Note: The following is a redacted version of the original report published November 3, 2022 [30 pgs].

Goldman Sachs

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Carbonomics

Affordability, Security and Innovation

The higher cost of capital for high carbon vs. low carbon investments is driving **under-investment in energy, transport and heavy industries**. More regulatory clarity could close this **$0.5 trn pa missed investment opportunity** and **spur a $1 trn increase in annual energy spend by 2026E** to provide reliable, affordable and cleaner energy supply, in line with the UN Sustainable Development Goals.

We update our Carbonomics cost curve and arrive at three key conclusions:

1) clean technologies associated with energy efficiency and substitution of natural gas **(renewables, clean hydrogen, biogas) keep moving lower on the cost curve;**

2) technologies substituting oil **(EVs, biofuels) have become less competitive;**

3) the biggest policy breakthrough this year – **the US Inflation Reduction Act – is transformational for the economics of hydrogen and carbon capture.**

Overall, '**the revenge of the old carbon economy**' keeps driving a disjointed de-carbonization process that is both inflationary and inefficient. That said, we see some clean tech green shoots, with clean hydrogen at the cusp of a regulatory and economic breakthrough.

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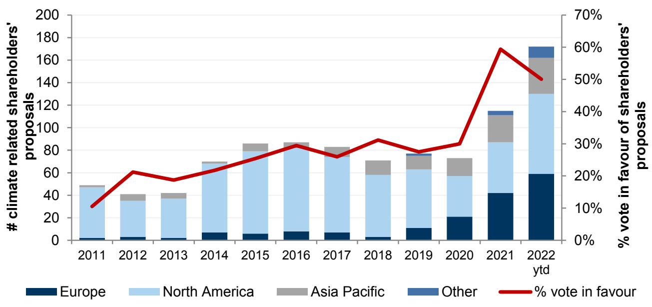
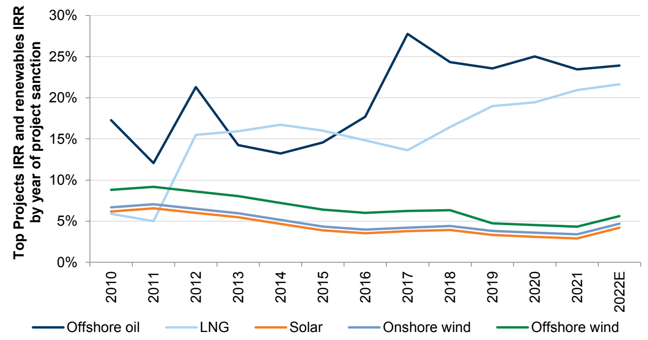
Carbonomics in 12 charts

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



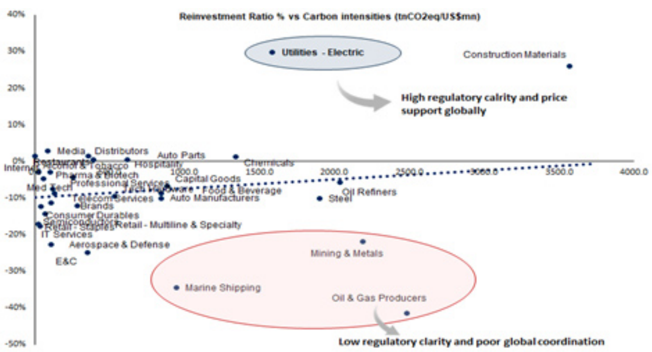
Source: ProxyInsight, Goldman Sachs Global Investment Research

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



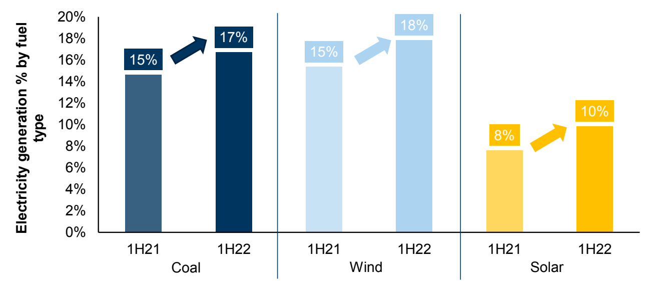
Source: Goldman Sachs Global Investment Research

Exhibit 3: ...which in combination with high regulatory uncertainty drives ongoing structural under-investment in carbon- intensive industries
Reinvestment ratio % (2022E vs. 10-yr average) vs. carbon intensities (Scope 1, 2, 3 emissions intensity per revenue (tnCO2eq/US$mn))



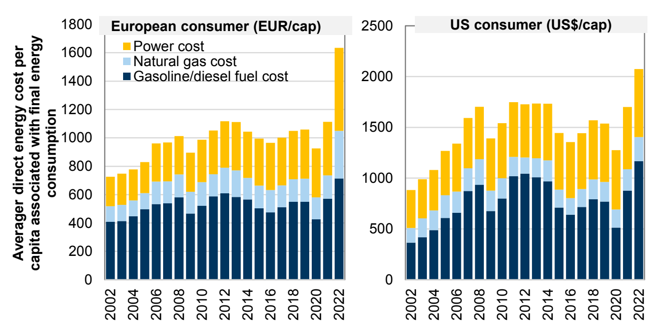
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 4: This is leading to a dis-jointed energy transition, with both the most emitting (coal) and least emitting (renewables) fuels on a growth trajectory ytd
Electricity generation % by fuel type, 1H22 vs 1H21, Europe



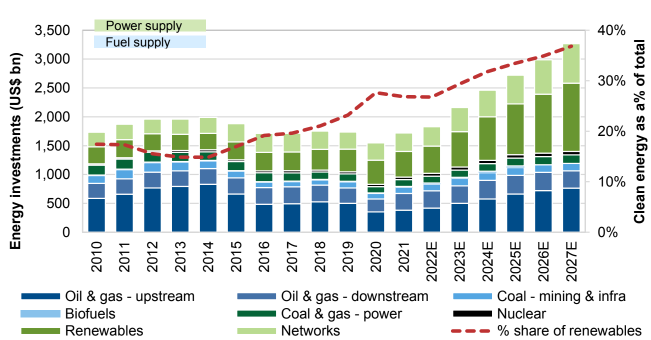
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 5: Structural under-investment in energy is driving an affordability crisis, with direct energy cost per capita reaching the highest level in over two decades
Average direct energy cost per capita associated with final energy consumption in Europe (LHS, EUR/capita) and the US (RHS, US$/capita)



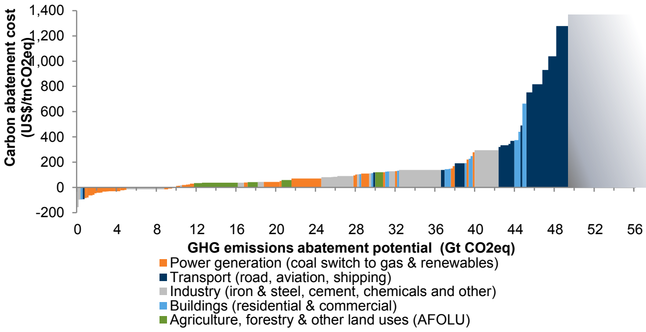
Source: Eurostat, EIA, IEA, US Bureau of Transportation Statistics (BTS), Goldman Sachs Global Investment Research

Exhibit 6: We believe a major increase in energy investment is required to resolve the dual challenge of energy affordability and security, across both clean energy and hydrocarbons
Global energy investments in energy (US$bn)



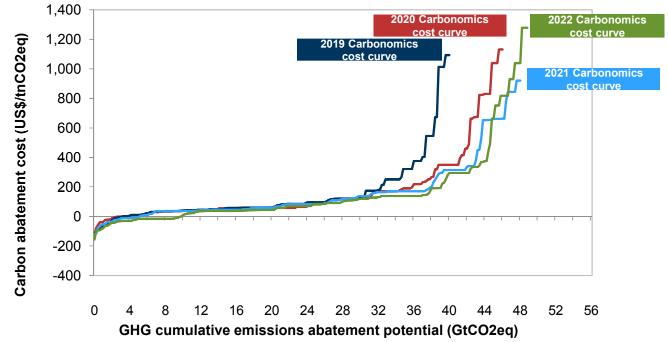
Source: IEA WEI, Goldman Sachs Global Investment Research

Exhibit 7: We update our annual cost curve of de-carbonization (Carbonomics cost curve) for the fourth consecutive year...
Carbonomics cost curve of de-carbonization for anthropogenic GHG emissions (GtCO2eq)



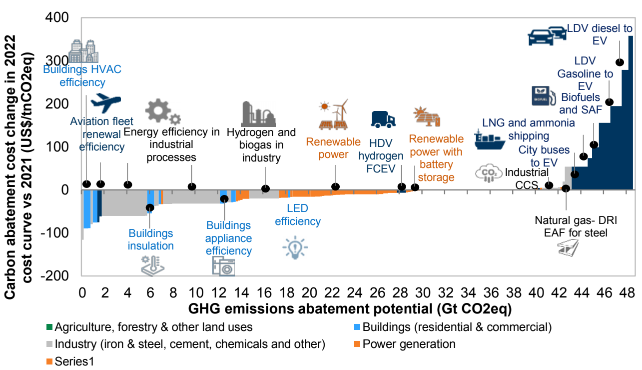
Source: Goldman Sachs Global Investment Research

Exhibit 8: ..and this year it shows a combination of lower and higher carbon abatement prices across different technologies...
Carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



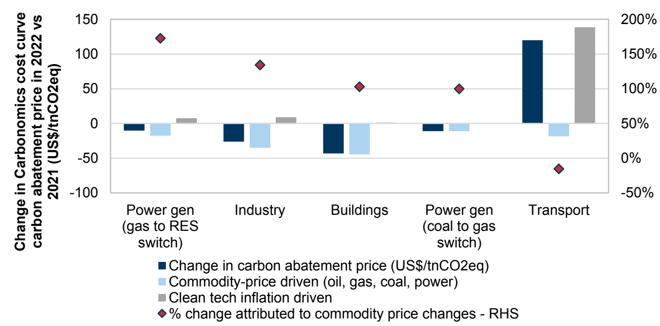
Source: Goldman Sachs Global Investment Research

Exhibit 9: ..with clean technologies associated with energy efficiency and substitution of natural gas (renewables, hydrogen, biogas) moving lower on the cost curve, as opposed to technologies substituting oil (EVs, biofuels)...
Carbon abatement cost change in 2022 cost curve vs 2021



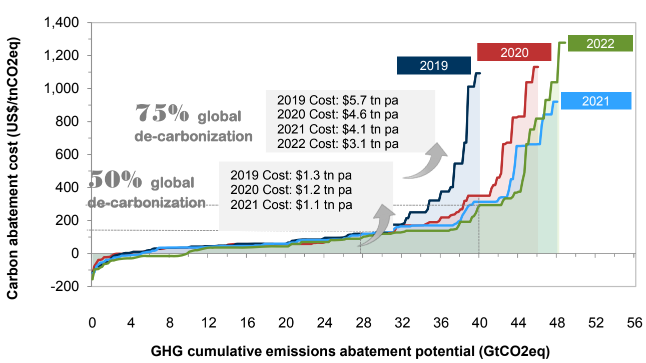
Source: Goldman Sachs Global Investment Research

Exhibit 10: ..leading to an overall lower carbon abatement price for power generation, industry and buildings, but a higher price for transport
Change in cost curve carbon abatement price of 2022 curve vs. 2021



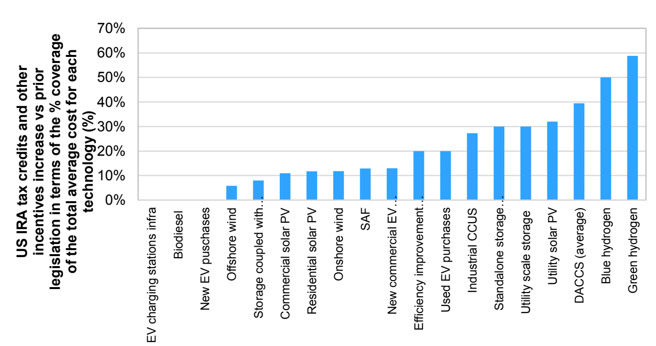
Source: Goldman Sachs Global Investment Research

Exhibit 11: The incremental cost of net zero carbon continues to improve (for c.75% de-carbonization), largely due to higher hydrocarbon prices impacting the lower end of the cost curve
Carbon abatement cost curve for anthropogenic GHG emissions



Source: Goldman Sachs Global Investment Research

Exhibit 12: Hydrogen, carbon capture, energy efficiency and storage are the key technologies that have benefited from the strongest regulatory momentum ytd
US IRA tax credits and incentives increase in coverage (vs prior legislation) of the total average cost by technology (%)



Source: The Senate of the United States, Goldman Sachs Global Investment Research

PM Summary

A 10 ppt divergence in the cost of capital of high carbon vs. low carbon investments is driving structural under-investment in energy, transport and heavy industries.

Leveraging our project-by-project modelling of giant long-term energy projects, we estimate that **the spread in the cost of capital of hydrocarbon vs. renewable developments has widened by >10 percentage points over the last five years**, on the back of increased focus on de-carbonization and climate change. This is in turn driving a historical turning point in energy investment, with global renewable power spend overtaking oil & gas developments for the first time in history. A higher cost of capital, uncertainty around future carbon regulation and the lack of global coordination on carbon pricing are impacting investment in several carbon-intensive global sectors, mostly in energy, materials and heavy transport. On our estimates, **there has been a decline in the re-investment ratio (10-year average vs. 2022E) of c.40% in oil & gas, heavy industry and heavy transport**. This under-investment is one of the key drivers of the current energy affordability crisis, in our view, and is leading to a dis-jointed de-carbonization process. If we take Europe as an example, we are seeing growth in both the most carbon intensive fuels (coal) and the lowest carbon intensive fuels (renewable power), with a declining role of gas as a transition fuel. This is leading to an increase in energy costs without meaningful reduction in net carbon emissions.

A $1 trn pa increase in global annual energy spend by 2026E is required to provide reliable, affordable and cleaner energy supply, in line with the UN Sustainable Development Goals.

We believe that the energy industry has been under-investing for the past eight years. Since the peak of 2014, investments in traditional energy (oil, gas upstream) fell 57% from the peak, driving a >30% reduction in global primary energy investments, from $1.3 trn in 2014 to $0.8 trn in 2020. Similarly, total investments in energy (not just primary) have fallen from $2.0 trn at the peak in 2014 to just $1.5 trn in 2020, a 22% decline. The focus has shifted in recent years to energy sustainability, but we note that the overall growth of the investments in renewables was not sufficient to compensate for the abrupt drop in investments in the traditional energy space, given the smaller scale and higher capital intensity per unit of energy output. We believe total energy investments must almost double from here to solve the dual challenge of energy affordability and security, but also sustainability. We estimate that total energy investments must increase by $1 trn pa by 2026E. This is driven, on our estimates, by a major increase in renewable power and networks infrastructure capex but also by the revival of capex in traditional fuels, in particular natural gas (LNG), required to facilitate a more resilient and affordable energy transition. Moreover, we estimate that, on average, clean technologies (renewables in power generation and electric mobility) require c.2-3x the capex per unit of output energy compared to the traditional hydrocarbon sources and technologies they displace, further exacerbating the need for higher investments to support growing energy demand.

We update our Carbonomics cost curve for innovation, cost inflation and commodity prices.

In this report, we update our Carbonomics cost curve of de-carbonization for the fourth consecutive year, encompassing >100 different applications of GHG conservation technologies across all key emitting sectors globally. The newly updated de-carbonization cost curve shows a mix of technologies moving lower and higher on the cost curve relative to last year. This is driven by the dual impact of capital markets outlined in this report with contributions from (a) higher long-term energy prices (oil, natural gas, coal, power) reducing the implied cost of the switch to cleaner alternative technologies and (b) clean tech cost inflation for existing technologies, mostly driven by higher raw material and labour costs. Overall, clean technologies focused on improving energy efficiency (in buildings as well as in industry) have moved notably lower on the cost curve, as the benefit associated with them has increased in light of higher energy prices, reducing the implied carbon abatement cost. A similar trend is observed for technologies substituting natural gas (the fuel that has seen the largest yoy price increase in the forward curves), as the potential cost saving from natural gas substitution outweighs the clean tech cost inflation seen by these technologies this year. Amongst these are renewable power, clean hydrogen and biogas. On the contrary, clean technologies substituting oil have overall moved higher on the cost curve this year, as the increase in oil prices yoy has been more than offset by the cost inflation observed in these technologies - higher battery costs, power prices in EVs and higher feedstock prices for biofuels.

The biggest policy breakthrough (US Inflation Reduction Act) is transformational for the economics of hydrogen and carbon capture.

The current energy affordability and security crisis has led to a transformational step-up in regulatory momentum for a number of technologies. Both REPowerEU in Europe and the US IRA (approved by the US House of Representatives on August 12 as the "Inflation Reduction Act of 2022") have provided a substantial improvement in the regulatory framework for clean tech. Carbon capture, clean hydrogen, and solar PV are some of the technologies benefiting the most from the current legislation in the US, as measured by the % of total average cost for each technology covered by tax credits and other incentives and in terms of regulatory momentum. The greatest step-up in incentives from the US IRA vs prior legislation has come for hydrogen, carbon capture, energy storage and energy efficiency technologies.

Higher cost of capital and regulatory uncertainty continue to drive structural under-investment in energy, contributing to an energy affordability crisis and a dis-jointed de-carbonization process

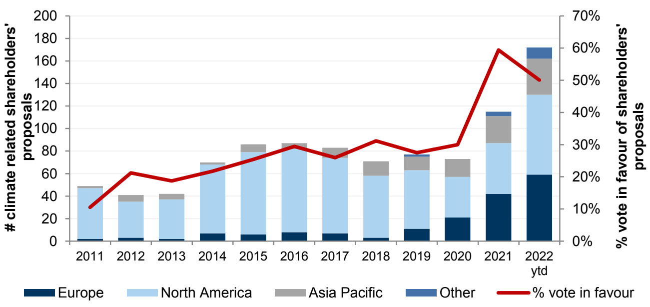
Capital markets pressure: The rise of ESG is driving capital towards de-carbonization, but regulatory uncertainty and the lack of global coordination are generating structural under-investment in key materials, oil & gas and heavy transport sectors, raising price inflation and affordability concerns.

Capital markets' focus on de-carbonization has been on the rise in recent years. With the increase in global GHG emissions, investors have been driving the climate change debate by placing pressure on corporate management to incorporate climate change into their business plans and strategies. The number of climate-related shareholder proposals (as shown by data from ProxyInsight) has increased four-fold since 2011 and the **percentage of investors voting in favour has increased five-fold over the same period.** So far, 2022 has been another year of strong shareholder engagement on climate change, with year-to-date climate-related shareholder resolutions exceeding last year's on an annualized basis and the percentage vote in favour remaining at high levels, around c.50%, as shown in Exhibit 1. While the 2021 increase in the number of climate-related shareholder resolutions was primarily attributed to Europe, 2022 has seen a notable acceleration in the number of these resolutions in North America as well as RoW. This investor pressure, however, is not uniformly distributed across sectors and shows **a clear bias towards energy producers** vs. energy consumers, with data since 2014 showing >50% of proposals targeting energy producers (oil & gas, utilities) while only 30% of the proposals target the sectors that account for most of the final energy consumption. As such, the energy sector is one of the most susceptible to the capital markets' focus on the topic of climate change and is one where the largest divergence and impacts can be observed and therefore the sections that follow use it as a primary example.

Today >$100 trn of global assets under management have signed up to UN PRI and are implementing ESG metrics as part of their investment process. This wave of "green" investments is driving capital towards de-carbonization technologies through a divergence in the cost of capital of high carbon vs. low carbon investments. Looking at the energy sector, we estimate that the spread in the **cost of capital of hydrocarbon vs. renewable developments has widened by >10 percentage points over the last five years.** This is in turn driving a historical turning point in energy investment, with global renewable power spend overtaking oil & gas developments for the first time in history. **A higher cost of capital, uncertainty around future carbon regulation and the lack of global coordination on carbon pricing are impacting investment in several sectors, mostly in energy**, materials and heavy transport. On our estimates, there has been a decline in the re-investment ratio (10-year average vs. 2022E) of c.40% in oil & gas, steel, mining and marine shipping: global carbon-intensive sectors which suffer from lack of clear policies around de-carbonization. In contrast, electric utilities is an example of a sector where clear de-carbonization incentives and strategies are actually leading to higher investment than in the past, as shown in Exhibit 3. We believe that the continued lack of coordination runs the risk of severe under-investment in core parts of the 'Old Carbon Economy' that could lead to supply tightness as we already are starting to experience in parts of the materials, oil & gas and transport industries.

Exhibit 13: Capital markets' engagement in climate change and sustainability keeps rising...

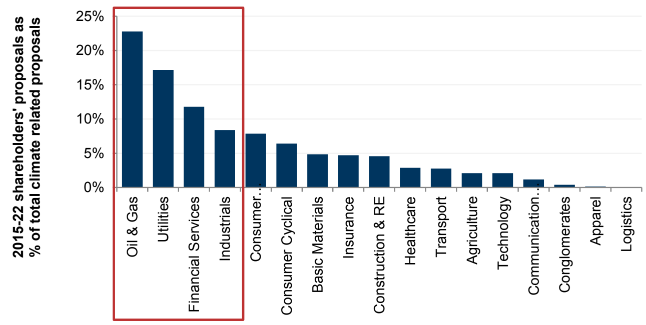
Number of climate-related shareholder proposals and % vote in favour



Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 14: ...but with a clear bias towards energy producers and financers...

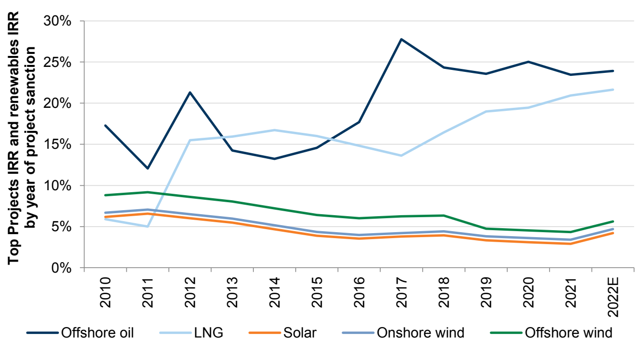
2015-22 shareholders' proposals as a % of total climate-related proposals



Source: ProxyInsight, Goldman Sachs Global Investment Research

Exhibit 15: ...driving the ongoing divergence in the cost of capital of low vs. high carbon investments...

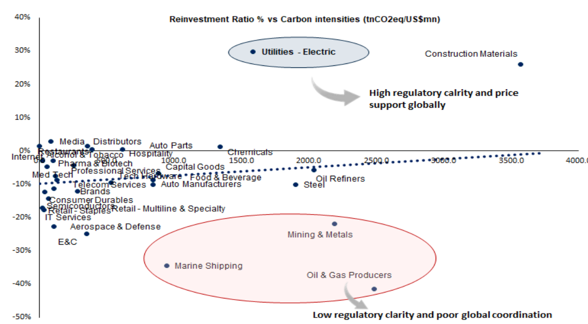
Top Projects IRR for oil & gas and renewable projects by year of project sanction



Source: Goldman Sachs Global Investment Research

Exhibit 16: ..which in combination with high regulatory uncertainty drives ongoing structural under-investment in carbon-intensive industries

Reinvestment ratio % (2022E vs. 10-yr average) vs. carbon intensities (Scope 1, 2, 3 emissions intensity per revenue (tnCO2eq/US$mn))



Source: Company data, Goldman Sachs Global Investment Research

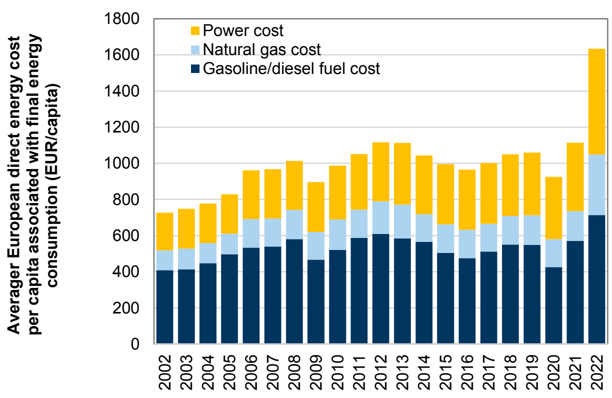
Structural under-investment in energy is leading to an energy affordability crisis but also a dis-jointed de-carbonization process

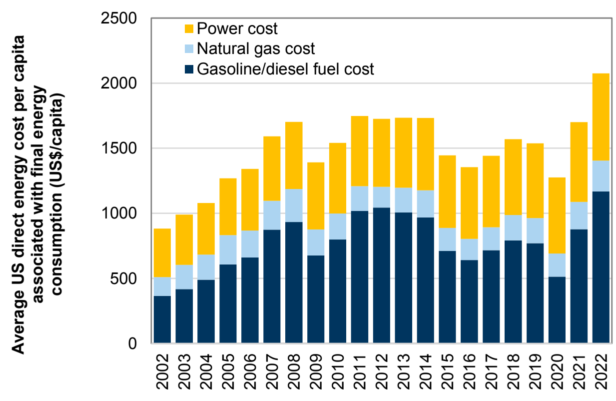
The under-investment in the energy sector is leading to a global affordability crisis, not only in Europe but also globally. We estimate the **direct energy cost to the average consumer in Europe (on a per capita basis) has increased by c.50% yoy on average in 2022, reaching the highest level in decades.** Our analysis focuses on the **direct cost the average energy consumer pays in Europe** and includes the total cost of fuel at the pump (gasoline, diesel for passenger road transport), natural gas final energy consumption in residential buildings and final electricity consumption for residential buildings but also for transport electrification. We note that this analysis is done **based on the retail prices that consumers pay for energy and which include all relevant taxes and levies.** The results of the analysis are presented in Exhibit 5. The average European energy cost per capita is going through an abrupt and large increase in 2022, consistent with the trends observed across the energy price benchmarks (oil products, natural gas and power prices). We believe a higher level of investment is required to bring this figure down, with the higher share of power in the average European consumer's energy spending as well as the improved energy efficiency of Europe and a return of investment in natural gas (long-term LNG contracts) driving a gradual reduction in total energy cost per capita, assuming that the higher share of renewables and PPAs drives the wholesale and subsequently power price lower long term.

The affordability crisis is not Europe-centric, but rather a global phenomenon also impacting energy independent regions, as shown in Exhibit 17, with the average direct energy cost per capita in the United States also reaching the highest level in two decades in 2022. The absolute figure remains nonetheless higher than in Europe given the higher energy intensity per capita of the US relative to Europe (direct energy consumption per capita).

Exhibit 17: Structural under-investment is driving an affordability crisis, with direct energy cost per capita reaching the highest level in decades in Europe

Average direct energy cost per capita associated with final energy consumption in Europe (LHS, EUR/capita) and the US (RHS, US$/capita)

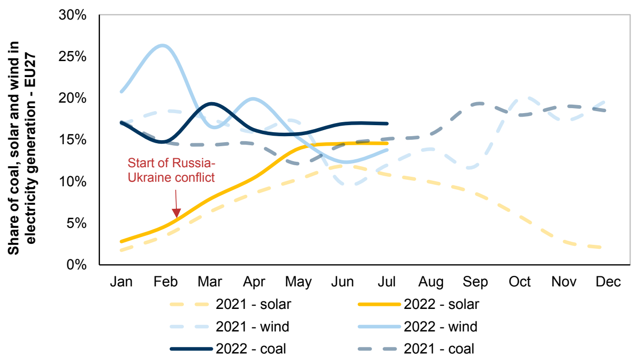




Source: Eurostat, EIA, IEA, US Bureau of Transportation Statistics (BTS), Goldman Sachs Global Investment Research

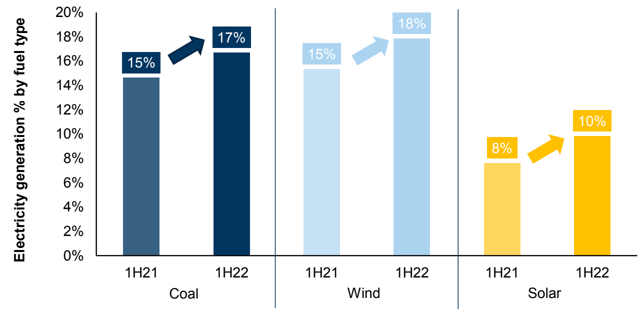
The chronic under-investment in energy is not only leading to an energy affordability crisis, but **also driving a dis-jointed de-carbonization process, with both the most carbon intensive fuels (coal) and the lowest carbon intensive fuels (renewable power) trending higher ytd,** as evidenced by Eurostat data for Europe. This dis-jointed de-carbonization process is not, on a net basis, meaningfully contributing to a reduction in carbon intensity and overall emissions. As a result, the under-investment in energy is not only negatively impacting energy affordability and energy security but also potentially energy sustainability with the return of some of the most carbon intensive fuels (coal) at the expense of transition fuels such as natural gas.

Exhibit 18: The energy affordability crisis is also leading to a dis-jointed de-carbonization process, with both the most carbon intensive (coal) and least carbon intensive fuels (renewables)...
Share of coal, solar and wind in power generation for 2022 ytd vs 2021



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 19: ...trending higher ytd, as evidenced by power generation data for the EU ytd
Power generation share by fuel, 1H22 vs 1H21



Source: Eurostat, Goldman Sachs Global Investment Research

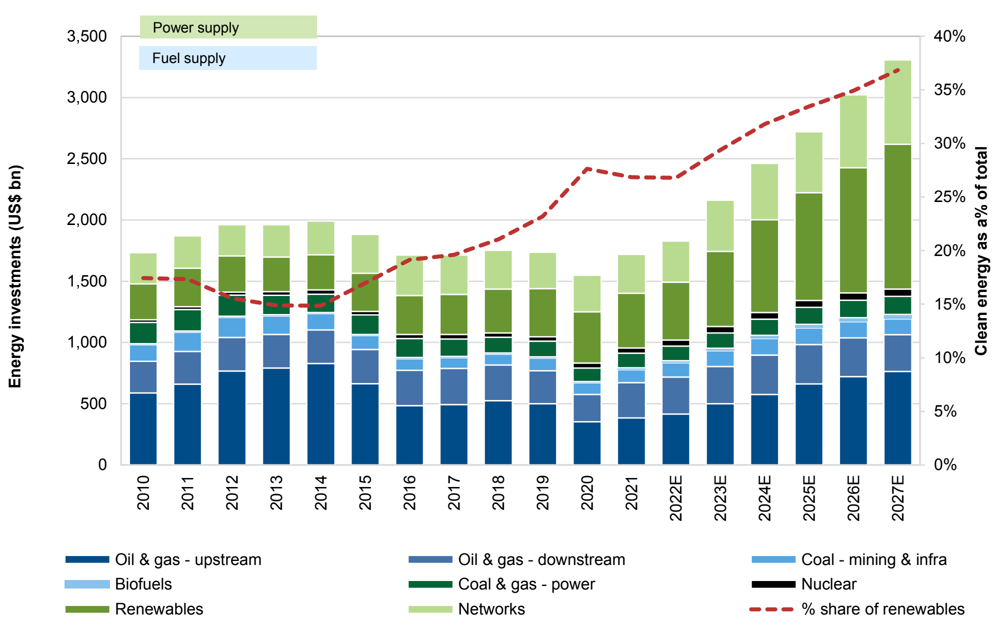
Energy investments need to reach $3.0 trn by 2026E to solve the dual challenge of energy affordability and energy security

The energy industry has been under-investing since the peak in 2014, mostly across hydrocarbons, but also in renewables, given their higher capital intensity per unit of output energy...

We believe that the energy industry has been under-investing since the peak of 2014, with investments in traditional energy (oil, gas upstream) falling 57% from the peak and driving a >30% reduction in global primary energy investments, from $1.3 trn in 2014 to $0.8 trn in 2020 (as shown in Exhibit 13). Similarly**, total investments in energy** (not just primary) **have fallen from $2.0 trn at the peak in 2014 to just $1.5 trn in 2020,** a c.22% decline. The focus has shifted in recent years to energy sustainability, but we note that the **overall growth of the investments in renewables was not sufficient to compensate for the abrupt drop in investments in the traditional energy space, given the smaller scale and higher capital intensity per unit of energy output.** We believe total energy investments must grow notably from here to solve the dual challenge of energy affordability and security, but also sustainability. **We estimate that total energy investments must increase by $1 trn pa by 2026E and almost double reaching $3.3 trn by 2027E (from $1.7 trn in 2021)**.

Exhibit 20: Total energy investments have fallen by >20% over the past decade, and we expect them to almost double by 2027E, reaching $3.3 trn (from $1.7 trn in 2021)

Global energy investments (US$ bn), split between power and fuel supply



Source: IEA WEI, Goldman Sachs Global Investment Research

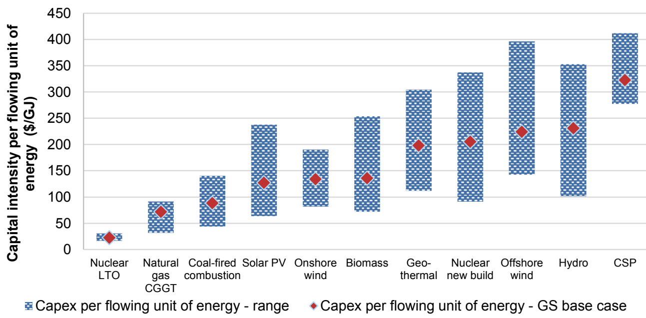
…and we believe it is time for this trend to reverse, supporting energy resilience and security

We believe that the recent focus on energy security, resilience and diversification will drive a new era for energy investments, which we argue should rise above the historical peak of $2 trn pa by 2023E, reaching c.$3.0 trn by 2026E to support the rising energy needs globally. This is driven, on our estimates, by a major increase in renewable power and networks infrastructure capex but also by the revival of capex in traditional fuels, in particular natural gas (LNG), required to facilitate a more resilient and affordable energy transition.

2020 marked the first year in history when renewable investments exceeded upstream oil & gas; whilst we expect this trend to continue, with clean energies (renewables and bioenergy) maintaining a >25% share in global total energy supply investments, we note that investments must also be supported in other parts of the energy ecosystem, primarily natural gas (required for energy resilience and a key transition fuel) in the near term, networks throughout this decade and clean hydrogen longer term. Green infrastructure will play a major role in the future of energy investments, with clean technologies in general (global average costs) being more capital intensive on average compared to the traditional energy (hydrocarbon) they displace, but also benefiting from a much lower cost of capital under the right regulatory framework, making it a strong example of a successful pro-growth pro-environment public-private partnership.

Investments in low carbon are to be further accelerated by the need for energy diversification and lower carbon intensity. Moreover, we estimate that, on average, clean technologies (renewables in power generation and electric mobility) require c.2-3x the capex per unit of output energy compared to the traditional hydrocarbon sources and technologies they displace, further exacerbating the need for higher investments to support growing energy demand. In the exhibits that follow, we present the capital intensity (capex) per unit of output energy for each type of power generation and transport technologies. We present the results both in units of capex per flowing unit of energy (US$/GJ of peak energy capacity) and per unit of energy over the life of the asset (US$/GJ). This shows **higher capital intensity per unit of energy as we move to cleaner alternatives for power generation and transport**. This, however, does not necessarily translate into higher costs for the consumer, thanks to the availability of cheap financing (under an attractive and stable long-term regulatory framework) and lower opex, compared to traditional hydrocarbon developments.

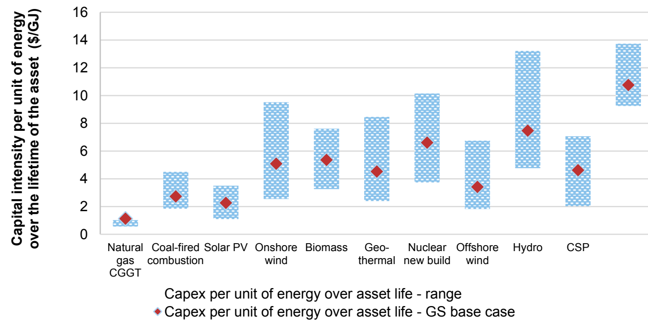
Exhibit 21: All renewable clean technologies in power generation have higher capital intensity compared to traditional fossil fuel sources based on per flowing unit of energy...
Capex per flowing unit of energy (US$/GJ)



*LTO: Long term operation of existing nuclear assets

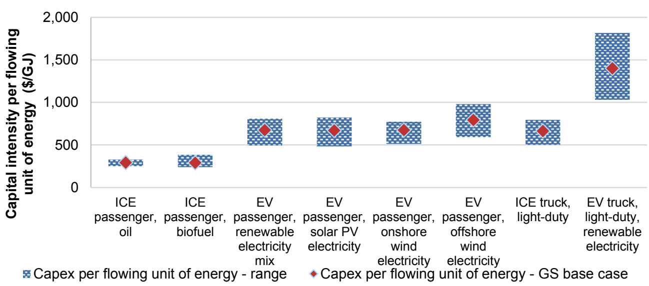
Source: IRENA, EIA, Goldman Sachs Global Investment Research

Exhibit 22: ...and over the lifetime of the asset
Capex per unit of energy over the life of the asset (US$/GJ) for each technology



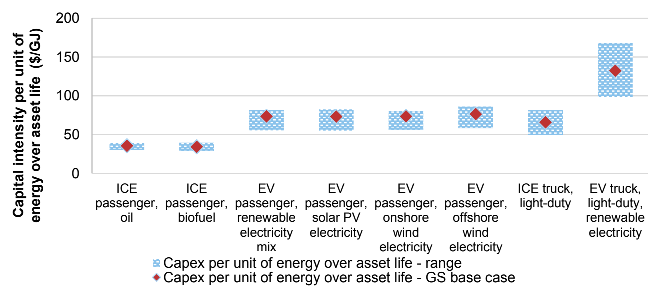
Source: IRENA, EIA, Goldman Sachs Global Investment Research

Exhibit 23: Similarly, in transport, clean technology alternatives have a higher capital intensity than their equivalent traditional fossil-fuel technologies per unit of flowing output energy...
Capex per flowing unit of energy (US$/GJ)



Source: EIA, Goldman Sachs Global Investment Research

Exhibit 24: ...and per unit of energy over the lifetime of the technology
Capex per unit of energy over the life of the asset (US$/GJ) for each technology



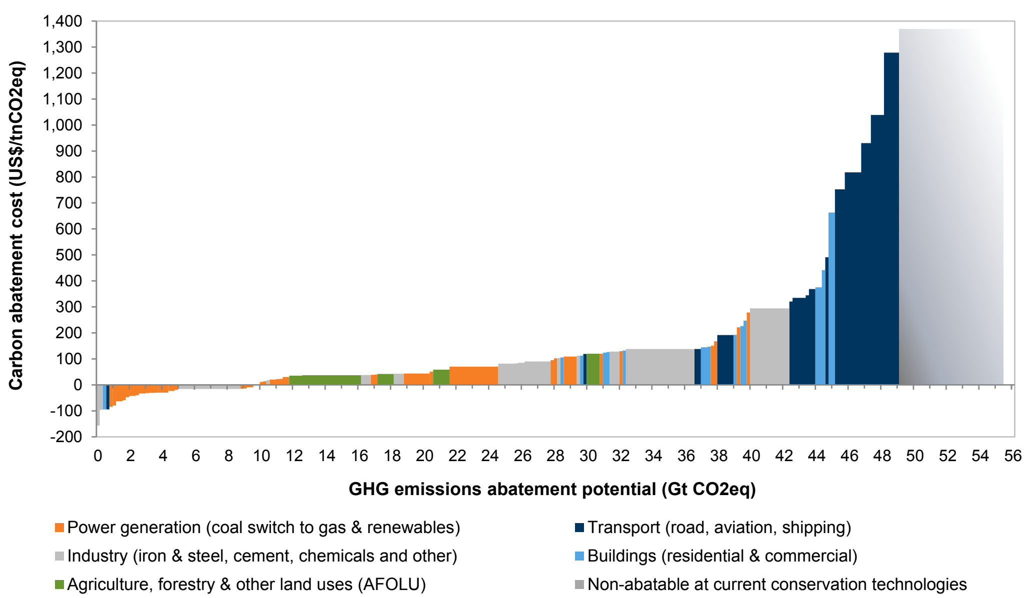
Source: EIA, Goldman Sachs Global Investment Research

High energy prices and clean tech inflation both impact the Carbonomics cost curve, with energy efficiency and gas-substituting technologies moving lower on the cost curve, whilst oil-competing technologies move higher

In our first deep-dive de-carbonization report, *Carbonomics: The future of energy in the Age of Climate Change* in 2019, we introduced our inaugural estimate of the carbon abatement cost curve. The **Carbonomics cost curve shows the reduction potential for anthropogenic GHG emissions relative to the latest reported global anthropogenic GHG emissions**. It comprises de-carbonization technologies that are currently available at commercial scale (commercial operation & development), presenting the findings at the current costs associated with each technology's adoption. We include conservation technologies and process specific sequestration technologies (process specific carbon capture) across all key emission-contributing industries globally: power generation, industry and industrial waste, transport, buildings and agriculture. **In this report, we update our Carbonomics cost curve of de-carbonization for the fourth consecutive year**, **encompassing >100 different applications of GHG conservation technologies across all key emitting sectors globally**. The newly updated de-carbonization cost curve is shown in Exhibit 25 and the transformation of the 2022 Carbonomics cost curve and the comparison to the 2021/2020/2019 comparable Carbonomics cost curves is shown in Exhibit 27.

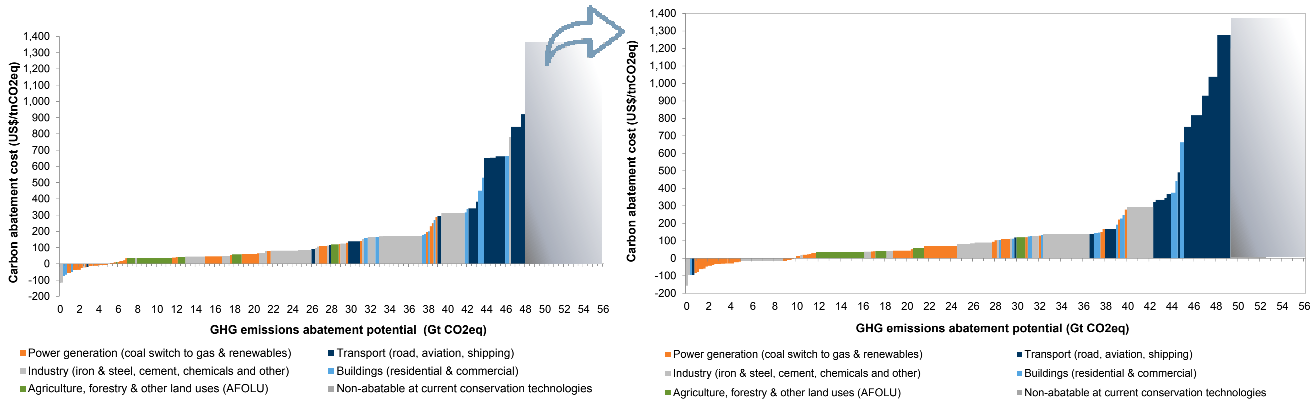
Exhibit 25: In this report, we update our Carbonomics cost curve of de-carbonization for the fourth consecutive year, encompassing >100 different applications of GHG conservation technologies across all key emitting sectors globally. A combination of higher energy prices and clean tech inflation both impact the carbon abatement cost of technologies constituting our cost curve

2022 carbon abatement cost curve for anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase



Source: Goldman Sachs Global Investment Research

Exhibit 26: Summary of key technologies considered in the construction of the carbonomics cost curve



TRANSPORTATION

De-carbonization technologies

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

POWER GENERATION

De-carbonization technologies

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

AFOLU

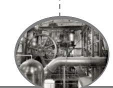
De-carbonization technologies

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

BUILDINGS

De-carbonization technologies

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



INDUSTRY & WASTE

De-carbonization technologies

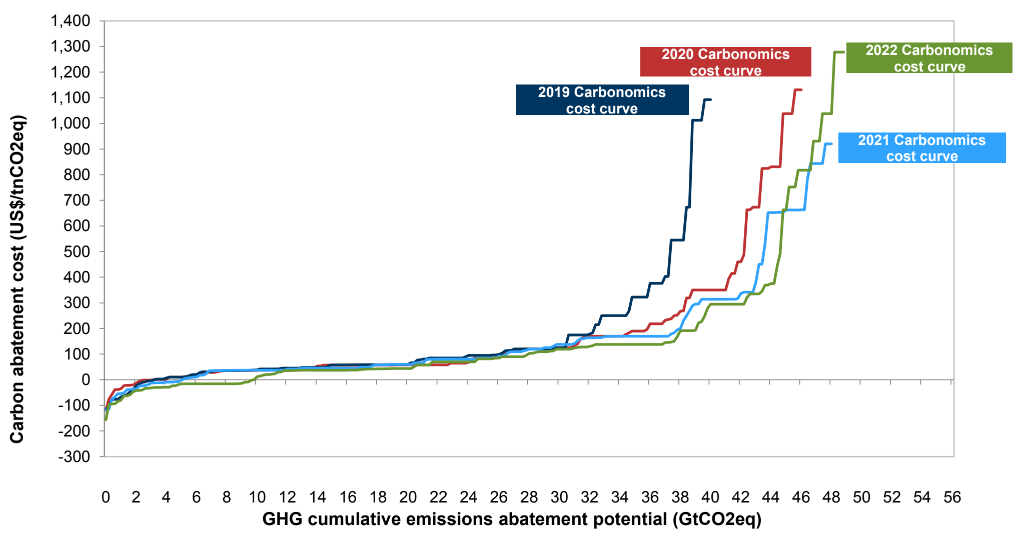
- **Industrial combustion/ heating:** Across major emitting industrial sectors, a considerable amount of emissions are associated with the use of energy, primarily through industrial combustion (heat) processes. Switch from coal, natural gas to biomass, biogas, clean hydrogen or electrification (in cases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

Source: Goldman Sachs Global Investment Research

The Carbonomics cost curve is updated for the fourth consecutive year, with high energy prices and clean tech inflation both having an impact. Energy efficiency and gas-substituting technologies are moving lower, whilst oil-substituting technologies move higher on the cost curve

Exhibit 27 shows the comparison between the 2022 Carbonomics cost curve and the 2021/20/19 comparable cost curves. As shown in the exhibit, the 2022 Carbonomics cost curve this year shows a mix of technologies moving lower and higher on the cost curve relative to last year. Overall, the lower end of the cost curve continues to move lower whilst the higher end of the cost curve has moved notably higher. This is driven by the dual impact of capital markets outlined in the previous sections of this report with contributions from **(a) higher long-term energy prices** (oil, natural gas, coal, power) **reducing the implied cost of the switch to cleaner alternative technologies** and **(b) clean tech cost inflation** for existing technologies (such as battery costs)**. Overall, clean technologies focused on improving energy efficiency (in buildings as well as in industry) have moved notably lower on the cost curve, as the benefit associated with them has increased in light of higher energy prices, reducing the implied carbon abatement cost. A similar trend is observed for technologies substituting natural gas (the fuel that has seen the largest yoy price increase in our cost curve), as the potential cost saving from natural gas substitution outweighs the clean tech cost inflation seen by these technologies this year. Amongst these are renewable power, hydrogen and biogas. On the contrary, clean technologies substituting oil have overall moved higher on the cost curve this year, as the increase in oil prices yoy has been more than offset by the cost inflation observed in these technologies - higher battery costs, power prices in EVs and higher feedstock prices for biofuels.**

Exhibit 27: We update our Carbonomics cost curve for the fourth consecutive year, indicating a move lower for the bottom end of the curve and a move higher for the upper end of the cost curve relative to last year
2022 vs 2021/20/19 comparable carbon abatement cost curves for anthropogenic GHG emissions, based on current technologies and costs, assuming economies of scale for technologies in pilot phase

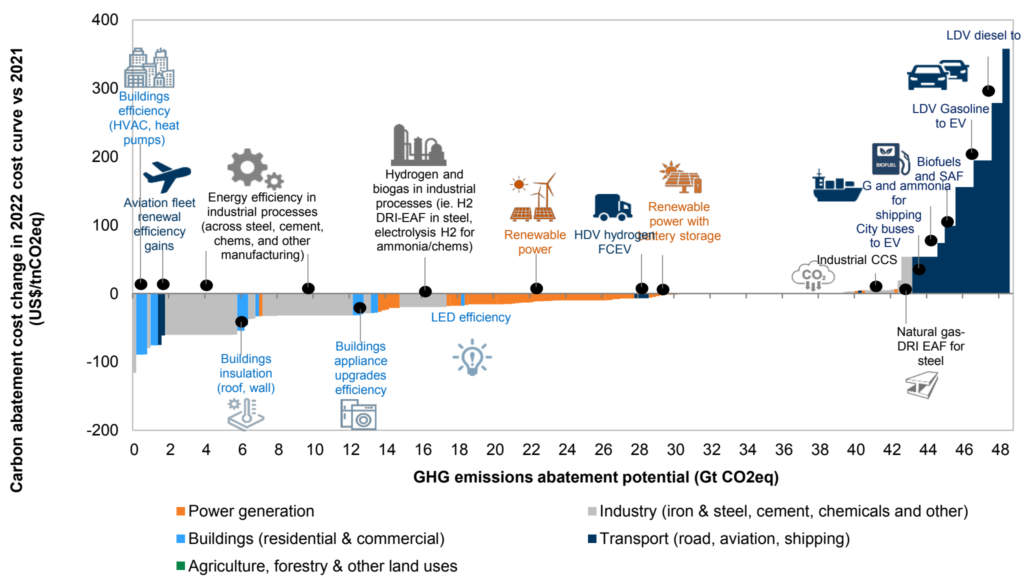


Source: Goldman Sachs Global Investment Research

The impact described above is summarized in Exhibit 28 below, which shows the change in carbon abatement cost for technologies in the 2022 Carbonomics cost curve vs last year's cost curve. Consistent with what we outlined in the previous paragraph, technologies focused on energy efficiency and natural gas substitution have seen a reduction in their carbon abatement cost yoy. These include energy efficiency technologies in buildings (HVAC efficiency measures and insulation, BAT appliances, LED lighting), in industry (energy efficiency improvements across industrial sub-segments), and renewable power, green hydrogen and biogas - all substituting natural gas in power and industry respectively. Clean technologies substituting oil have overall moved higher on the cost curve this year, as mentioned previously, as the increase in oil prices yoy has been more than offset by the cost inflation observed in these technologies. Notable examples here include EVs (impacted by higher battery and power costs), LNG in shipping for substitution of marine fuel and natural gas DRI-EAF for substitution of coal in steel, and biofuels (impacted by a notable increase in feedstock prices).

Exhibit 28: Technologies that are focused on energy efficiency (across buildings, industry) are moving lower on the cost curve as their benefit has increased in light of higher energy prices and so are technologies that are directly substituting gas, with the move higher in gas prices offsetting clean tech cost inflation (renewable power, hydrogen, biogas). In contrast, technologies substituting oil have moved higher on the cost curve (parimarily EVs and biofuels), as the move higher in oil prices has been more than offset by clean tech cost inflation observed in battery costs, power prices (for EVs) and feedstock prices (for biofuels)

Carbon abatement cost change in the 2022 Carbonomics cost curve vs 2021 by technology (US$/tnCO2)



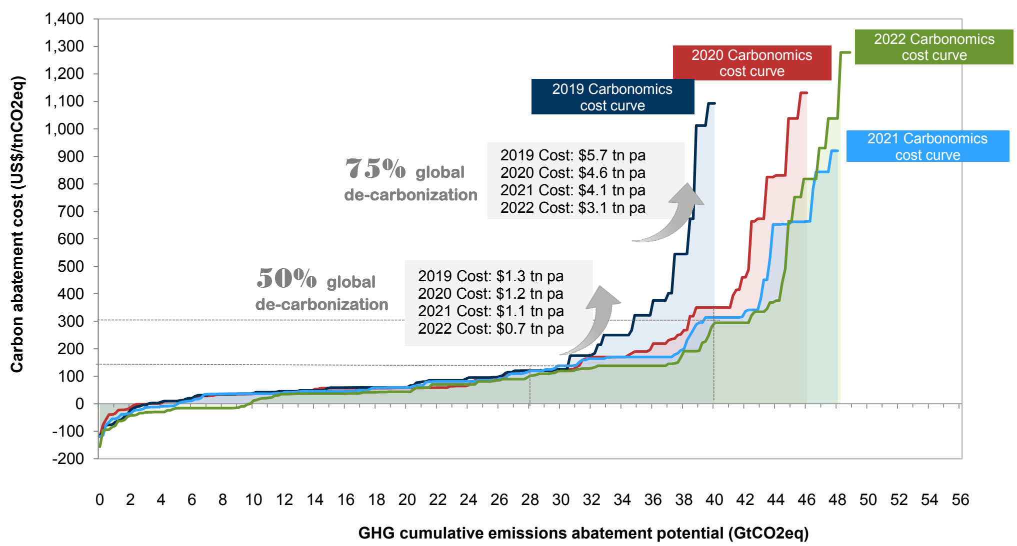
Source: Goldman Sachs Global Investment Research

Evolution of the cost curve through energy prices and innovation impacts the affordability to net zero

The evolution of the Carbonomics cost curve results, on our estimates, in a c.$1.0 trn pa reduction in the global cost to reach 75% de-carbonization but an increase in the cost of achieving the remaining 25% de-carbonization

The transformation of the cost curve brings with it a **change in the global annual cost to achieve de-carbonization** from existing, large-scale commercially available technologies. As outlined in the previous section of this report, a combination of higher energy prices and higher clean tech costs (inflation) is having a dual impact on the Carbonomics cost curve, with the lower end moving lower but the higher end moving higher. As shown in Exhibit 29, the initial c.50% of global anthropogenic GHG emissions, what we classify as **'low-cost de-carbonization'**, can be abated at an **annual cost that is $0.4 trn pa lower**, at c.$0.7 trn pa based on the 2022 cost curve vs. $1.1 trn pa based on 2021, largely driven by the energy efficiency and gas-substituting technologies moving lower. Similarly, the cost of achieving c. 75% de-carbonization has reduced by $1.0 trn pa, at c.$3.1 trn pa based on the 2022 cost curve vs. $4.1 trn pa based on the 2021 curve. Nonetheless, as we move towards 100% de-carbonization, we enter into the **'high-cost de-carbonization'** spectrum, with the curves – and subsequently the annual cost required to achieve de-carbonization – diverging significantly, with the 2022 Carbonomics cost curve resulting in a higher pa cost to abate the last 25% of emissions. This can be aided by the use of non-specific carbon sequestration - **natural sinks and DACCS offsets.**

Exhibit 29: The evolution of the de-carbonization cost curve this year results in c.$1.0 trn annual savings for 75% de-carbonization but a more costly abatement for the remaining 25% of emissions
2022 vs. 2021/2020/2019 Carbonomics cost curve for anthropogenic GHG emissions - comparison of the cumulative area under each curve, based on current technologies, assuming economies of scale for technologies in pilot



Source: Goldman Sachs Global Investment Research

Innovation and policy momentum: Hydrogen, carbon capture, energy efficiency and storage take the lead on regulatory policy momentum this year

Looking across different technologies in our Carbonomics cost curve, the current energy affordability and security crisis has led to a **transformational step-up in regulatory momentum** for a number of technologies, namely **clean hydrogen, carbon capture utilisation and storage (CCUS), energy storage and energy efficiency**. Both the REPowerEU in Europe and the US IRA (approved by the US House of Representatives on August 12 as the "Inflation Reduction Act of 2022" (IRA), following its passage through the US Senate on August 7, a climate, health and tax bill intended amongst other things to tackle energy costs and climate change) have stepped up ambitions across these key technologies. Whilst not a transformational step-up in regulatory momentum, the regulatory framework remains supportive for renewables, EVs, nuclear and other low emission fuels.

Transformational policy momentum:

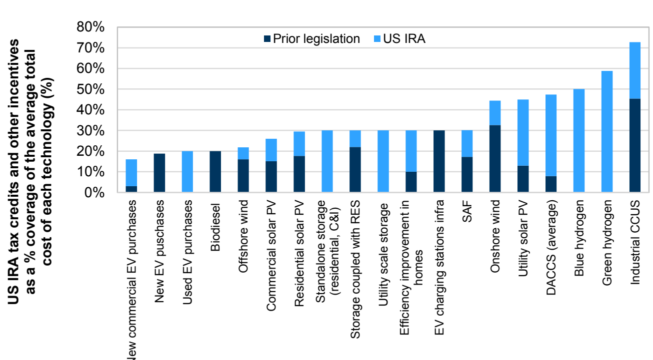
- **Clean hydrogen:** The REPowerEU has proposed a notable step-up (c.3.5x) to the volumes of hydrogen targeted for the region by 2030, to 10 Mt, further supported by the formation of the Hydrogen Bank and the ongoing legislative act work required to set up the framework for carbon contracts for difference. Meanwhile, the US IRA is a game-changer for the clean hydrogen economy, with **the introduction of the 45V production tax credit (PTC) with a headline rate of $0.6/kgH2 and up to $3/kgH2** (depending on its carbon intensity and subject to prevailing wage/apprenticeship and other requirements), **investment tax credit (ITC),** the inclusion of hydrogen in the scope of 'energy storage technologies' eligible for ITC**,** the extension of the 'clean vehicle' credits to commercial vehicles including fuel cell vehicles and the revival of tax credits for alternative fuel refueling property.
- **CCUS & DACCS:** US IRA extends 45Q credits to projects starting construction prior to 2033, reduces the min captured volume thresholds and **significantly increases the max amount of credit value per ton CO2 captured**, particularly for direct air carbon capture (DACCS) projects and industrial CCUS with geological storage (non-EOR). More specifically, the tax credit (45Q) applied to carbon capture, utilisation and storage (CCUS) is increased to $85 per metric ton of directly sequestered carbon, $60 per mt for carbon utilised for enhance oil recovery (EOR) and other uses, and $180 per mt for DACCS assuming direct sequestration.
- **Energy Storage - Utility and residential standalone:** The US IRA includes battery storage technology, qualified biogas property, electrochromic glass and microgrid controllers as properties that would qualify for the existing ITC. The tax credit rate has also been increased to 30% from 26% in 2022. Under the IRA, Battery Storage can benefit from a 30% ITC regardless of co-location with renewables, potentially paving the way for an acceleration in standalone deployments due to significant improvements in project economics.

- **Energy Efficiency solutions:** For commercial buildings, the tax incentive for energy efficiency improvements in the IRA has significantly improved versus prior law, both in terms of the credit amount and the efficiency improvement threshold needed to claim the credit. Energy efficiency improvements (relative to a "reference building") needed to claim the tax deduction are now 25%, down from 50% previously. Additionally, the base rate for the credit is now set at $2.50 per square foot, with an additional $0.10 per square foot that can be earned for every percentage point of efficiency improvement above the 25% threshold. In total, commercial buildings can earn up to $5.00 per square foot in efficiency credits. This compares to the prior credit of $1.80 per square foot. For residential home improvements, the IRA significantly expanded the tax credit for energy efficiency purchases by increasing the credit rate and broadening its scope**.** The renamed energy efficient home improvement credit offers a 30% credit rate, versus 10% previously, and the credit limit has been expanded to $1,200 per year and $600 per item, versus a $500 lifetime limit previously. Notably, under the IRA, taxpayers can earn the home improvement credit on all their homes, versus only primary residences previously.

In the exhibits that follow, we address the regulatory support for various clean technologies, with a focus on the US, showing the % coverage of the average total cost of each technology through US IRA tax credits and other incentives. As shown in Exhibit 30, **carbon capture, hydrogen, and solar PV** are some of the technologies benefiting from the highest cost coverage - in terms of the % of average total cost for these technologies (LCOH, US$/tnCO2, LCOE respectively) covered by such incentives, on our estimates, under the current US IRA legislation. **To address policy momentum this year,** in Exhibit 31, we only show the incremental % coverage of the average total cost for each technology under the US IRA that was not covered under the prior legislation. The **technologies showing the greatest policy momentum YTD** are **clean hydrogen, carbon capture, energy storage (standalone and utility scale) and energy efficiency.**

Exhibit 30: Carbon capture, clean hydrogen, and solar PV are some of the technologies benefiting the most from the current legislation in the US, as measured by the % of total average cost for each technology covered by tax credits and other incentives...

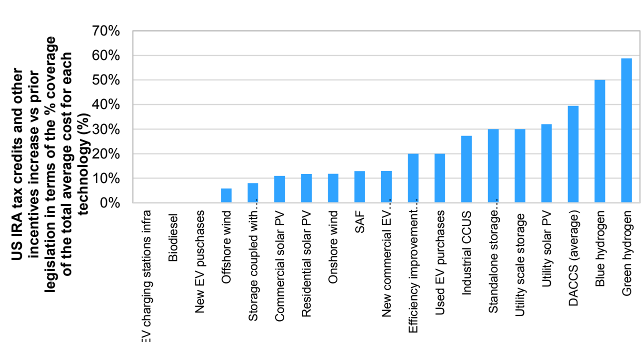
US IRA tax credits and other incentives as a % of coverage of the average total cost of each clean technology (%)



Source: The Senate of the United States, Goldman Sachs Global Investment Research

Exhibit 31: ..and in terms of regulatory momentum, the greatest step-up in incentives from the US IRA vs prior legislation has come for hydrogen, carbon capture, energy storage and energy efficiency technologies

US IRA tax credits and incentives increase - coverage (vs prior legislation) of the total average cost by technology (%)



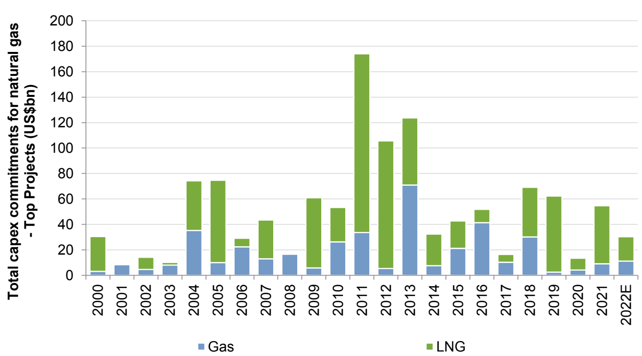
Source: The Senate of the United States, Goldman Sachs Global Investment Research

Natural gas continues to play a key role as a transition fuel and is critical for energy security

The fuel that has undoubtedly faced the largest increase in its long-term price as part of our Carbonomics framework and cost curve analysis is natural gas. Whilst the global energy transformation will lead to a reduction in the consumption of hydrocarbon energy sources over time, we note that the outlook across hydrocarbons differs depending on the end consuming sectors (markets) they serve and their respective pace of energy transformation, as well as the respective carbon content. For natural gas, depending on the climate scenario considered, demand may still continue to increase this decade, as shown in Exhibit 33. Even in Europe, one of the most committed regions globally with respect to de-carbonization and the energy transition, we believe we have sufficient visibility for the role of natural gas for at least another decade, making the role of LNG one of critical importance to the energy security of the region. Nonetheless, the global trend of under-investment observed over recent years does not appear to have changed so far in 2022 despite the observed tightness in the market, as shown in Exhibit 32.

Exhibit 32: Despite the rise in global natural gas prices, the trend of under-investment in this industry appears to continue so far in 2022, with litte capex senctioned

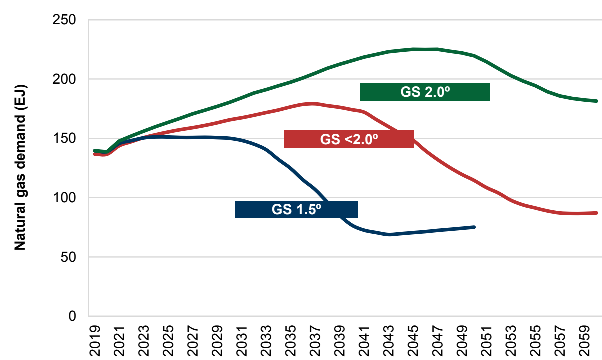
Top Projects natural gas capex sanctioned by year (excl. Russia)



Source: Goldman Sachs Global Investment Research

Exhibit 33: Depending on the climate scenario considered, natural gas demand most likely continues to increase for at least the next 10 years

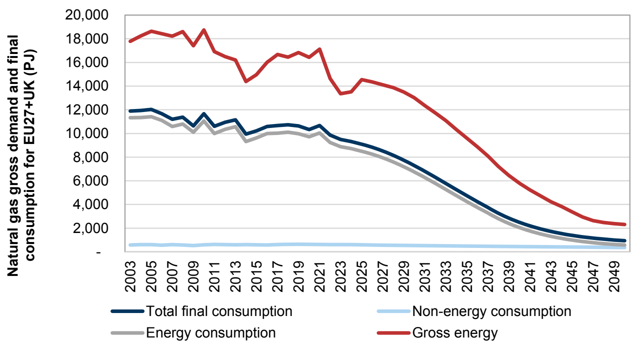
GS Net zero carbon scenarios showing the overall global demand for natural gas (EJ)



Source: Goldman Sachs Global Investment Research

Exhibit 34: Even in Europe, one of the most ambitious regions in terms of de-carbonization, natural gas remains a critical part of the energy system for another two decades, we believe, even when incorporating some level of near-term rationing and acceleration of the shift away from it in the event of technological readiness of alternatives

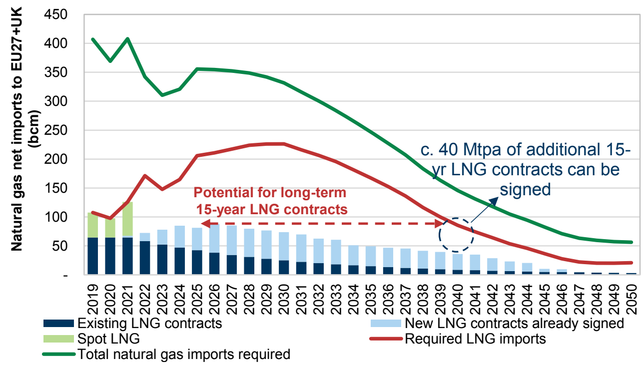
Natural gas gross energy demand and final consumption (split between energy and non energy) for EU27+UK (PJ)



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

Exhibit 35: Our European natural gas demand profile, incorporating the EU's ambition for 2/3 reduction in Russian gas imports by the end of this year and zero gas imports by the end of this decade (2030), leads us to conclude that the shortfall may need to be met with incremental LNG imports, potentially through 15-year LNG contracts

Natural gas net imports to EU27+UK (PJ)



Source: Goldman Sachs Global Investment Research

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Reg AC

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Growth is based on a stock's forward-looking sales growth, EBITDA growth and EPS growth (for financial stocks, only EPS and sales growth), with a higher percentile indicating a higher growth company. **Financial Returns** is based on a stock's forward-looking ROE, ROCE and CROCI (for financial stocks, only ROE), with a higher percentile indicating a company with higher financial returns. **Multiple** is based on a stock's forward-looking P/E, P/B, price/dividend (P/D), EV/EBITDA, EV/FCF and EV/Debt Adjusted Cash Flow (DACF) (for financial stocks, only P/E, P/B and P/D), with a higher percentile indicating a stock trading at a higher multiple. The **Integrated** percentile is calculated as the average of the Growth percentile, Financial Returns percentile and (100% - Multiple percentile).

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