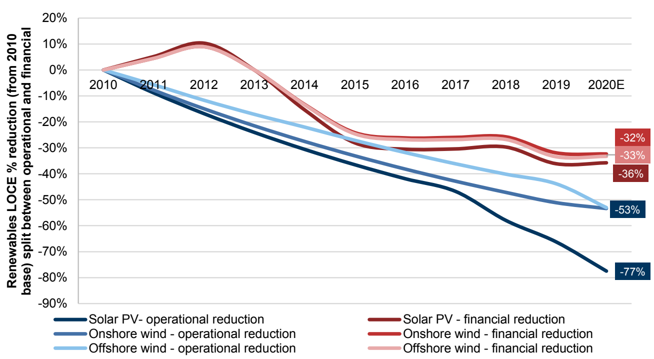
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 24: ...on the back of ongoing operational cost reduction as the industry continues to grow and benefits from economies of scale...
Global renewables (solar & wind) installed capacity (GW)



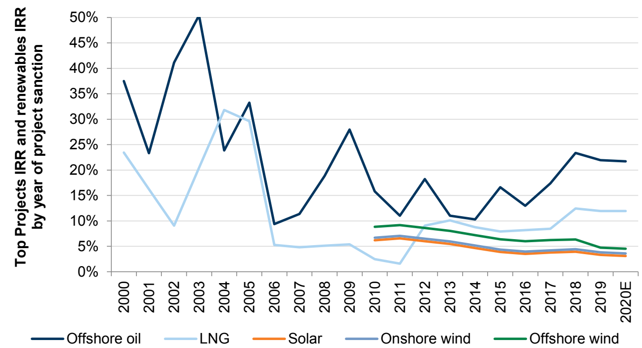
Source: IRENA, Goldman Sachs Global Investment Research

Exhibit 25: ...but also benefiting from 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

Exhibit 26: 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



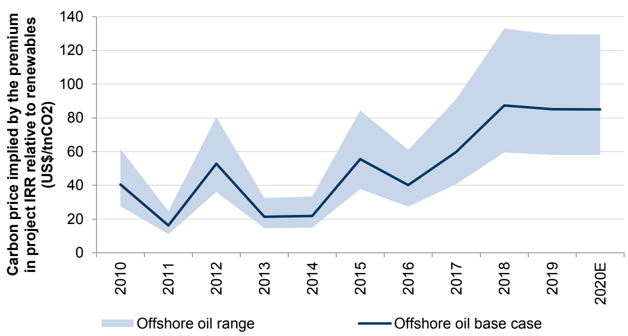
Source: Goldman Sachs Global Investment Research

...and on our estimates implies a carbon price of US$40-80/ton on hydrocarbon developments

In the charts below, we present the carbon price implied by the IRR premium of long-life offshore oil (deepwater) and LNG projects compared with renewables. We calculate the implied carbon price by leveraging our Top Projects database of the most important oil & gas projects in the world. We estimate the projects' "well to wheel" carbon intensity (scope 1+2+3) and charge each project the cost of carbon in full (we assume the producer takes the full economic hit from carbon pricing, without passing on any of the cost to the consumer through higher oil and gas prices). We calculate the IRR sensitivity by oil & gas field to different CO_2 prices and work out the carbon price that would bring the IRR of the project in line with the IRR of low-carbon projects (renewables) that were developed in the same year. We estimate that the IRR sensitivity of oil and LNG projects is 14-32 bps for each US$1/ton of carbon pricing, with an average of 21 bps. We make two critical assumptions in this analysis: (1) we assume that the carbon cost associated with the use of the oil and gas produced (scope 3) is fully paid by the producers and not by the final consumer of those hydrocarbons; and (2) we consider the different risk profile of renewables vs. hydrocarbon developments given the implicit incentive for renewables provided by governments, and include its value in the implied carbon price.

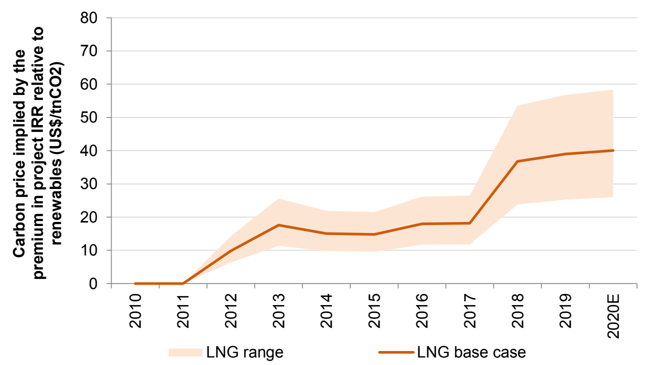
Our results indicate that the long-cycle offshore oil and LNG projects' IRR premium relative to renewables implies a carbon price in the range of US$60-130/tn CO_2 (US$80/ton on average) for offshore oil and US$30-60/tn CO_2 (US$40/ton on average) for LNG. The capital markets are therefore implying a materially higher cost of carbon than the global average carbon price of c.US$3/tn CO_2.

Exhibit 27: The current IRR project premium for offshore oil developments compared with renewables implies a carbon price range of US$60-130/tn CO2...
Carbon price implied by the IRR premium for offshore oil projects compared with renewables (US$/tn CO2)



Source: Goldman Sachs Global Investment Research

Exhibit 28: ...and a range of US$30-60/tn CO2 for LNG projects
Carbon price implied by the IRR premium for LNG projects compared with renewables (US$/tn CO2)



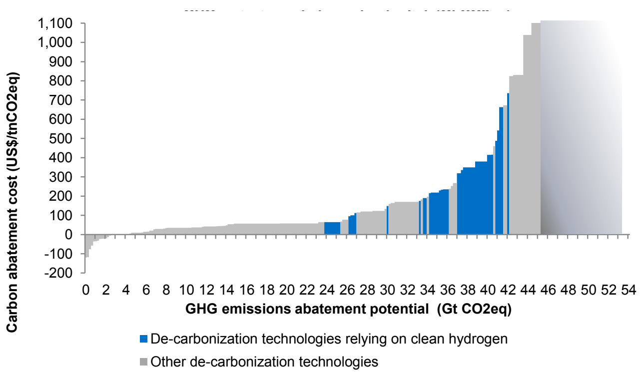
Source: Goldman Sachs Global Investment Research

2) Clean hydrogen: The rising technology that can transform the high end of the Carbonomics cost curve

Clean hydrogen is the single **most important and transformational technology addition to our 2020 Carbonomics cost curve of de-carbonization, underpinning the vast majority of technologies added** in this year's updated cost curve edition, as shown in Exhibit 15 (including FCEVs for long-haul transport, hydrogen energy storage enabling the full uptake of renewables in power generation, and hydrogen for buildings' heating systems and for other industrial applications such as iron & steel and petrochemicals).

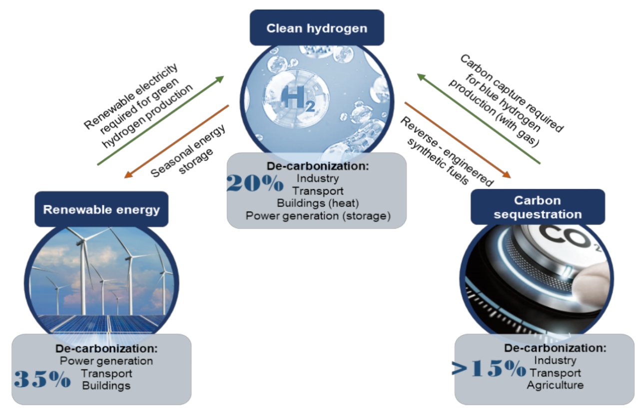
Exhibit 29: We estimate that c.20% of total GHG anthropogenic emissions could be abated through de-carbonization technologies that rely on clean hydrogen...

2020 Conservation carbon abatement cost curve for anthropogenic GHG emissions, with blue indicating clean hydrogen-reliant technologies



Source: Goldman Sachs Global Investment Research

Exhibit 30: ...with hydrogen forming a key connecting pillar between the renewable power and carbon capture



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. Despite characteristics that make hydrogen uniquely attractive for energy applications (storage, fuel and feedstock), hydrogen in its ambient form is a highly reactive (i.e. combustible) gas with very low energy density (energy content per unit volume), requiring careful handling, transport and distribution, as well as typically high pressure systems for its use in final applications.

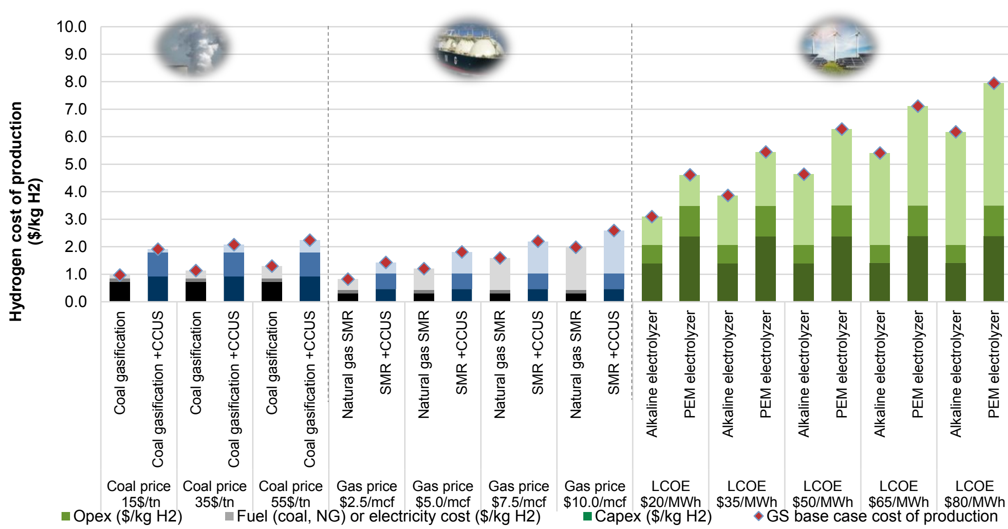
While hydrogen has gone through several waves of interest in the past 50 years, none has translated into sustainably rising investment and broader adoption in energy systems. Nonetheless, the recent focus on de-carbonization and the scaling up and accelerated growth of low-carbon technologies such as 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 31, 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. On our estimates, the cost of production of 'blue' hydrogen from natural gas SMR is c.US$0.6/kg H_2, higher than traditional SMR without carbon capture. For 'green' hydrogen, the cost of production is primarily related to the capex of the electrolyzer, the electrolyzer's conversion efficiency, load hours and, most importantly, the cost of electricity.

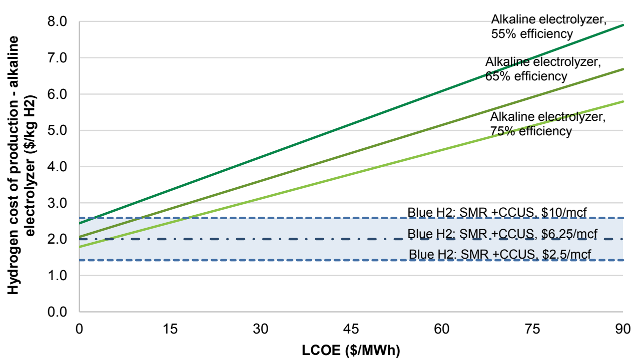
Exhibit 31: 'Blue' and 'green' hydrogen set the stage for de-carbonization, with 'blue' currently having a lower cost of production compared with 'green' hydrogen, but both being more costly than traditional 'grey' hydrogen



Source: Company data, Goldman Sachs Global Investment Research

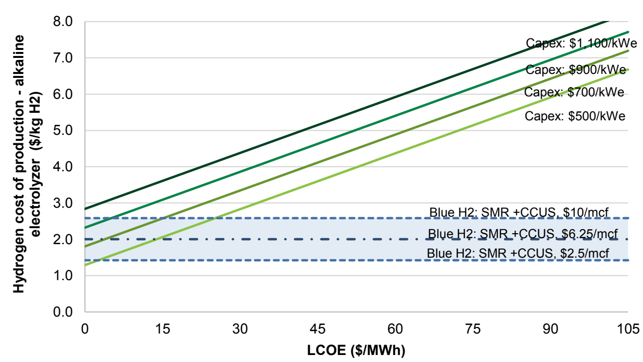
Overall, we estimate the **cost of production** of **green hydrogen could be 1.3-5.5x that of blue hydrogen,** depending on the price of natural gas and the LCOE. This leads us to conclude that **both 'blue' and 'green' hydrogen will form key pillars of the low-carbon transition**, but with **'blue' facilitating the near- and medium-term transition** until **'green' reaches cost parity longer term**. For the purpose of our cost curve of de-carbonization, we assume a 50/50 split of 'blue' and 'green' hydrogen when referring to clean hydrogen more broadly. In Exhibit 32, we show our estimates of the hydrogen cost of production (using the simplest, lowest cost and most widely adopted alkaline electrolysis route) for different costs of electricity (LCOE) and for different electrolyzer efficiencies. Overall, this implies that the cost of electricity required for 'green' hydrogen to come into cost parity with high-cost 'blue' hydrogen needs to be in the order of US$5-25/MWh LCOE assuming that the electrolyzer and carbon capture technologies capital costs remain at the current level (only the electricity cost varies along the 'green' hydrogen lines and natural gas cost varies along 'blue' hydrogen lines).

Exhibit 32: 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 33: ...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)

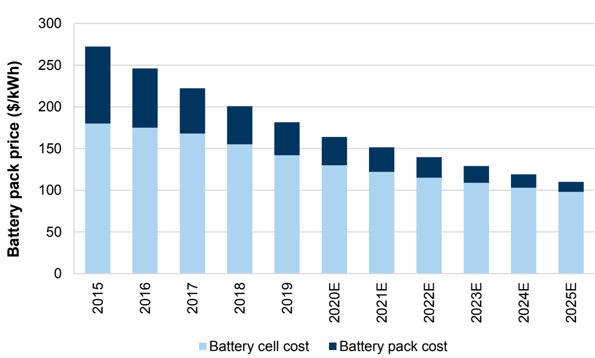


Source: Goldman Sachs Global Investment Research

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

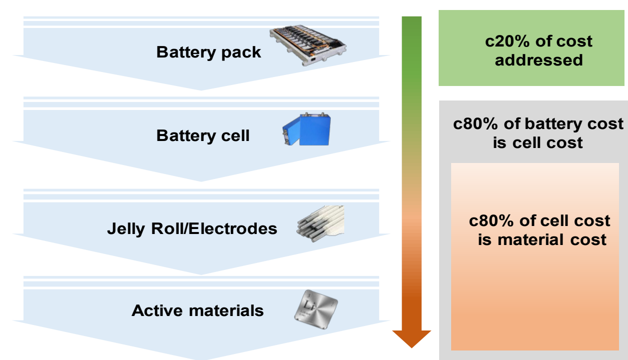
Battery technology and its evolution play a key role in aiding de-carbonization of both transport and power generation. The high focus on electric batteries over the past decade has helped to reduce battery costs by over c.50% in the past five years alone (Exhibit 34) owing to the rapid scale-up of battery 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 34: 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 35: ...with the remaining cost reductions required to come from the cell
Battery pack and cell cost breakdown

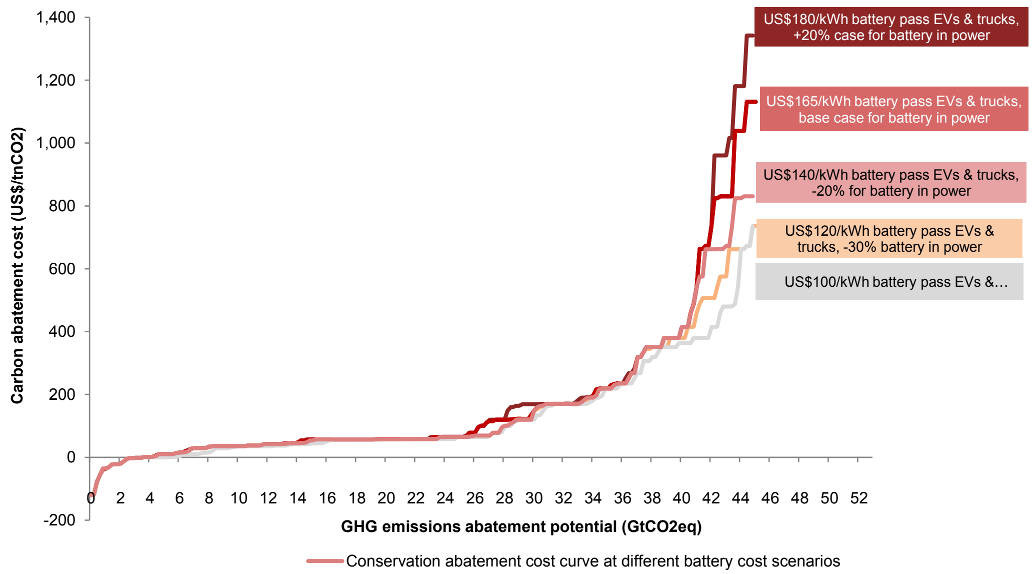


Source: Company data, Goldman Sachs Global Investment Research

Assessing the potential impact of a breakthrough in battery technology on the de-carbonization cost curve

In the exhibit below, we analyze the case for different battery cost scenarios (full battery pack cost) for electric vehicles, including short-haul trucks, and for energy storage in power generation. This shows a relatively high sensitivity of the shape of the cost curve to battery costs, suggesting the battery technology has the potential to transform the higher end of the de-carbonization cost spectrum, which is dominated by transport. Lower battery costs for passenger EVs, both rural and urban, as well as trucks, could have a notable impact in reducing the overall cost of de-carbonization. However, battery technology in its current construct remains unlikely to offer a solution to the de-carbonization of aviation and shipping and seasonal variations in power demand, providing hydrogen with a key role to play in these areas, as we outlined in the previous section.

Exhibit 36: A potential breakthrough in battery technology and associated costs could help transform the current de-carbonization cost curve through lower costs in transport and power generation
Conservation carbon abatement cost curve for anthropogenic GHG emissions, for different battery cost scenarios in passenger transport and power generation



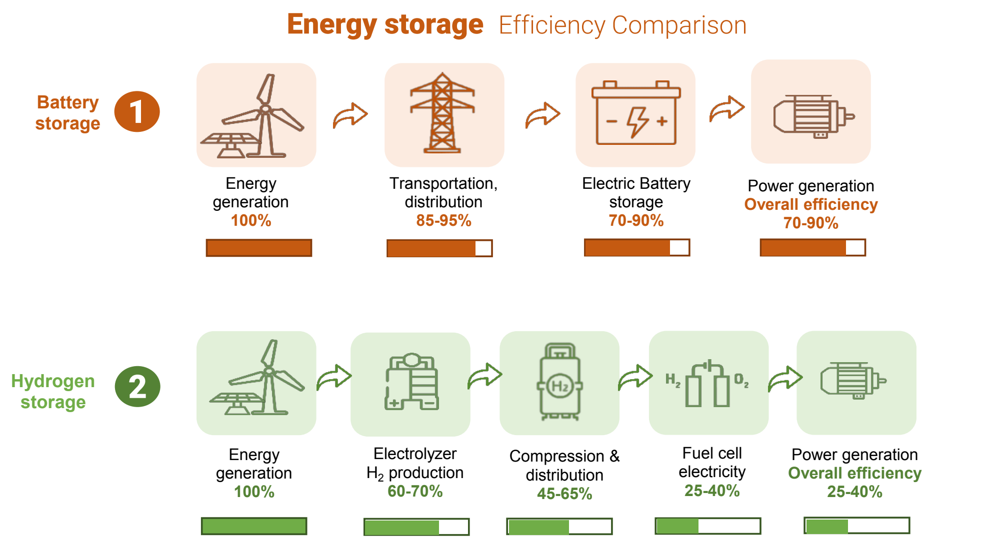
** Battery costs involve the full battery pack for electric vehicles*

Source: 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 37

Exhibit 37: 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



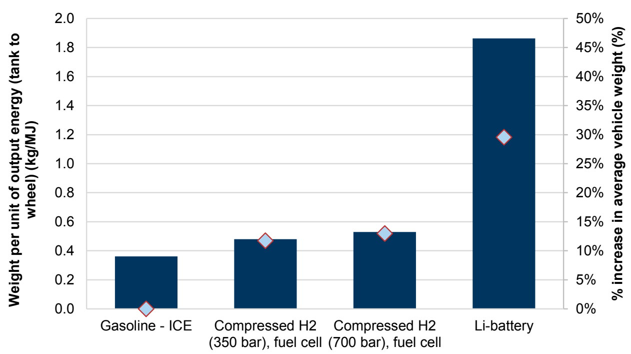
Source: Company data, Goldman Sachs Global Investment Research

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.

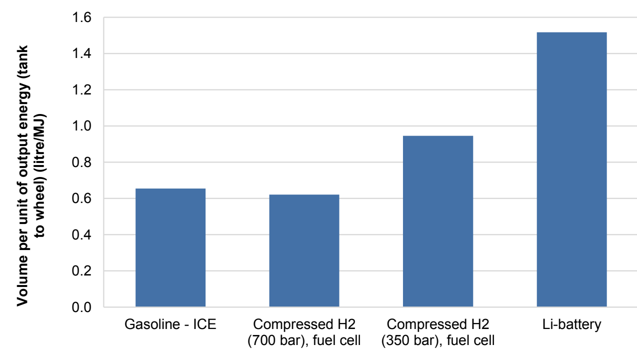
The exhibits that follow present our **comparative analysis for hydrogen** fuel cell electric vehicles (FCEVs) and how these screen on weight per unit of output energy and volume per unit of output energy compared with other large-scale employed commercial vehicles – electric vehicles (EVs) and gasoline internal combustion engine vehicles (ICE). Exhibit 38 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). Similarly, hydrogen in its compressed form leads to FCEVs screening attractively on volume per unit of energy output compared with EVs. However, FCEVs screen less attractively in terms of the cost (US$) per unit of output energy, which is >2x the cost for equivalent EVs and ICE gasoline passenger vehicles. **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**. For the purposes of this analysis, we consider the weight and the volume of the system that stores and converts input energy to output energy across all three types of vehicles. This includes the internal combustion engine and gasoline tank components for ICE passenger vehicles, the Li-battery for EVs, and the fuel cell and compressed hydrogen storage tank for FCEVs.

Exhibit 38: 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 different average passenger vehicles and % increase in average vehicle weight



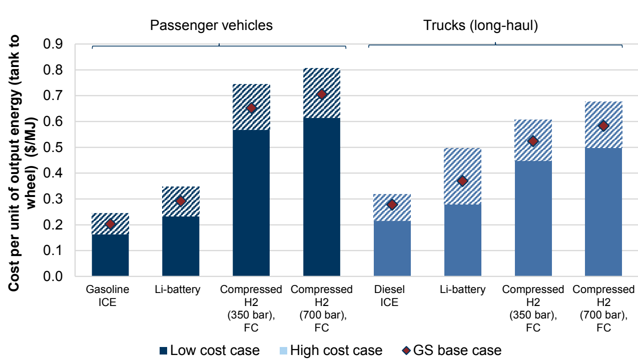
Source: US Department of Energy, EIA, Goldman Sachs Global Investment Research

Exhibit 39: ...and considering the compressed form of hydrogen used in FCEVs, they also screen attractively on a volume per unit of output basis
Volume per unit of output energy (tank-to-wheel basis) (litre/MJ)



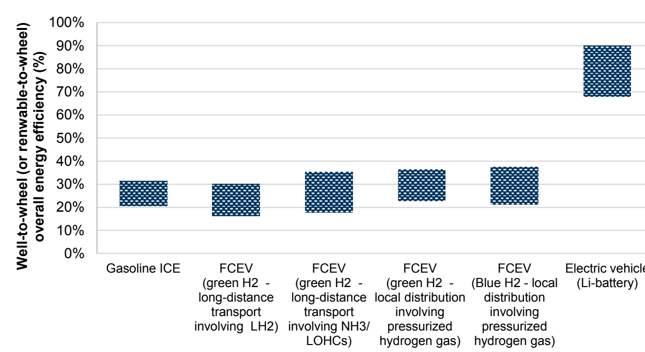
Source: US Department of Energy, Company data, Goldman Sachs Global Investment Research

Exhibit 40: FCEVs screen less attractively compared with EVs and gasoline ICE for short-haul passenger vehicles, but they become more competitive in long-haul transport applications (such as trucks)
Cost per unit of output energy (tank-to-wheel basis, $/MJ)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 41: 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 (%)

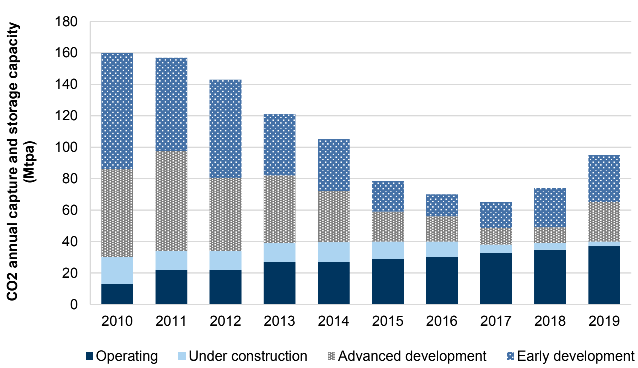


Source: Company data, Goldman Sachs Global Investment Research

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

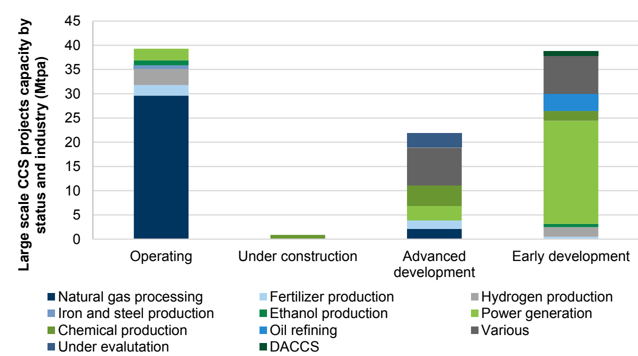
CCUS technologies can be an **effective route to global de-carbonization for industrial and power sources**: they can be used to significantly reduce emissions from coal and gas power generation, as well as across industrial processes with emissions characterized as 'harder to abate' such as iron & steel, cement and chemicals. CCUS encompasses 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 solution or utilization. The CCUS chain constitutes processes that can be broadly categorized into three major parts: (1) **the separation and capture** of CO_2 from gaseous emissions; (2) the subsequent **transport** of this captured CO_2, typically through pipelines, to suitable geological formations; and (3) the **storage** of the CO_2, primarily in deep geological formations such as former oil and gas fields, saline formations or depleting oil fields or the **utilization** of captured CO_2 for alternative uses and applications. When CO_2 is injected into an oil field to recover oil reserves, the method is known as Enhanced Oil Recovery (EOR), and the majority of existing operating CCS projects globally have adopted this route of storage as it offers the potential for higher return on investment. Ocean and mineral storage options also exist.

Exhibit 42: 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 2019

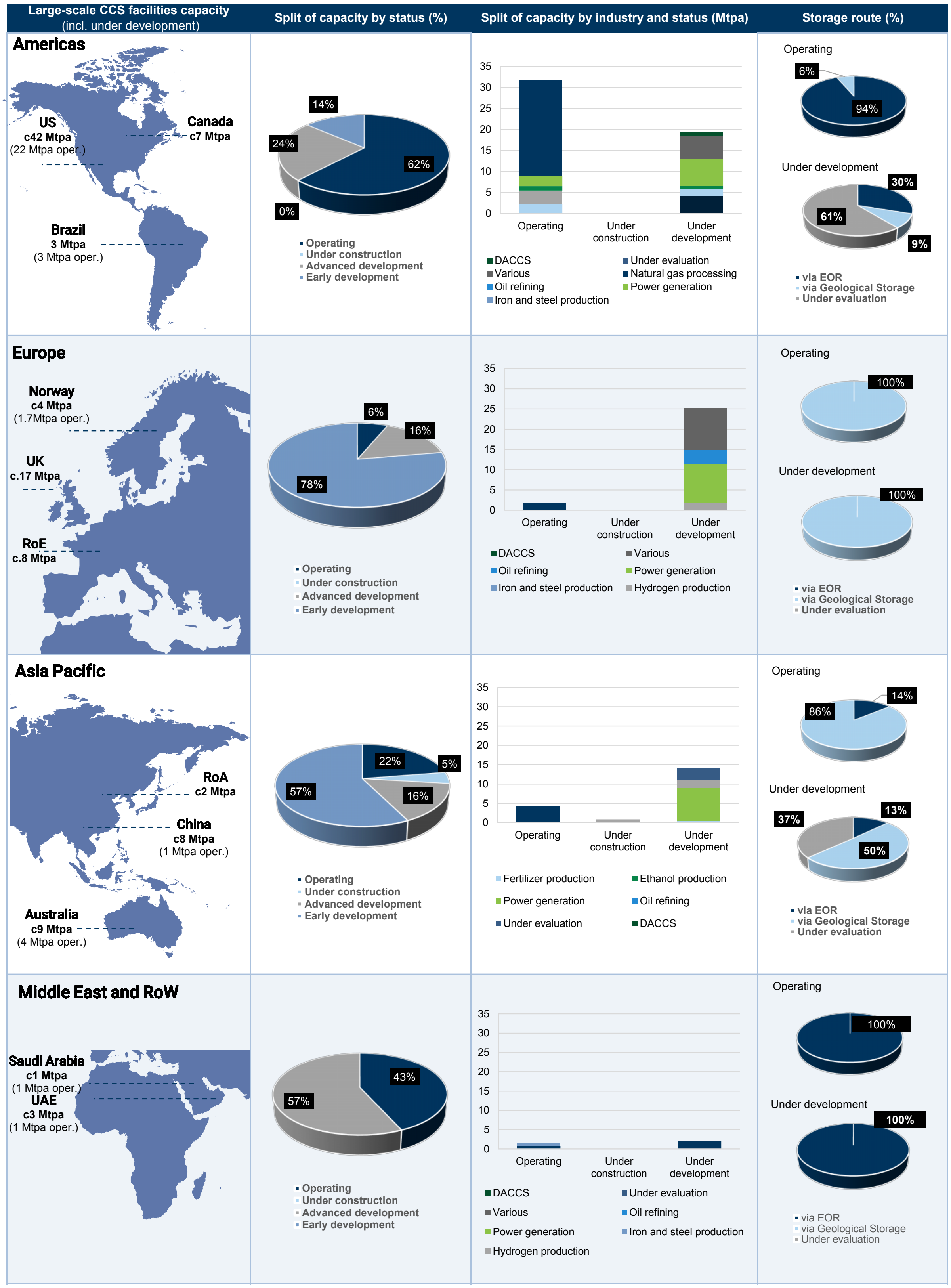
Exhibit 43: ...as more projects in the development stage start to focus on industries with lower CO2 stream concentrations (industrial & power generation as opposed to natural gas processing)
Large-scale CCS projects by status and industry of capture (Mtpa, 2019)



Source: Global CCS Institute, Goldman Sachs Global Investment Research

Currently, we identify c.20 large-scale CCS facilities operating globally (mostly in the US, Canada and Norway), with a total capacity exceeding 30 Mtpa. 2019 was marked by the advancement of two large-scale CCS facilities: the start of CO_2 injection at the Gorgon natural gas processing plant in Australia, the largest dedicated geological CO_2 storage facility when ramped up to full capacity (4.0 Mtpa of CO_2), and the Alberta Carbon Trunk Line (ACTL) development. In 2020, the Northern Lights project made its entry. According to the involved companies, Phase 1 includes capacity to transport, inject and store up to 1.5 $MtCO_2$ per year. Once the CO_2 is captured onshore, it will be transported by ships, injected and permanently stored in the North Sea.

Exhibit 44: Summary of global large-scale CCS projects (capacity >0.4Mtpa) including operating, under construction and under early development projects



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

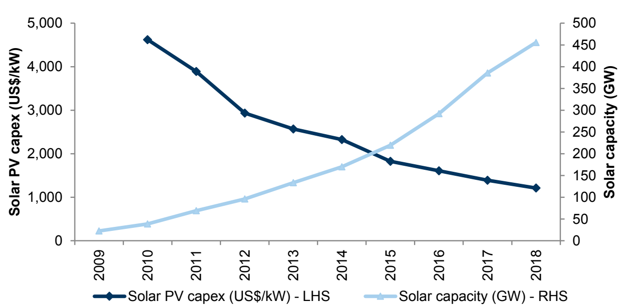
Historical under-investment in CCUS has held back large-scale adoption and economies of scale. However, the tide may be turning, with several projects moving forward in Europe and North America

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

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

Exhibit 45: Solar PV cost per unit of electricity has fallen 70%+ over the last decade as cumulative solar capacity has increased exponentially...

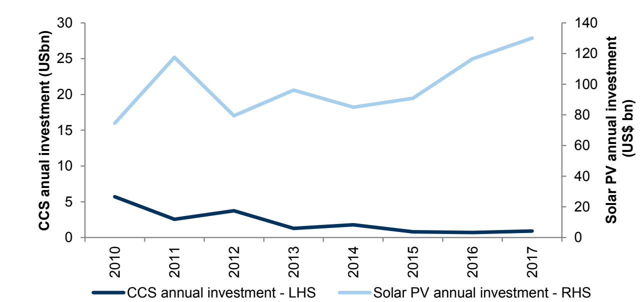
Solar PV capex (US$/kW) vs. global cumulative solar PV capacity (GW)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 46: ...while the languishing investment in CCS sequestration technologies has possibly prevented a similar cost improvement

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

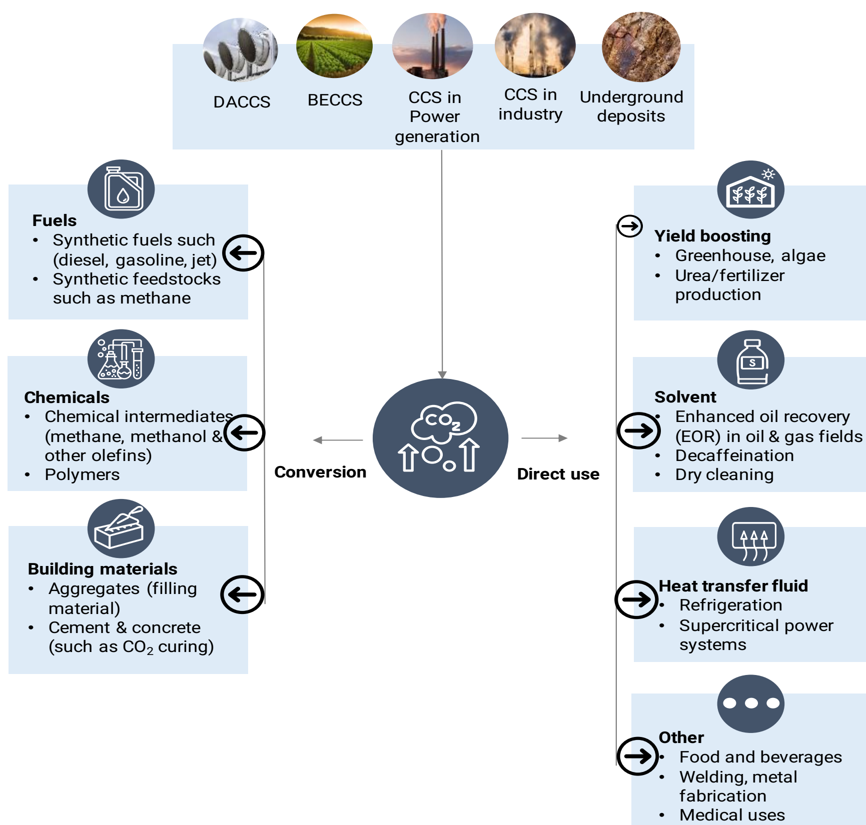


Source: Company data, IEA, IRENA, Goldman Sachs Global Investment Research

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

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

Exhibit 47: There exists a very wide range of potential uses and applications for captured CO2 globally, involving both direct use and conversion



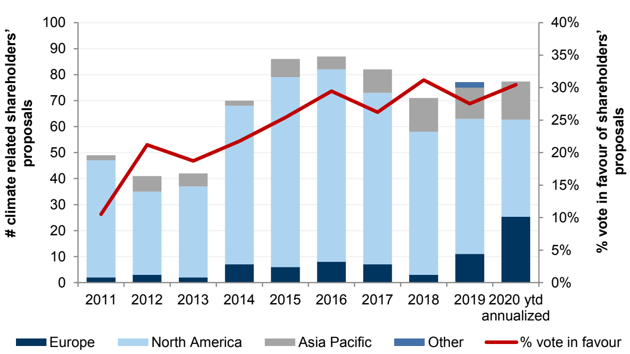
Source: IEA, Goldman Sachs Global Investment Research

De-carbonization and capital markets: The rise of green shareholder proposals

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 tripled over the same period. So far, 2020 has been, despite the outbreak of COVID-19, another year of strong shareholder engagement on climate change, with the year-to-date climate-related shareholder resolutions exceeding last year's on an annualized basis (the most notable increase coming from Europe). Similarly, the percentage vote in favour has increased yoy, currently at c.30%.

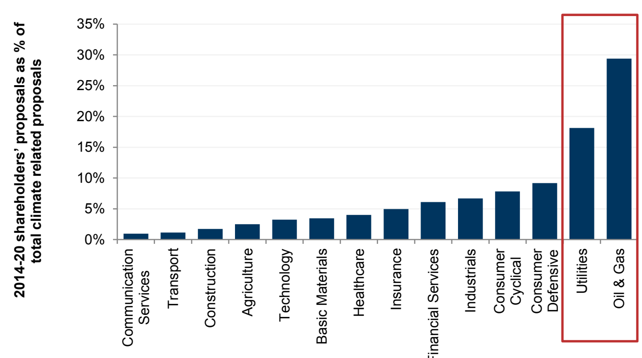
This investor pressure, however, is not uniformly distributed across sectors and shows a clear bias towards energy producers vs. energy consumers, with data since 2014 showing 50% of proposals targeting energy producers (oil & gas, utilities) while only 30% of the proposals target the sectors that account for most of the final energy consumption. Oil & gas show the highest engagement by far (examples such as TOTAL, Equinor, Chevron, RDShell), with Financial Services (JP Morgan Chase, Danske Bank, Toronto Dominion Bank), Consumer cyclical and defensives (Yum! Brands, Amazon.com, Bloomin' Brands, Walmart, Dollar Tree), Utilities and Basic Materials in aggregate accounting for a similar share as oil & gas alone.

Exhibit 48: The number of climate-related shareholder resolutions and % vote in favour continues to gain momentum so far in 2020...
Number of climate-related shareholders' proposals vs. % vote in favour



Source: ProxyInsight, Goldman Sachs Global Investment Research

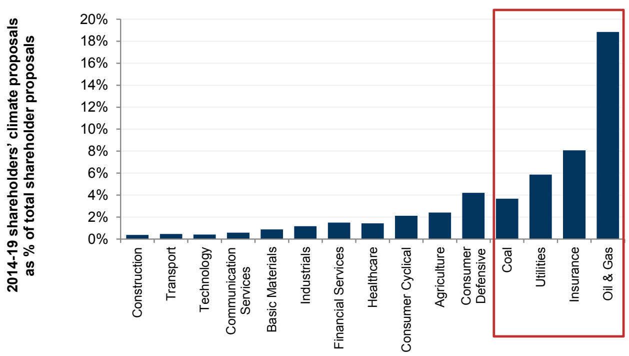
Exhibit 49: ...with a targeted focus on energy producers (oil & gas, utilities)...
% of climate-related shareholder proposals, split by industry, 2014-20



Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 50: …which also have the largest proportion of climate-related proposals relative to total shareholder proposals

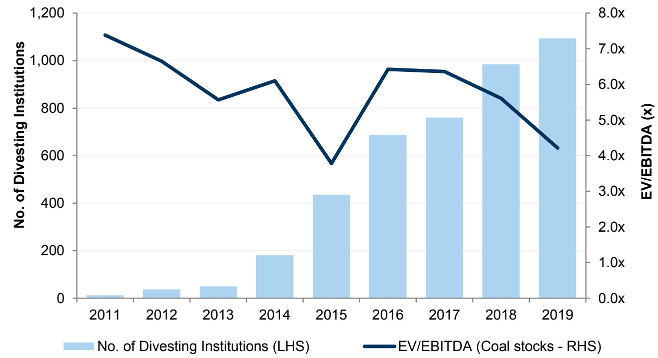
% of shareholder proposals that are climate-related, 2014-19



Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 51: Investor divestments are already evident in the coal industry

Number of divesting institutions (LHS) vs. coal stocks EV/EBITDA (RHS)



Source: Thomson Reuters Datastream, DivestInvest, Goldman Sachs Global Investment Research

The symbiotic relationship between carbon pricing and technological innovation

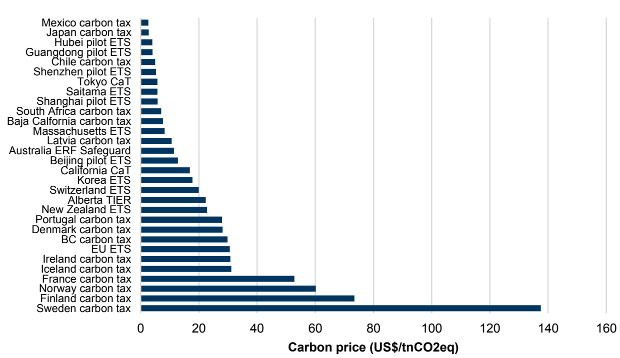
Carbon pricing a key ingredient for de-carbonization, with global initiatives accelerating, but still currently covering only c.15%-20% of total global emissions

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 two approaches to de-carbonization, conservation and sequestration, are both vital in achieving net zero carbon emissions as emissions continue to overshoot the path associated with the more benign global warming paths. In the short term, we believe that **carbon prices should be sufficiently high to incentivize innovation and healthy competition between conservation and sequestration technologies**, 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, 64 carbon pricing initiatives have been implemented or are scheduled for implementation, covering 46 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, expected to launch the initial phase of its own ETS roadmap in 2021. These carbon pricing systems have shown varying degrees of success in reducing carbon emissions; together, according to the World Bank Group, all of these initiatives (including China) cover 13GtCO2eq, representing c.24% of the world's total GHG emissions.

Exhibit 52: The carbon prices associated with global national and sub-national carbon price initiatives (carbon taxes & ETS) show a wide regional variability...

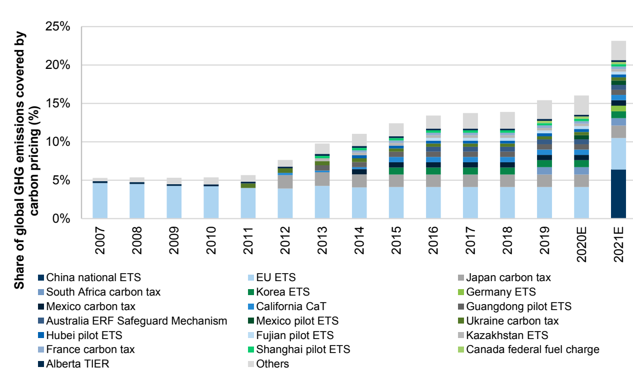
Carbon prices through taxes and ETS (August 2020)



Source: World Bank Group

Exhibit 53: ...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

Appendix: De-carbonization cost curve in detail

Exhibit 54: De-carbonization conservation cost curve with the carbon abatement price range (US$/tnCO2eq) and abatement potential (GtCO2eq) split by industry

Conservation carbon abatement routes	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 coal to gas - North America (ex-US)	Power generation	-13	-17	-10	0.04
Switch coal to gas - US	Power generation	0.9	0.7	1.1	0.44
Switch from coal to gas -CIS	Power generation	0.9	0.7	1.1	0.22
Switch from coal to gas -Middle East	Power generation	29	22	36	0.02
Switch from coal to gas -Asia Pacific (low gas price)	Power generation	29	22	36	0.28
Switch from coal to gas -Latin America	Power generation	29	22	36	0.06
Switch from coal to gas -Europe	Power generation	29	22	36	0.41
Switch from coal to gas -Africa	Power generation	43	32	54	0.17
Switch from coal to gas -Other Europe	Power generation	43	32	54	0.03
Switch from coal to gas -Asia Pacific (high gas price)	Power generation	57	43	71	4.48
Power generation - switch to renewables					
Solar low cost scenario, high gas price	Power generation	-39	-47	-31	0.24
Solar medium cost scenario, high gas price	Power generation	-36	-43	-28	0.24
Onshore wind low cost scenario, high gas price	Power generation	-23	-27	-18	0.14
Solar medium cost scenario, medium gas price	Power generation	-22	-27	-18	0.24
Solar low cost scenario, medium gas price	Power generation	-22	-26	-17	0.24
Onshore wind medium cost scenario, high gas price	Power generation	-19	-23	-15	0.14
Onshore wind low cost scenario, medium gas price	Power generation	-9	-11	-8	0.14
Solar+battery low cost scenario, high gas price	Power generation	-7	-8	-5	0.04
Onshore wind medium cost scenario, medium gas price	Power generation	-5	-6	-4	0.14
Solar medium cost scenario, low gas price	Power generation	-2	-2	-2	0.48
Solar low cost scenario, low gas price	Power generation	-2	-1	-2	0.48
Offshore wind low cost scenario, high gas price	Power generation	2	1	2	0.25
Onshore wind +battery low cost scenario, high gas price	Power generation	6	4	7	0.02
Solar+battery low cost scenario, medium gas price	Power generation	7	5	8	0.04
Onshore wind low cost scenario, low gas price	Power generation	11	9	13	0.27
Onshore wind high cost scenario, high gas price	Power generation	14	11	17	0.14
Onshore wind medium cost scenario, low gas price	Power generation	15	12	18	0.27
Offshore wind low cost scenario, medium gas price	Power generation	15	12	18	0.25
Onshore wind +battery low cost scenario, medium gas price	Power generation	19	15	23	0.02
Offshore wind +battery low cost scenario, high gas price	Power generation	20	16	24	0.03
Offshore wind high cost scenario, high gas price	Power generation	20	16	24	0.25
Solar+battery low cost scenario, low gas price	Power generation	27	21	32	0.07
Onshore wind high cost scenario, medium gas price	Power generation	28	22	33	0.14
Solar high cost scenario, high gas price	Power generation	31	25	37	0.24
Offshore wind +battery low cost scenario, medium gas price	Power generation	33	27	40	0.03
Offshore wind high cost scenario, medium gas price	Power generation	34	27	41	0.25
Offshore wind low cost scenario, low gas price	Power generation	35	28	42	0.51
Onshore wind +battery low cost scenario, low gas price	Power generation	39	25	53	0.04
Solar high cost scenario, medium gas price	Power generation	44	29	60	0.24
Onshore wind high cost scenario, low gas price	Power generation	48	31	64	0.27
Offshore wind +battery low cost scenario, low gas price	Power generation	54	35	72	0.05
Offshore wind high cost scenario, low gas price	Power generation	54	35	73	0.51
Solar high cost scenario, low gas price	Power generation	64	42	87	0.48
Onshore wind +battery high cost scenario, high gas price	Power generation	82	53	111	0.02
Solar + hydrogen storage low cost scenario, high gas price	Power generation	88	57	119	0.05
Hydrogen CGGT, low gas price	Power generation	88	57	119	0.08
Hydrogen CGGT, medium gas price	Power generation	95	62	128	0.04
Onshore wind +battery high cost scenario, medium gas price	Power generation	96	62	129	0.02
Solar+battery high cost scenario, high gas price	Power generation	99	64	133	0.04
Offshore wind +battery high cost scenario, high gas price	Power generation	101	65	136	0.03
Onshore wind + hydrogen storage low cost scenario, high gas price	Power generation	101	65	136	0.03
Solar + hydrogen storage low cost scenario, medium gas price	Power generation	102	66	137	0.05
Solar+battery high cost scenario, medium gas price	Power generation	112	73	151	0.04
Hydrogen CGGT, high gas price	Power generation	114	74	154	0.04
Offshore wind +battery high cost scenario, medium gas price	Power generation	114	74	154	0.03
Onshore wind + hydrogen storage low cost scenario, medium gas price	Power generation	114	74	154	0.03
Offshore wind + hydrogen storage low cost scenario, high gas price	Power generation	115	75	155	0.04
Onshore wind +battery high cost scenario, low gas price	Power generation	116	75	156	0.04
Solar + hydrogen storage low cost scenario, low gas price	Power generation	122	79	164	0.11
Offshore wind + hydrogen storage low cost scenario, medium gas price	Power generation	129	84	173	0.04
Solar+battery high cost scenario, low gas price	Power generation	132	86	178	0.07
Offshore wind +battery high cost scenario, low gas price	Power generation	134	87	181	0.05
Onshore wind + hydrogen storage low cost scenario, low gas price	Power generation	134	87	181	0.06
Offshore wind + hydrogen storage low cost scenario, low gas price	Power generation	149	97	201	0.08
Onshore wind + hydrogen storage high cost scenario, high gas price	Power generation	199	130	269	0.03
Onshore wind+ hydrogen storage high cost scenario, medium gas price	Power generation	213	138	287	0.03
Solar + hydrogen storage high cost scenario, high gas price	Power generation	216	140	292	0.05
Solar + hydrogen storage high cost scenario, medium gas price	Power generation	229	149	310	0.05
Onshore wind + hydrogen storage high cost scenario, low gas price	Power generation	233	151	315	0.06
Solar + hydrogen storage high cost scenario, low gas price	Power generation	250	162	337	0.11
Offshore wind + hydrogen storage high cost scenario, high gas price	Power generation	255	166	344	0.04
Offshore wind+ hydrogen storage high cost scenario, medium gas price	Power generation	268	174	362	0.04
Offshore wind + hydrogen storage high cost scenario, low gas price	Power generation	289	188	390	0.08

Source: Goldman Sachs Global Investment Research

Conservation carbon abatement routes	Industry	Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
Transport		(US$/tnCO2 eq)	(US$/tnCO2 eq)	(US$/tnCO2 eq)	(GtCO2eq)
Switch aircraft to one of highest efficiency	Transport	40	6	91	0.12
LNG fuel in shipping	Transport	68	21	115	0.16
City Buses to electric buses	Transport	115	46	192	0.33
Switch to electric trucks, short-haul	Transport	123	69	169	1.05
Hydrogen FCEV truck, long-haul	Transport	219	164	273	0.94
Marine biofuels	Transport	235	215	254	0.02
Switch to electric trucks, medium-haul	Transport	238	192	284	0.16
Biofuels on road transport	Transport	268	179	357	0.29
Clean ammonia fuel-run ships	Transport	319	250	393	0.32
Aviation biofuels	Transport	673	594	752	0.47
Diesel vehicle to EV, urban	Transport	824	575	1,016	0.52
Gasoline vehicle to EV, urban	Transport	831	662	960	0.86
Gasoline vehicle to EV, rural	Transport	1,038	831	1,181	0.81
Diesel vehicle to EV, rural	Transport	1,131	824	1,342	0.50
Industry & industrial waste					
Efficiency gains & plastics recycling	Industry & waste	-120	-144	-96	0.05
Secondary production through scrap/recycling in aluminium	Industry & waste	-117	-141	-94	0.23
Energy & process efficiency through recycling and BAT in pulp & paper	Industry & waste	-23	-28	-19	0.09
Efficiency gains in ammonia production	Industry & waste	35	28	42	0.08
Other petrochemical process efficiency gains	Industry & waste	45	32	59	0.48
Efficiency industrial gains other low cost	Industry & waste	58	41	75	2.46
Iron & steel efficiency gains	Industry & waste	65	52	78	1.63
Other material & energy efficiency improvements in cement (ie. BAT)	Industry & waste	78	62	94	0.58
Charcoal biomass as fuel and feedstock for iron & steel	Industry & waste	85	68	102	0.02
Switch to electrolysis-derived hydrogen as feedstock in ammonia	Industry & waste	101	60	141	0.33
DIR-EAF with zero carbon electricity in iron & steel	Industry & waste	112	90	134	0.12
Efficiency industrial gains other medium cost	Industry & waste	170	119	221	2.46
Switch to clean hydrogen as feedstock in petrochemicals	Industry & waste	177	142	213	0.17
Hydrogen or biogas DIR-EAF in iron & steel (switch from BF-BOF)	Industry & waste	190	152	228	0.48
Fuel switch to biomass & waste in cement	Industry & waste	235	188	282	0.62
Efficiency industrial gains other high cost	Industry & waste	350	245	455	2.46
Reducing clinker to cement ratio in cement	Industry & waste	460	368	552	0.24
Switch to biogas or biomass as a feedstock in ammonia process	Industry & waste	542	433	650	0.10
Switch to biogas or biomass as a feedstock in petrochemicals	Industry & waste	736	588	883	0.09
Buildings					
LED and increased efficiency - commercial	Buildings	-77	-96	-58	0.14
LED and increased efficiency, residential	Buildings	-67	-83	-50	0.11
Insulation (cavity and wall) - commercial buildings	Buildings	-58	-72	-43	0.08
Insulation (cavity wall) for new residential	Buildings	-50	-63	-38	0.05
HVAC smart systems/efficiency gains - commercial	Buildings	-48	-60	-36	0.04
HVAC Systems/thermostat & smart meters for residential new	Buildings	-42	-52	-31	0.02
HVAC Systems/thermostat & smart meters residential retrofit	Buildings	-32	-40	-24	0.05
Insulation (cavity wall) - residential retrofit	Buildings	-20	-15	-25	0.10
Heat pumps - water heating - commercial	Buildings	140	105	174	0.13
Renewable heat (solar thermal, PV) - water heating - commercial	Buildings	149	112	186	0.06
BACS systems/efficiency gains/BAT appliances residential	Buildings	159	120	199	0.24
Heat pumps - water heating (ground source heat pump), residential	Buildings	164	123	205	0.28
Renewable heat (solar thermal, PV) - water heating, residential	Buildings	175	131	219	0.12
BACS systems - commercial	Buildings	183	138	229	0.07
Heat pumps - commercial buildings	Buildings	197	148	246	0.20
Heat pumps (air to air), residential, new	Buildings	232	174	290	0.12
Heat pumps (air to air), residencial retrofit	Buildings	253	190	316	0.19
Heat pumps running on energy seasonally stored via hydrogen - commercial	Buildings	336	252	420	0.16
Heat pumps running on energy seasonally stored via hydrogen - residential	Buildings	395	296	494	0.10
Hydrogen boiler (switch from gas boiler) - commercial	Buildings	415	311	518	0.31
Heat pumps running on energy seasonally stored via hydrogen - residential, retrofit	Buildings	416	312	519	0.19
Hydrogen boiler (switch from gas boiler) - residential	Buildings	488	366	610	0.19
Hydrogen boiler (switch from gas boiler) - residential, retrofit	Buildings	663	498	829	0.44
Agriculture, Forestry and Other Land uses (AFOLU)					
Fire & disaster improved mannagement practices	Agriculture, forestry & other land uses	10	6	14	1.00
Reduced soil erosion, salinization and compaction	Agriculture, forestry & other land uses	35	21	49	1.70
Improved forest management practices	Agriculture, forestry & other land uses	37	22	52	1.00
Improved cropland management practices	Agriculture, forestry & other land uses	42	25	59	1.35
Improved grazing land management practices	Agriculture, forestry & other land uses	58	35	81	1.49
Improved livestock management practices	Agriculture, forestry & other land uses	120	72	168	1.09

Source: Goldman Sachs Global Investment Research

Disclosure Appendix

Reg AC

We, Michele Della Vigna, CFA, Zoe Stavrinou, Alberto Gandolfi, Derek R. Bingham, Sharmini Chetwode, Ph.D., Evan Tylenda, CFA and Sipho Arntzen, 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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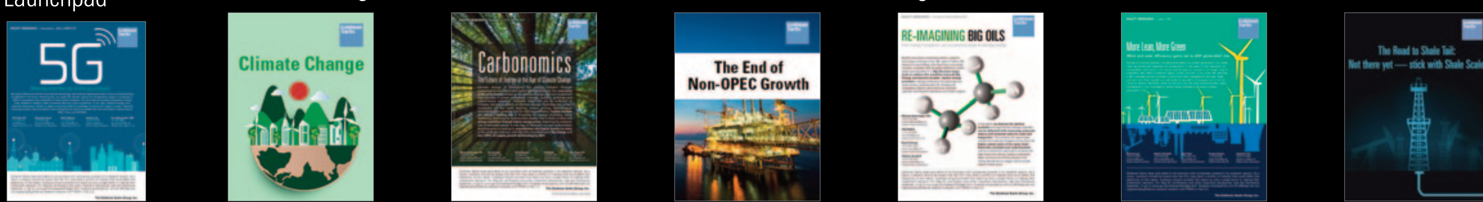

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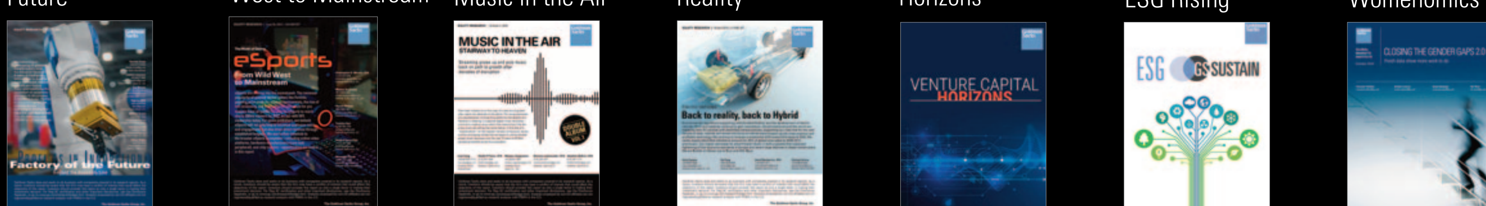

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