Note: The following is a redacted version of the original report published March 17, 2022 [34 pgs].

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Goldman Sachs | Research

Carbonomics

Security of Supply and the Return of Energy Capex

We believe that the Russia-Ukraine conflict is a **turning point for the energy sector**, similar to and potentially greater than the 2011 concurrence of the Fukushima nuclear accident/Libyan civil war. Similarly to 2011, we expect an acceleration of US shale and global LNG construction. However, seven years of hydrocarbon under-investment (2015-21) and an ongoing focus on de-carbonization mean this energy investment cycle will be different. In this report, we analyze in detail this Return of Energy Capex, with five key conclusions:

1) **Primary energy capex** fell 35% over the past decade, and we expect it **to grow 60% by 2025 to $1.4 trn** (from c.$0.9 trn in 2021).

2) This European energy crisis has a **strong seasonal component** (winter demand for gas is >2x higher than in summer) **that requires LNG imports and hydrogen** to complement renewable power growth.

3) Analyzing the **global LNG project pipeline, we identify 156 mtpa, or c.US$139 bn of new projects** to be sanctioned over the next 5 years, with average economics of $8-10/mcf.

4) **Green Hydrogen is Europe's long-term solution to security of supply, seasonal storage and industrial demand**. RePowerEU targets a 4x upgrade to previous Green Hydrogen production by 2030.

5) **The average capex intensity of low carbon energy developments is c.2x that of hydrocarbons**, further enhancing the need for energy capex; we estimate the need for an incremental $1.5trn pa of capex by 2032.

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PM Summary: The Return of Energy Capex

We believe that **the Russia-Ukraine conflict is a turning point for the energy sector investment cycle**, similar to and potentially greater than the 2011 concurrence of the Fukushima nuclear accident/Libyan Civil War. Similarly to 2011, we expect an acceleration of US shale and global LNG construction, as the world revives short-cycle oil production and globally fungible gas supply. However, we also identify several differences: in 2011, the sector was seven years into a cycle of exploration and mega-projects build-up that was fuelling resource expansion and a revival of non-OPEC growth. The current situation is the exact opposite, with seven years of hydrocarbon under-investment (2015-21), falling oil reserve life (-50% since 2014) and declining non-OPEC ex-shale, requiring a steeper capex recovery in both long-cycle and short-cycle production. Also, **the ongoing focus on de-carbonization – driving a higher cost of capital in oil & gas developments – means this energy investment cycle will be different, characterized by a continued emphasis on renewables.**

Primary energy capex fell 40% over the past decade, and we expect it to grow 60% by 2025 to $1.4 trn (from $0.9 trn in 2021)

We believe that **the energy industry has been under-investing since the peak of 2014**, with investments in traditional energy (oil, gas upstream) falling 61% from the peak and driving a 35% reduction in global primary energy investments, from US$1.3trn in 2014 to US$0.8trn in 2020. A number of oil and gas project investment decisions have been delayed since 2014, translating into 3/10 mboe/d of lost LNG/oil production in 2024-25, on our estimates. 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. **The average capex intensity of low carbon energy developments is c.2x that of hydrocarbons, further enhancing the need for energy capex; we estimate the need for an incremental $1.5trn pa capex by 2032**. **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 US$2trn pa by 2024E to support the globe's rising energy needs**. 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 c.25% share in global total energy supply investments to the middle of this decade, 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.

The path to next zero: Mobilizing an extra $2trn per annum in low carbon investments across low carbon technologies and network infrastructure

In aggregate, we estimate a total investment opportunity in clean tech infrastructure of US$56 trn by 2050 in our path to global net zero by 2050 (GS 1.5°), as outlined in our Carbonomics: Net Zero framework. **This figure focuses solely on incremental infrastructure investments** and does not include maintenance and other end-use capex. Overall, the average annual investments in de-carbonization that we estimate over 2021-50 are c.US$1.9 trn, with the peak in 2036 (US$2.9 trn) representing 2.3% of global GDP (vs. US$1.6 trn pa, with a peak of US$2.5 trn in 2041 in the GS <2.0° scenario). We estimate that **c.50% of de-carbonization is reliant on access to clean power generation**, including electrification of transport and various industrial processes, electricity used for heating and more. Overall, we expect **total demand for power generation** in a global net zero scenario by 2050 **to increase three-fold (vs. that of 2019) and surpass 70,000 TWh as the de-carbonization process unfolds**. Based on our GS 1.5° model, power generation almost entirely de-carbonizes by 2040 (2055 under the GS <2.0° scenario).

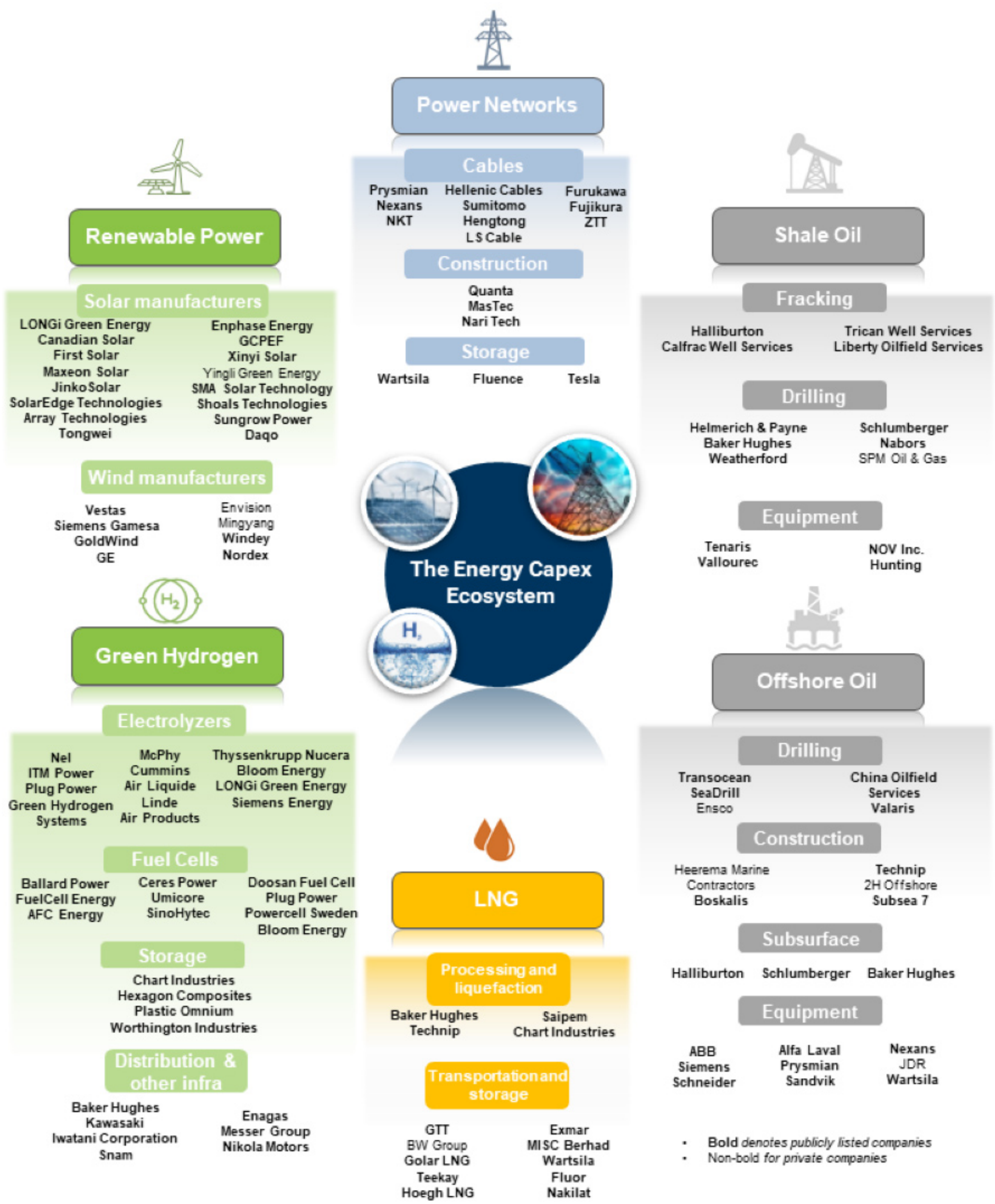
This European energy crisis has a strong seasonal component (winter demand for gas is >2x higher than in summer) that requires LNG imports and hydrogen to complement renewable power growth

Renewable power generation is a key driver of the path to net zero carbon. However, it suffers from two key problems that need to be addressed: intermittency and seasonality. The seasonal nature of natural gas consumption, with EU average monthly consumption of c.20bcm in Jun/July/Aug vs. c.45-50 bcm in Dec/Jan/Feb, will make it very difficult for Russian gas to be substituted with renewable power – especially solar power, which has opposite seasonality. As the growth in renewable power accelerates, intraday and seasonal variability has to be addressed through energy storage solutions. **To reach full replacement of coal and natural gas and de-carbonization of power markets, we believe two key technologies will likely contribute to solving the energy storage challenge: utility-scale batteries and hydrogen, each having a complementary role**, with batteries addressing intermittency and hydrogen addressing seasonality. **This low carbon infrastructure however will require decades to be built. In the meantime, LNG remains a key transition fuel that both improves security of supply and offers a lower-carbon alternative to coal-fired power generation**. We analyze the global LNG project pipeline, identifying 156 mtpa, or c.US$139 bn of new projects to be sanctioned over the next 5 years, with average economics of $8-10/mcf. Our Top Projects analysis indicates a new wave of LNG projects potentially coming at very competitive cost levels relative to history (US$1.0-2.1bn/mtpa in 2022-2025E vs US$4.0bn/mtpa in 2015-16) in Qatar, Canada and the US among others, contributing to a significantly lower cost curve in 2022 vs 2014.

Green Hydrogen is Europe's long-term solution to security of supply, seasonal storage and industrial demand.

Green (renewable) hydrogen is identified as a critical technology in helping to unlock further diversification away from natural gas in the coming years and **the REPowerEU proposal includes a notable upgrade of the 'Fit for 55' target of 5.6 Mt of renewable hydrogen by 2030 to 20 Mt over the same timeframe** based on a combination of locally produced and imported volumes. **This represents a c.4x upward revision of an already ambitious target for the region and can aid the replacement of 25-50 bcm pa by 2030, representing c.16%-32% of imported Russian gas volumes**, according to the document. In this report, we outline the key role we believe the technology will play in enhancing Europe's energy security and energy resilience: (1) **The push for electrification and renewable power accelerates the need for seasonal energy storage, with green hydrogen the optimal solution**. (2) **Renewable hydrogen and biogas are the natural successors of fossil gas for diversification of energy supply in energy-intensive industrial processes**: we view hydrogen and biogas as the key natural successors of natural gas in high-temperature industrial processes. Around 30% of Europe's (EU27+UK) natural gas demand stems from industrial processes including steel, chemical plants, cement and others. Given the high energy intensity (temperatures) required for many of these processes, direct electrification is often not feasible, making hydrogen and biogas the two natural molecular successors for the displacement of fossil gas. (3) **Higher spot EU natural gas prices tilt the scale in favour of green (renewable) vs blue and grey (natural gas-based) hydrogen**, providing upside for installed electrolysis capacity and technological innovation: at current spot European gas prices, green hydrogen is already achieving cost parity with grey (fossil-based) hydrogen in key parts of Europe (green hydrogen projects with low-cost renewable power relying on PPAs not exposed to the power price volatility). This is tilting the scale in favour of green vs grey and blue hydrogen, leading to upside to the global installed electrolysis capacity estimates and encouraging further technological innovation in the electrolysis space.

The Energy Capex Corporate Ecosystem

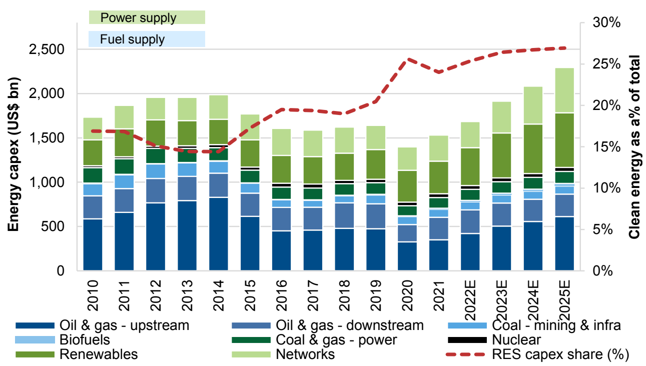


* Please note that the list of companies in the ecosystem we present above is not exhaustive

Source: Goldman Sachs Global Investment Research

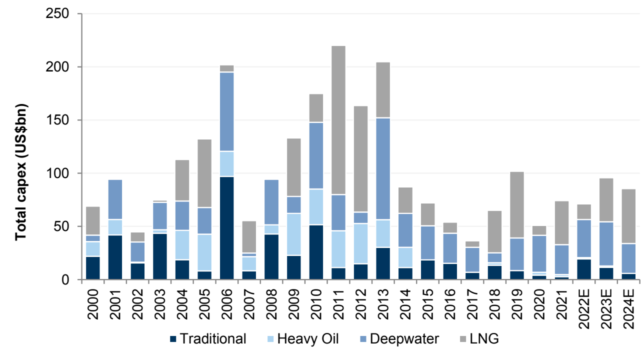
Carbonomics: Thesis in 12 charts

Exhibit 1: Primary energy capex fell 35% over the past decade, but we expect it to grow 60% by 2025...
Energy supply capex split by fuel and power supply source (US$bn - LHS), and clean energy (renewables, biofuels) as a % of total (% - RHS)



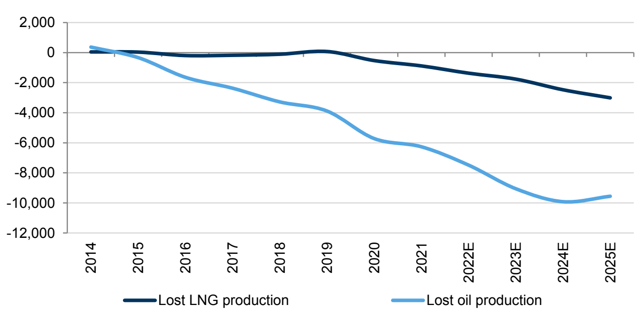
Source: IEA WEI (historicals), Goldman Sachs Global Investment Research

Exhibit 2: ...signalling the end of seven years of hydrocarbon under-investment (2015-21)...
Top Projects capex sanctioned in oil by year, split by winzone



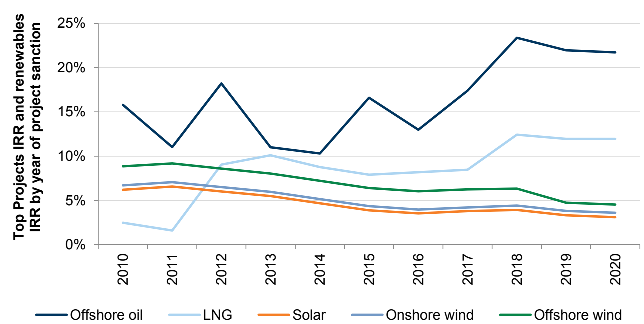
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 3: ...that we estimate will cost 10 mn blsd of oil production by 2025.
Top Projects lost LNG, offshore and onshore oil production from long-cycle developments; Top Projects 2021 vs. 2014 expectations



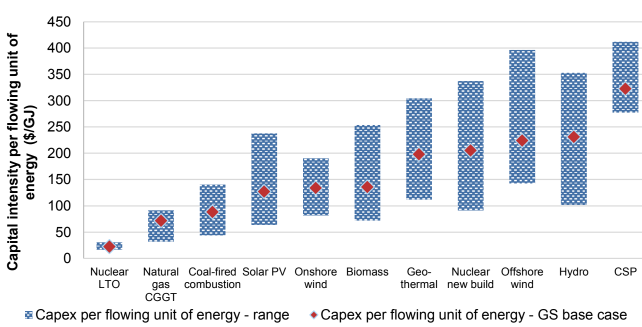
Source: Goldman Sachs Global Investment Research

Exhibit 4: The shift to low carbon will continue, fuelled by a 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

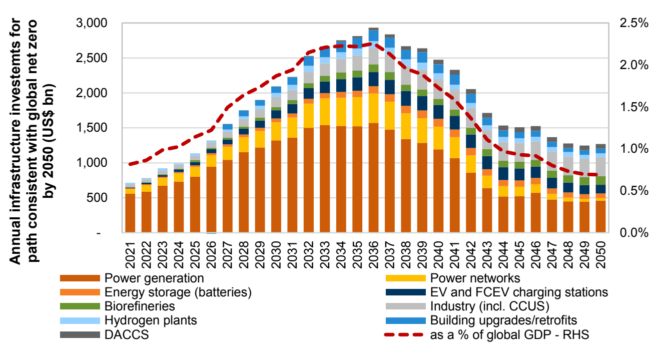
Exhibit 5: ...enhancing capital intensity, as low carbon energy developments are c.2x more capex intensive than hydrocarbons.
Capex per flowing unit of energy (US$/GJ)



*LTO: Long-term operation of existing nuclear assets

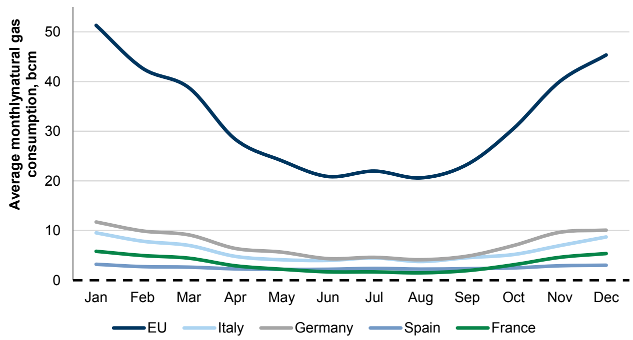
Source: IRENA, EIA, Goldman Sachs Global Investment Research

Exhibit 6: We estimate that an incremental $1.5trn pa capex is needed by 2032.
Annual infrastructure investments for net zero by 2050 (US$ tn)



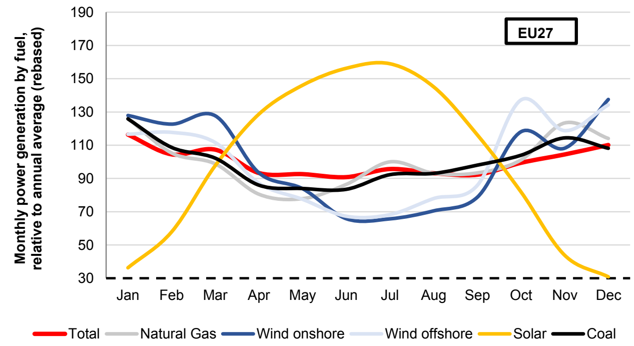
Source: Goldman Sachs Global Investment Research

Exhibit 7: This European energy crisis has a strong seasonal component (winter demand for gas is >2x higher than in summer)...
Average monthly natural gas consumption, bcm



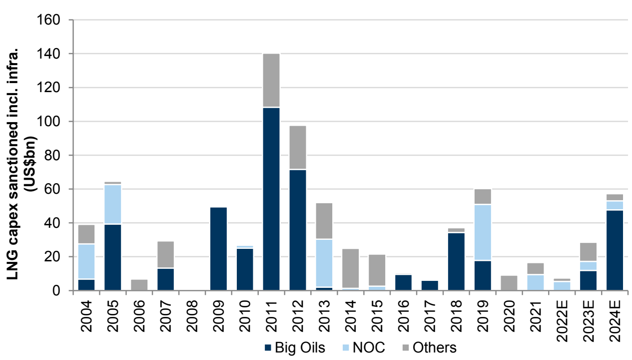
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 8: ...that requires LNG imports and hydrogen to complement renewable power growth (especially solar)
EU27 average monthly power generation by fuel type relative to annual average, rebased



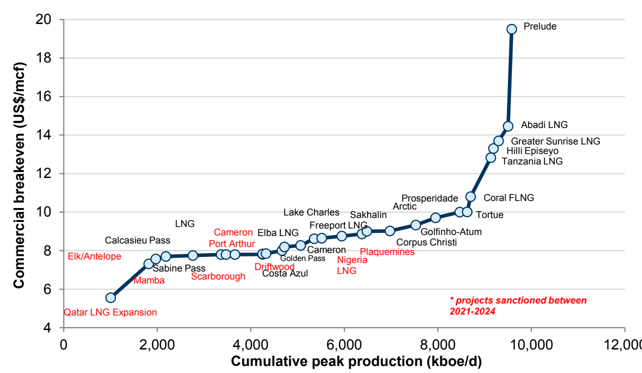
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 9: We analyze the global LNG project pipeline, identifying 156mtpa, or c.US$139bn of new projects over the next 5 years...
LNG capex sanctioned including infrastructure (US$bn)



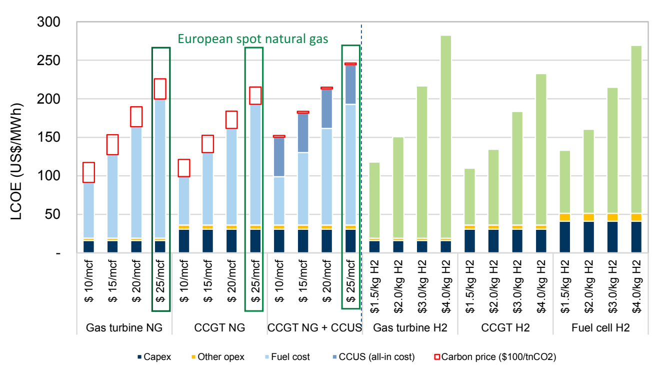
Source: Goldman Sachs Global Investment Research

Exhibit 10: ...with average full-cycle economics of $8-10/mcf.
Commercial breakeven by project (US$/mcf)



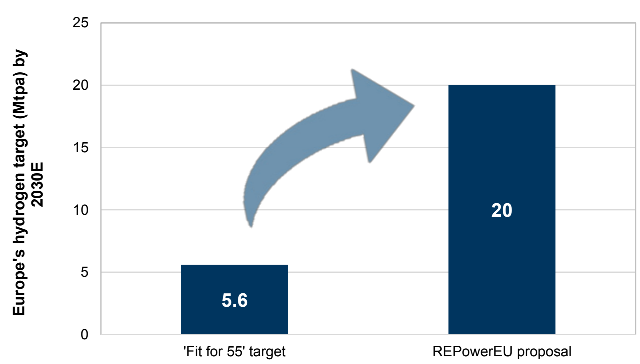
Source: Goldman Sachs Global Investment Research

Exhibit 11: Green Hydrogen is Europe's long-term solution to security of supply, seasonal storage and industrial demand.
Levelized cost of electricity - LCOE (US$/MWh)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 12: RePowerEU targets a 4x upgrade to previous Green Hydrogen production by 2030
Europe's hydrogen aim (Mtpa) by 2030E



Source: EU Commission, Goldman Sachs Global Investment Research

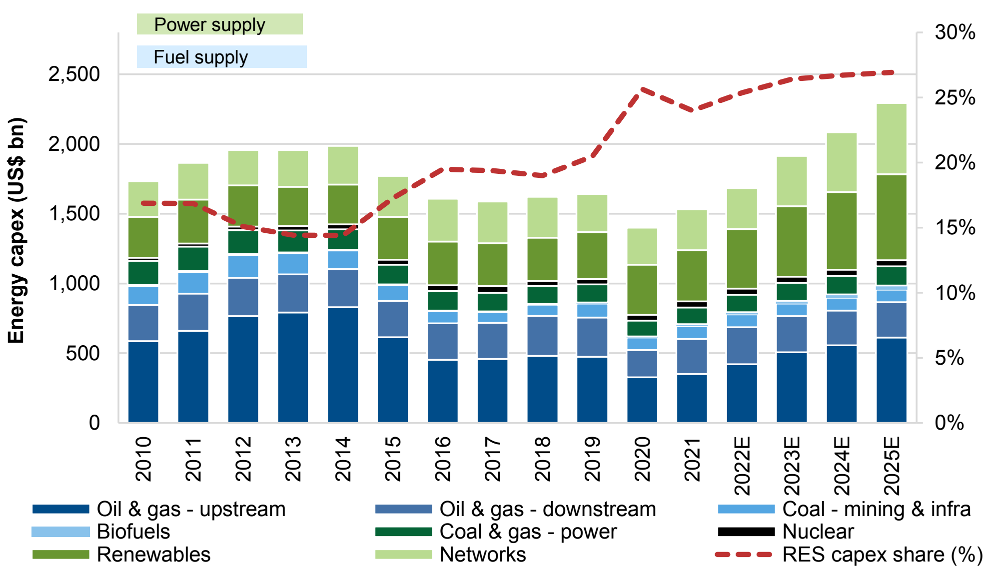
The revival of energy investments: Reversal of a seven-year under-investment period for the energy industry

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 61% from the peak and driving a 35% reduction in global primary energy investments, from US$1.3trn in 2014 to US$0.8trn in 2020 (as shown in Exhibit 13). 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.

Exhibit 13: Global energy investments are set to return to growth (11% per annum to 2025E) and exceed the historical peak of US$2trn pa by 2024

Energy supply capex split by fuel and power supply source (US$bn - LHS), and clean energy (renewables, biofuels) as a % of total (% - RHS)



*Primary energy capex is defined as the sum of upstream oil, gas & coal, biofuels, renewables and nuclear.

Source: IEA WEI (historicals), Goldman Sachs Global Investment Research

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

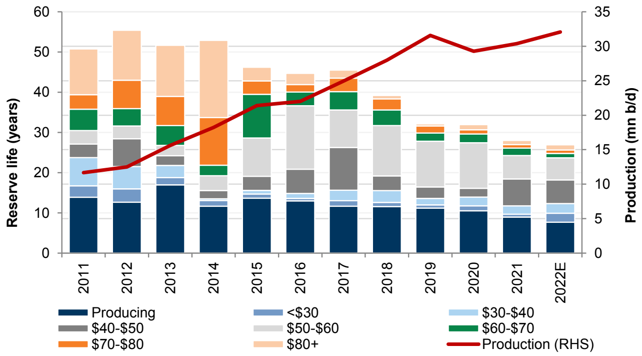
We believe that the recent focus on energy security, resilience and diversification will drive a new era for energy investments, which we argue should rise above the historical peak of US$2trn pa by 2024E to support the globe's rising energy needs. This is driven, on our estimates, by a major increase 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 c.25% share in global total energy supply investments to the middle of this decade, 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.

In oil & gas the under-investment is now starting to reverse, particularly for natural gas and LNG

With CO_2 emissions on a persistent upward trajectory globally over the past few years, investors are taking a leading role in driving the climate change debate, pushing corporate management of oil & gas producers toward incorporating climate change actions in their business plans and strategy. The number of climate-related shareholder proposals has more than doubled since 2011 and the percentage of shareholders voting in favor tripled over the same period, according to ProxyInsight. This is reflected in a structural shift in the industry's scale of investments (capex commitments for long cycle developments have fallen 45% in the past 6 years compared to the previous six) and its mix (more focus on gas and brownfield developments and less on long-cycle greenfield oil developments). According to our analysis, the resource life of our database of the largest oil & gas developments in the world – Top Projects (recoverable resources/production) falls to c.25 years in 2022E from >50 years in 2014, a halving since the end of the 2004-14 'super-cycle'. Yet the economics are much healthier even under lower Brent and gas price assumptions, with c.70% of the undeveloped resources profitable at a Brent price <US$60/bl vs. only 18% in 2014, on our estimates. In our view, this is symptomatic of the new 'Age of Restraint', with the market placing low value on undeveloped resources due to a high risk premium and with the value accruing to the companies that can self-finance the development and manage their risk through a large diversified portfolio with benefits of scale. **We believe that as the focus shifts from energy sustainability to energy security and affordability, the energy industry will experience a revival in investments to support a more affordable and inclusive energy transition. Whilst we do not expect the hydrocarbon industry to return to the level of investments seen in 2014, we do believe that a normalization of investments is underway, particularly for natural gas.**

Exhibit 14: Underinvestment in oil and gas since 2015 has led to depletion in oil reserves, consuming 25 years of oil resource life since 2014...

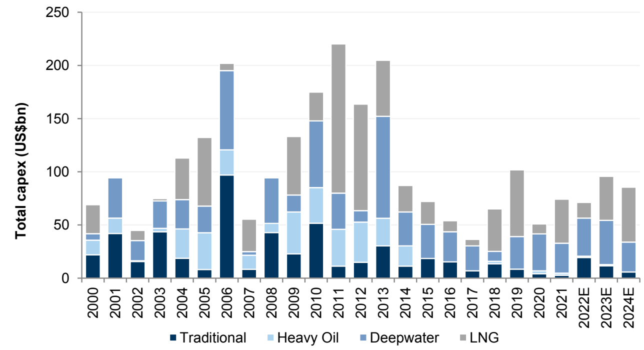
Top Projects reserve life, by year of report and breakeven



Source: Goldman Sachs Global Investment Research

Exhibit 15: ...but we believe oil and gas capex should recover from 2022E...

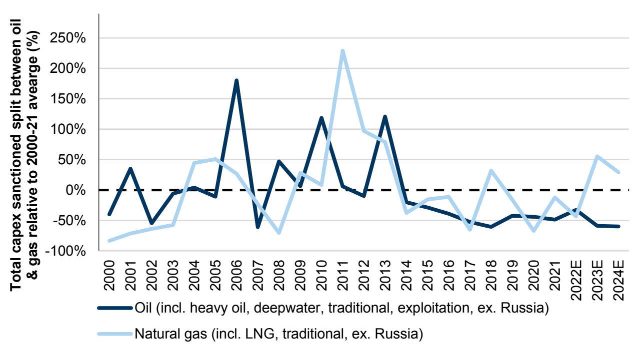
Top Projects capex sanctioned in oil by year, split by winzone



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 16: ...with gas capex (including LNG), in particular, recovering on our estimates...

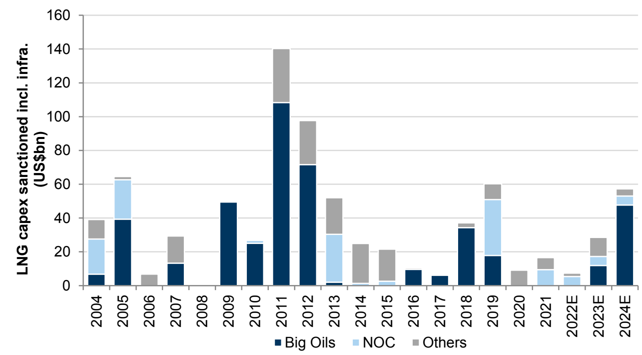
Total capex sanctioned split between oil & gas (inc. LNG) relative to 2000-21 average (%)



Source: Goldman Sachs Global Investment Research

Exhibit 17: ...driven primarily by LNG capex

LNG capex sanctioned including infrastructure (US$bn)

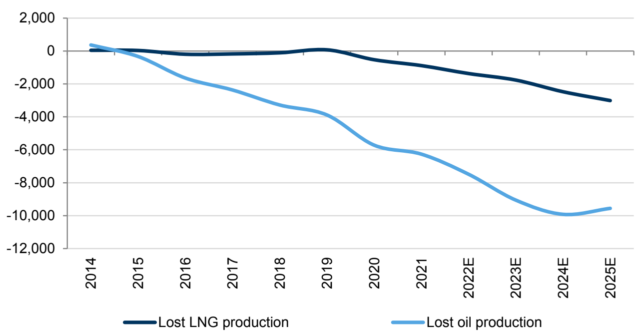


Source: Goldman Sachs Global Investment Research

Investment decisions have been at a historical trough, taking 10/3 mboe/d of oil/LNG out of 2025E supply

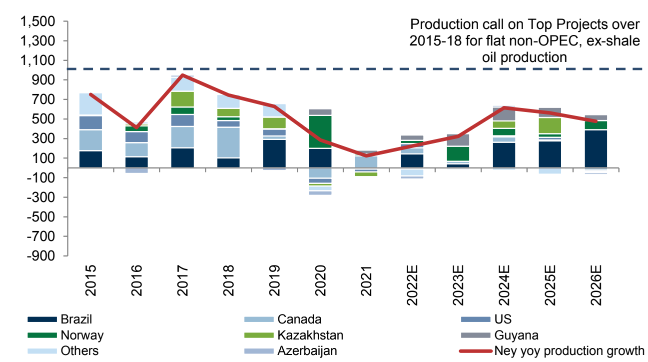
In Exhibit 18, we show lost oil production in the future owing to FID delays since the beginning of the previous oil price downturn by looking at our current Top Projects oil and LNG production estimates versus our initial expectations in 2014. With oil prices falling since the recovery from the previous downturn and NOCs/international E&Ps retreating to their domestic basins to focus on balance sheet management, a number of project FIDs have been delayed, translating into 3/10 mboe/d of lost LNG/oil production in 2024-25, on our estimates. This was exacerbated by the macro commodity downturn in 2020, which came at a time when we had previously expected a catch-up in the project FIDs pipeline from the industry and which prolonged project sanctions delays for another two years. This has started to notably contribute to a much tighter market for both oil and LNG, as indicated by the structurally higher commodity prices we are experiencing at present. We believe that this trend is in need of reversal, and Exhibit 19 shows that the ramp-up pace of long-cycle mega project oil production is likely to accelerate moderately from here, back to c.0.3-0.6 mn bl/d from 2022E.

Exhibit 18: Delayed investment decisions on long-cycle developments take c.10/3 mn boepd out of 2025E oil/ LNG supply...
Top Projects lost LNG, offshore and onshore oil production from long-cycle developments; Top Projects 2021 vs. 2014 expectations



Source: Goldman Sachs Global Investment Research

Exhibit 19: ...but moderate growth must be facilitated from here, albeit remaining below 2015-18 levels
YoY oil production growth (kboe/d) from non-OPEC, excluding Russia, shale projects (excluding impact of shut-ins) and net production growth including production shut-ins impact



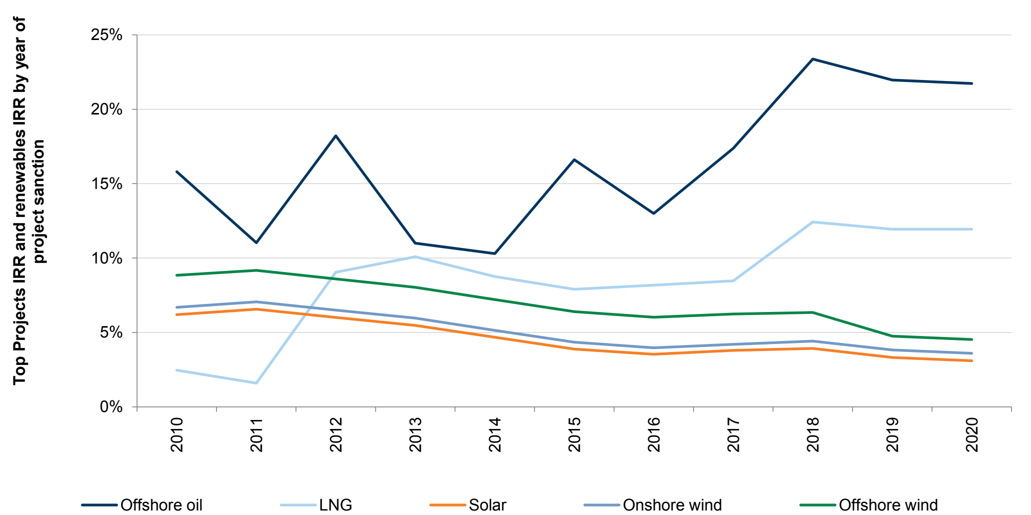
Source: Goldman Sachs Global Investment Research

A sustainable energy future calls for a major acceleration in clean energy investments, driving capex upside from here

Whilst investments in clean energy (renewables and bioenergy) have been trending higher, we believe a major acceleration is required, as low carbon energy technologies require 2-3x the capex per unit of output energy compared to the hydrocarbons they displace

The cost of capital for new clean energy projects continues on a downward trajectory, improving the affordability and competitiveness of clean energy. On the contrary, 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. 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 benefits 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.**

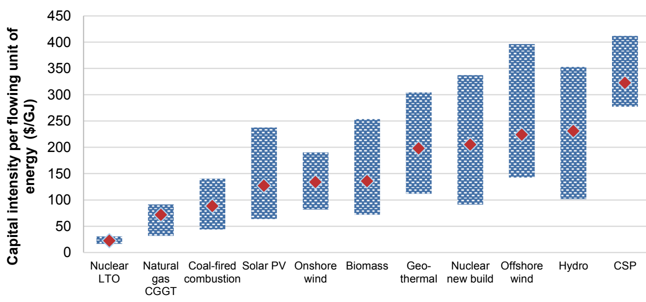
Exhibit 20: The bifurcation in the cost of capital for hydrocarbons vs. renewable energy developments is widening, on the back on investor pressure for de-carbonization
Top Projects IRR for oil & gas and renewable projects by year of project sanction



Source: Goldman Sachs Global Investment Research

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.

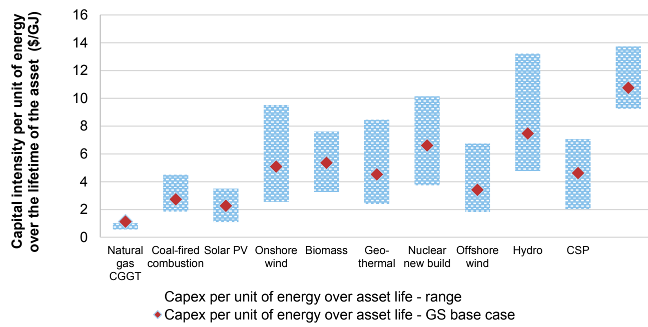
Exhibit 21: All renewable clean technologies in power generation have higher capital intensity compared to traditional fossil fuel sources based on per flowing unit of energy...
Capex per flowing unit of energy (US$/GJ)



*LTO: Long term operation of existing nuclear assets

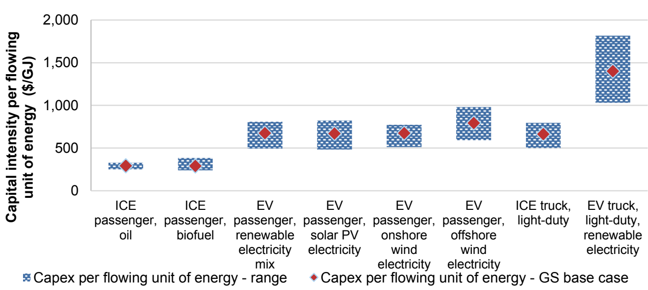
Source: IRENA, EIA, Goldman Sachs Global Investment Research

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



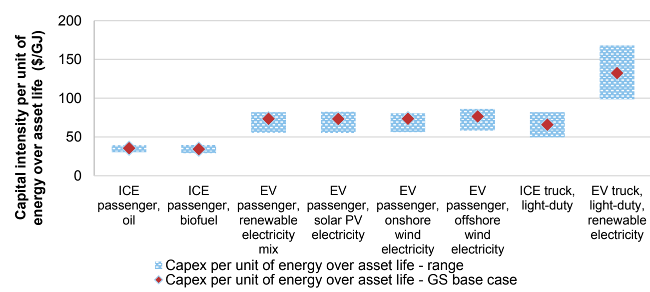
Source: IRENA, EIA, Goldman Sachs Global Investment Research

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

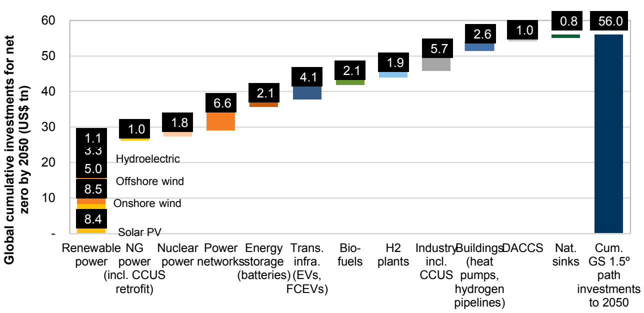


Source: EIA, Goldman Sachs Global Investment Research

The path to next zero: Mobilizing an extra $2trn per annum in low carbon investments across low carbon technologies and network infrastructure

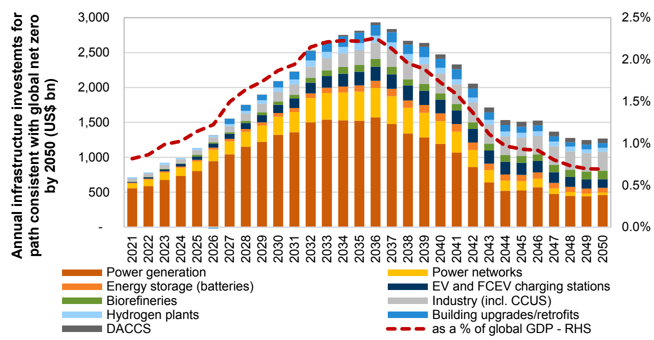
In aggregate, we estimate a total investment opportunity in clean tech infrastructure of US$56 trn by 2050 in our path to global net zero by 2050 (GS 1.5°), as outlined in our **Carbonomics: Net Zero** framework. This figure focuses solely on **incremental infrastructure investments** and does not include maintenance and other end-use capex. Overall, the average annual investments in de-carbonization that we estimate over 2021-50 are c.US$1.9 trn, with the peak in 2036 (US$2.9 trn) representing 2.3% of global GDP (vs. US$1.6 trn pa with a peak of US$2.5 trn in 2041 in the GS <2.0° scenario). We estimate that **c.50% of de-carbonization is reliant on access to clean power generation**, including electrification of transport and various industrial processes, electricity used for heating and more. Overall, we expect **total demand for power generation** in a global net zero scenario by 2050 to **increase three-fold (vs. that of 2019) and surpass 70,000 TWh as the de-carbonization process unfolds.** Based on our GS 1.5° model, power generation almost entirely de-carbonizes **by 2040** (2055 under the GS <2.0° scenario).

Exhibit 25: We expect US$56 trn of infrastructure investments to global Net Zero carbon...
Cumulative infrastructure investment opportunity for our GS 1.5° global net zero by 2050 model (US$ tn)



Source: Goldman Sachs Global Investment Research

Exhibit 26: ...reaching >2% of GDP by 2032 in the 1.5° scenario
Annual infrastructure investments for net zero by 2050 (US$ tn)



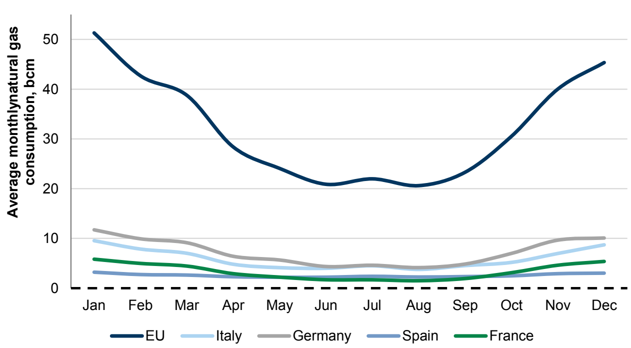
Source: Goldman Sachs Global Investment Research

A winter energy crisis: The imperative need for seasonal energy storage to support reliability

A rapid switch from natural gas to renewable power and the rise of electrification in the absence of energy storage infrastructure poses risks to energy reliability

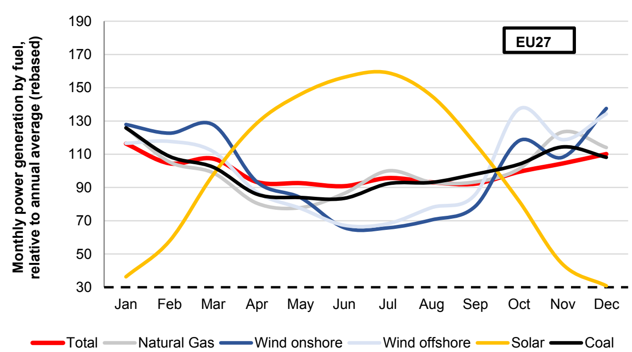
In the context of the current geopolitical developments, natural gas prices and supply uncertainties, policymakers are focused on reducing reliance on natural gas through accelerating the renewables roll-out (wind offshore, onshore and solar), especially in Europe. Based on our Carbonomics Cost Curve analysis, power generation currently dominates the low end of the carbon abatement cost spectrum, with renewable power technologies already developed at scale and costs having fallen rapidly over the past decade, making them competitive with fossil fuel power generation technologies in many regions globally. However, renewable power generation suffers from two key problems that need to be addressed: intermittency and seasonality. In the charts that follow, we emphasize the seasonal nature of natural gas consumption, with EU average monthly consumption of c.20bcm in Jun/July/Aug vs. c.45-50 bcm in Dec/Jan/Feb. Further, we show the significantly higher seasonality of power generation by solar and wind compared to natural gas and coal both at the EU level and at the country level, highlighting Germany and Spain specifically.

Exhibit 27: European (EU27) natural gas consumption in winter months is on average c.2.5x that of summer months...
Average monthly natural gas consumption, bcm



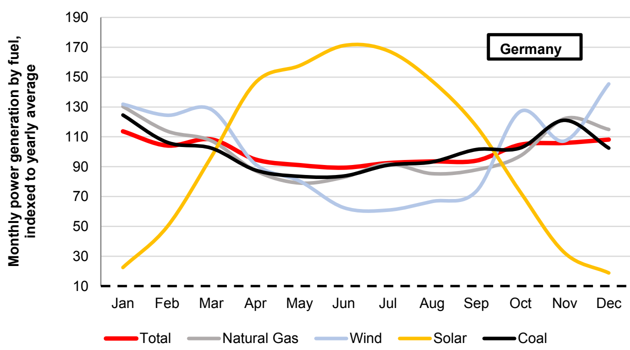
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 28: ...required to meet growing seasonal power demand and address the counter-seasonality of renewable power (in particular solar), which troughs at times of peak demand.
EU27 average monthly power generation by fuel type relative to annual average, rebased



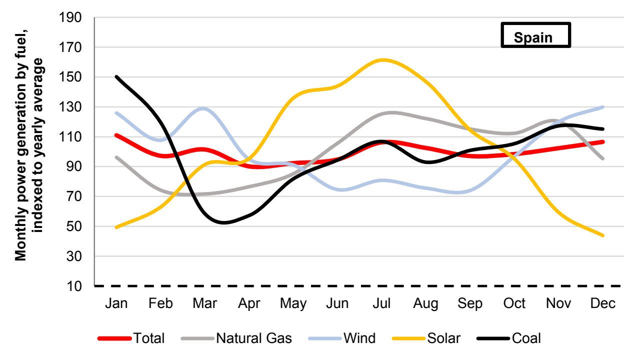
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 29: In Germany, the seasonality in power generation by solar and wind is higher than the EU average, making the need for seasonal energy storage of critical importance.
Germany average monthly power generation by fuel type relative to annual average, rebased



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 30: In Spain, wider solar availability makes renewable power relatively less seasonally varied compared to the EU average
Spain average monthly power generation by fuel type relative to annual average, rebased



Source: Eurostat, Goldman Sachs Global Investment Research

As the growth in renewable power accelerates, intraday and seasonal variability has to be addressed through energy storage solutions. **To reach full replacement of coal and natural gas and de-carbonization of power markets, we believe two key technologies will likely contribute to solving the energy storage challenge: utility-scale batteries and hydrogen, each having a complementary role.** We incorporate both of these technologies in our path to net zero. Energy storage and the need for extensive network infrastructure are particularly important considerations as demand for power generation growth accelerates, to ensure a resilient global energy ecosystem. While batteries are currently the most developed technology for intraday power generation storage, **we consider hydrogen as a more relevant technology for seasonal storage, implying the need for innovation and development of both technologies.** Batteries, for instance, are particularly suited to sunny climates, where solar PV production is largely stable throughout the year and can be stored for evening usage. Hydrogen on the other hand, and the process of storing energy in chemical form and reconverting it to power through fuel cells, could be used to offset the seasonal mismatch between power demand and renewable output. **Until the relevant energy storage infrastructure (networks and smart grids) and technologies (utility scale batteries and hydrogen) are ready to support an increasingly electrified energy economy, we argue that both natural gas and nuclear power have a role to play in the near term to enable a smooth energy transition and help avoid a power crunch.**

Solving for Europe's energy crisis: LNG capex and capacity returning to growth at a time of need

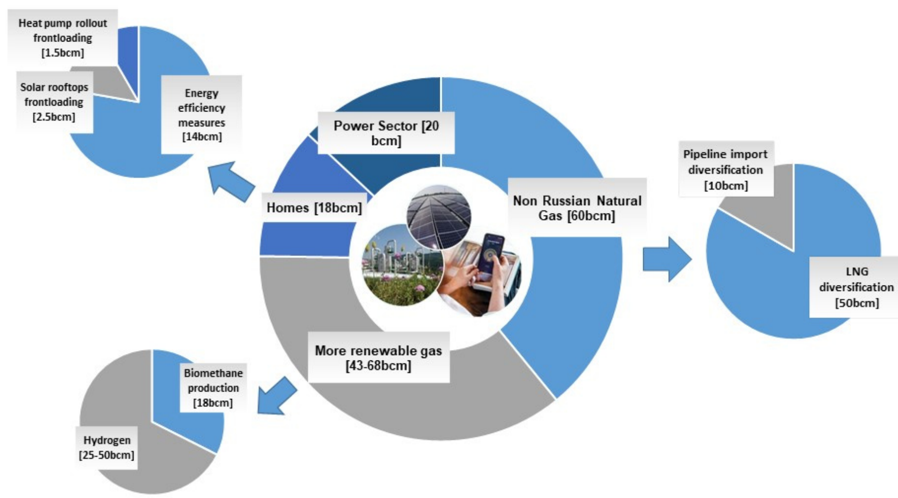
REPowerEU: A policy boost for LNG and hydrogen

The European Commission has published an outline of the 'REPowerEU' plan aimed at reducing Europe's dependency on Russian fossil fuels before the end of this decade (2030) in light of recent geopolitical events. The plan outlines a set of joint actions which could unlock a more affordable, secure and sustainable energy for the region, responding to rising energy prices in Europe with a focus on replenishing gas stocks for next winter but also diversifying gas supplies, speeding up the roll-out of renewable gases and replacing gas in heating and power generation.

The EU Commission proposes to develop a REPowerEU plan that will increase the resilience of the EU-wide energy system based on **diversifying gas supplies** via higher Liquefied Natural Gas (LNG) and pipeline imports from non-Russian suppliers, and larger volumes of biomethane and **renewable hydrogen production and imports.**

The REPowerEU plan aims to remove at least 155bcm of fossil gas use, which is the equivalent of the volume imported from Russia in 2021. Two thirds of the reduction is aimed by 2022. We summarize below the sources of gas diversification according to the proposal:

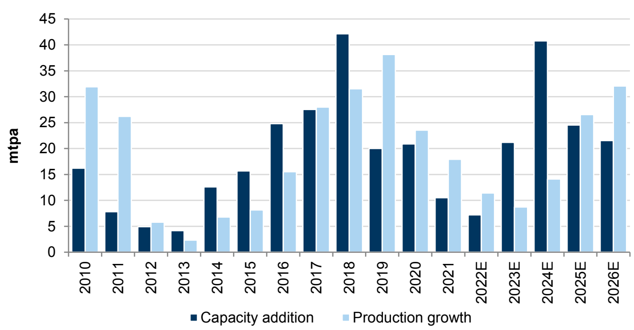
Exhibit 31: REPower EU summary graphic



Source: European Commission, Goldman Sachs Global Investment Research

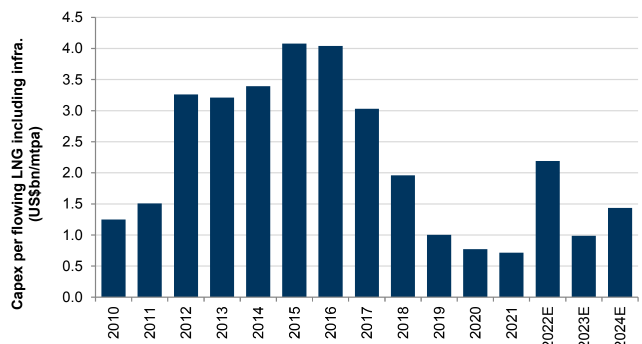
The last two years have been characterized by capital discipline across the industry, with FID postponements and capital expenditure reductions as a result of COVID-19. Capex in 2021 remained at very low levels for the industry, both in oil and LNG. Our Top Projects analysis suggests that aggregate capex in 2021 increased by 6% compared to 2020 yet remained c.31%/16% below 2015/2016 levels, respectively, during the previous commodity downcycle, and suffered a more abrupt change as the industry reacted quicker to rebase capex levels lower. In 2022, we anticipate the overall level of Top Projects capex to increase by c.13% yoy, yet to remain well below the historical and normalized levels (-12% vs 2019). **Looking into 2022-2024, we see LNG as a likely area of capex increases**; this is primarily owing to already committed capex that is largely spent and ramping up on LNG projects sanctioned over the past 2-3 years, many of which faced delays during the 2020 downturn. As highlighted earlier in this report, LNG benefits from a much lower cost of capital, making it a stronger area of capex growth that is pro-environment and aligns with Europe's plan to diversify away from Russian oil and gas in the short-to-medium term. Our Top Projects analysis indicates a new wave of LNG projects coming at very competitive cost levels relative to history (US$1.0-2.1bn/mtpa in 2022-2025E vs US$4.0bn/mtpa in 2015-16) as shown in Exhibit 33 and with projects in Qatar, Canada and the US, among others, contributing to a significantly lower cost curve in 2022 vs 2014.

Exhibit 32: The LNG market is set to return to capacity growth post 2022E, with most of the supply additions coming in 2025-26E.
Annual increase in LNG production and capacity in mtpa



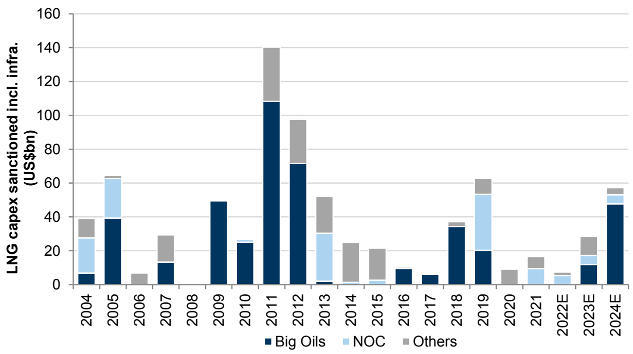
Source: Goldman Sachs Global Investment Research

Exhibit 33: The new wave of LNG projects is coming at a very competitive cost relative to history...
Top Projects capex per flowing LNG output, US$ bn per mtpa



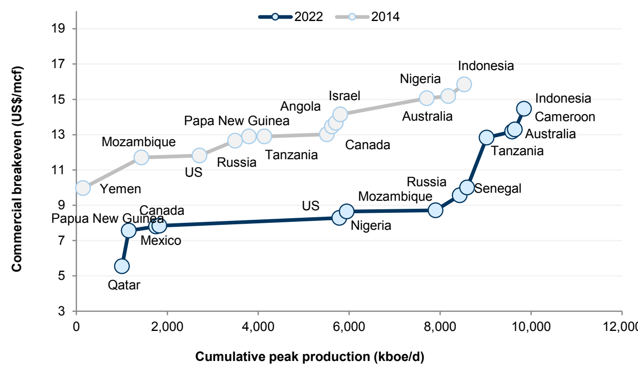
Source: Goldman Sachs Global Investment Research

Exhibit 34: ...contributing to an acceleration in LNG capex commitments
LNG capex sanctioned incl. infrastructure (US $bn)



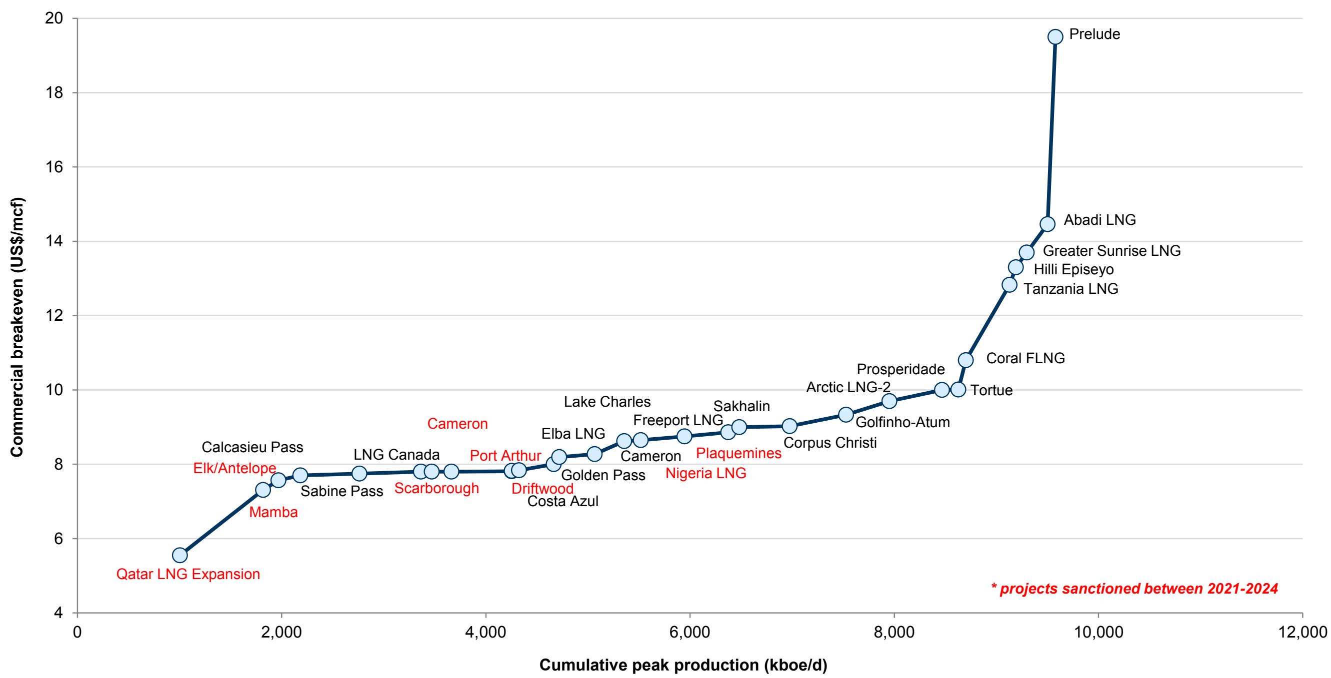
Source: Goldman Sachs Global Investment Research

Exhibit 35: Qatar, Canada and the US among others are contributing to capacity growth given their low cost positioning
LNG cost curve by region in Top Projects 2022 vs. 2014



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 36: LNG projects sanctioned between 2021 and 2024 display competitive breakevens, placing them on the lower end of our LNG cost curve
Commercial breakeven by project (US$/mcf)



Source: Goldman Sachs Global Investment Research

Solving for Europe’s energy crisis: The green hydrogen revolution

We believe the recent geopolitical events have changed the EU’s priority in relation to its energy policy, with the European Commission publishing the ‘REPowerEU’ plan last week (March 8th) outlining a set of joint actions to reduce Europe’s dependence on Russian gas imports and unlock increased investments and reforms for more affordable, sustainable and secure energy supply. While the energy policy focus appears to have shifted to energy security, one key priority which remains intact and is gaining momentum for the EU is the need to accelerate the renewables build-up and electrification, as well as **fast-track the roll-out of renewable gases: hydrogen** and **biogas**.

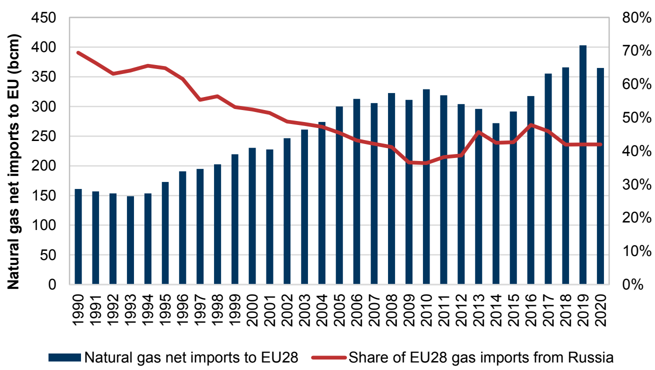
Green (renewable) hydrogen is identified as a critical technology in helping to unlock further diversification away from natural gas in the coming years; the proposal includes a **notable upgrade of the ‘Fit for 55’ target of 5.6 Mt** of renewable hydrogen by 2030 **to 20 Mt over the same timeframe** based on a combination of locally produced and imported volumes. This represents a >3.5x upward revision of an already ambitious target for the region and can **aid the replacement of 25-50 bcm pa by 2030, representing c.16%-32% of imported Russian gas volumes**, according to the document. We outline below the key role we believe the technology will play in enhancing Europe’s energy security and energy resilience:

- **(1) The push for electrification and renewable power accelerates the need for seasonal energy storage with green hydrogen the optimal solution, we believe:** We have previously argued (see here) that green hydrogen is highly interconnected with renewable power, acting as a key enabler of higher renewable power penetration and electrification. Its role as a transformational driver for the power industry lies in its ability to act **as the clean energy vector for seasonal energy storage**, providing buffer and resilience in an increasingly electrified economy. As renewable power increases its share in Europe’s energy mix, the issues of intermittency but also seasonality are becoming more prominent, **especially as electrification gains momentum in heating,** resulting in large power demand variations across seasons. **While batteries, super-capacitors and compressed air can also support balancing, they lack the power capacity or the storage time span needed to address seasonal imbalances, leaving hydrogen as the key seasonal energy storage solution to support an increasingly electrified energy ecosystem.** Electrolysis can convert excess electricity into hydrogen in times of power oversupply and the produced hydrogen can then be used to provide back-up power during periods of power deficits, preventing power crunches and enhancing the energy system’s resilience.
- **(2) Renewable hydrogen and biogas are the natural successors of fossil gas for diversification of energy supply in energy-intensive industrial processes:** We view hydrogen and biogas as the key natural successors of natural gas in high-temperature industrial processes. Around 30% of Europe’s (EU27+UK) natural gas demand stems from industrial processes including steel, chemical plants, cement and others. Given the high energy intensity (temperatures) required for

many of these processes, direct electrification is often not feasible, making hydrogen and biogas the two natural molecular successors for the displacement of fossil gas. Hydrogen blending in natural gas networks has already started, albeit to a small extent, and we believe this is likely to accelerate in the coming years as Europe intensifies its efforts to diversify its energy supply. This can lead to a profound reconfiguration of the gas grid infrastructure longer term.

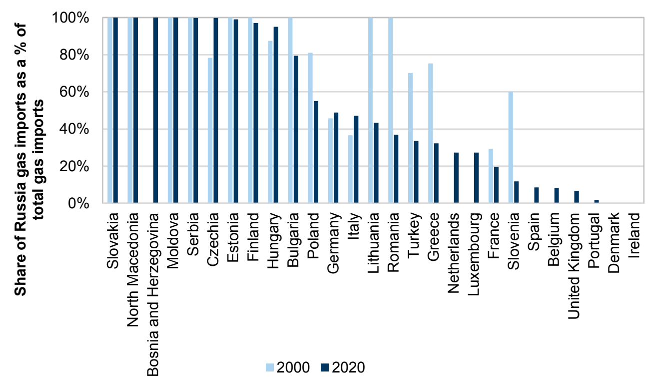
- **(3) <u>Higher spot EU natural gas prices tilt the scale in favour of green (renewable) vs blue and grey (natural gas-based) hydrogen, providing upside for installed electrolysis capacity and technological innovation:</u> At current spot European gas prices, green hydrogen is already achieving cost parity with grey** (fossil-based) hydrogen **in key parts of Europe** (green hydrogen projects with low-cost renewable power relying on PPAs not exposed to the power price volatility). This is **tilting the scale in favour of green vs grey and blue hydrogen** leading to upside to **the global installed electrolysis capacity estimates and encouraging further technological innovation on the electrolysis space.**

Exhibit 37: EU's energy security proposal aims to address (reduce by 2/3) EU's dependence on Russian energy imports (specifically gas)...
European net gas imports (EUR27+UK) and share of European gas imports from Russia (%)



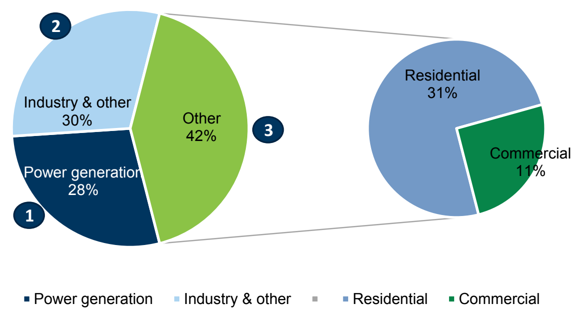
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 38: ...with Russia having accounted for >40% of EU27+UK's gaseous imports in 2020
Share of Russian gas imports as a % of total net gas import volumes



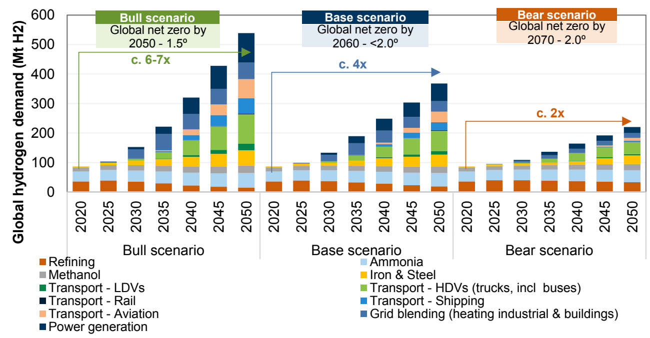
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 39: Europe's (EU27+UK) natural gas demand stems from three key industries: (a) industry, (b) power generation, and (c) buildings (commercial and residential, primarily for heating)...
EU27+UK natural gas demand by sector (2020, %)



Source: Eurostat

Exhibit 40: ...and green hydrogen can help address each of these areas through its ability to (a) act as an energy fuel and feedstock for key hard-to-electrify industrial processes, (b) provide a solution for seasonal energy storage, and (c) blend in existing natural gas networks and grids
Global hydrogen demand (Mt H2) under the three GS net zero models



For more details on our scenarios, see here.

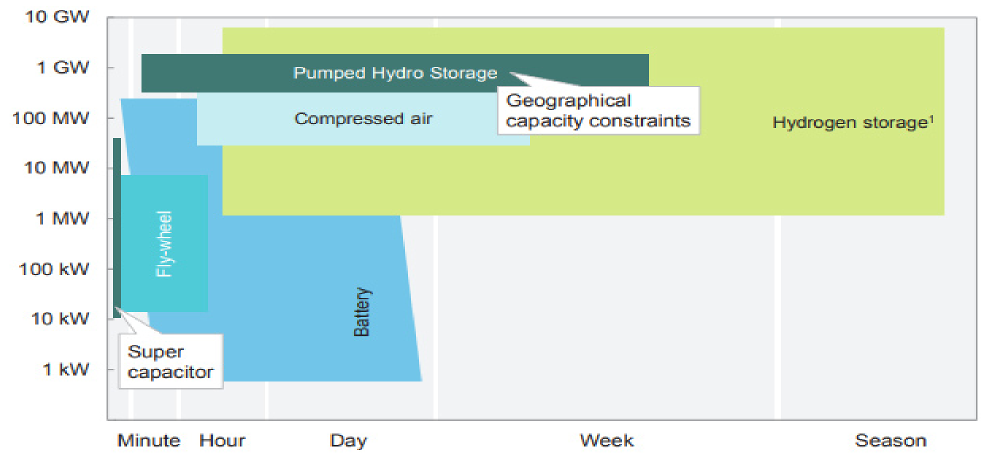
Source: Goldman Sachs Global Investment Research

Green hydrogen a key enabler of electrification, unlocking seasonal energy storage and having grid buffer capabilities

Hydrogen currently has a niche role in power generation. However, as power generation undergoes a complete transformation, hydrogen could emerge as a critical technology in this industry, complementing renewable power as **it unlocks seasonal energy storage capabilities and enhances the resilience of an increasingly electrified energy system**. The role of power generation is, in our view, only likely to increase in the coming decades, as the penetration and pace of electrification rapidly increase across sectors (including road transport, building heating, industrial manufacturing processes and low-temperature industrial heat) as they progressively follow their own de-carbonization path. **Accelerated electrification of heating is likely to result in large power demand and supply imbalances, making the role of a molecular seasonal energy storage solution vital.** We identify three key roles of clean hydrogen in the power generation industry that can enhance system resilience and enable higher uptake of renewable power:

(a) Large-scale seasonal energy storage: We believe hydrogen will be the preferred solution for long-term energy storage required to balance the seasonal variation of power generation demand; particularly important is that electricity through heat pumps for residential heating becomes a more prominent feature and rises in share in total power generation demand. While batteries, super-capacitors, and compressed air can also support balancing, they lack the power capacity or the storage timespan needed to address seasonal imbalances, as outlined by the Hydrogen Council and shown in Exhibit 41. While pumped hydro in particular offers an alternative to hydrogen for large-scale, long-term energy storage and has been to date the preferred power storage solution, accounting for more than 95% of global power storage, its remaining untapped potential is subject to local geographic conditions. The key disadvantage of hydrogen-based storage options remains its low round-trip efficiency, with the process of electrolysis and then conversion of hydrogen back to electricity consuming c.60% of the total energy. Yet given the abundance of the molecule (most abundant in the universe), we believe that, in the absence of alternative molecular, clean seasonal energy storage solutions, lower efficiency should not be a constraint for its wider adoption.

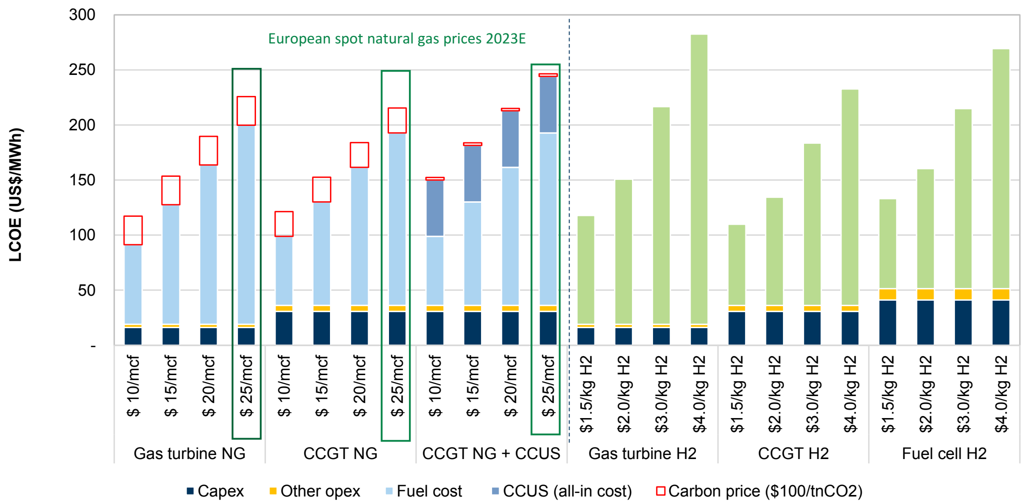
Exhibit 41: Hydrogen could be the optimal solution for large-scale, long-duration energy storage, particularly for discharge durations beyond 50 hours
Capacity vs discharge duration for energy storage



Source: Hydrogen Council

(b) Flexible power generation: Hydrogen-fired gas turbines and combined-cycle gas turbines could be used as a source of flexibility in electricity systems (substituting natural gas) with increasing shares of variable renewable energy (VRE) aiding the intermittency problem. Fuel cells can also be used with electrical efficiencies typically exceeding 50%-60% (similar to those of turbines), and the stationary fuel cells market has been growing steadily over the past decade. However, fuel cells typically have shorter technical lifetimes than gas turbines and smaller power output, making them more suited to distributed power. In the power sector, the timing of variable electricity supply and demand is not well-matched, requiring additional operational flexibility. Various options exist to resolve this intermittency issue such as grid infrastructure upgrades or technologies for short- or longer-term balancing of supply and demand (dynamic power networks), flexible back-up generation, demand-side management, or energy storage technologies. Given the current focus on reducing European natural gas demand, hydrogen-fired turbines can help complement renewable power in the power mix, with spot natural gas prices in Europe already making gas-based CCGTs and gas turbines less cost competitive compared to low-cost green hydrogen (produced with RES fixed PPAs with LCOE <US$30/MWh).

Exhibit 42: Hydrogen turbines and fuel cells can be used for load balancing; they are becoming increasingly competitive given the high spot EU gas prices
Levelized cost of electricity - LCOE (US$/MWh)



Source: Company data, Goldman Sachs Global Investment Research

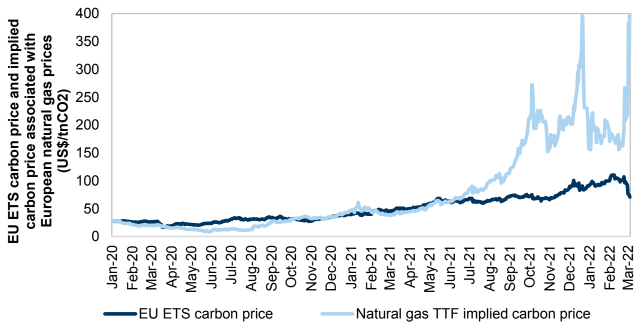
(c) Buffer, back-up and off-grid power supply: Hydrogen has valuable attributes that could make it a key solution for power generation system back-up as electrolysis can convert excess electricity into hydrogen during times of oversupply. The produced hydrogen can then be used to provide back-up power during power deficits or can be used in other sectors such as transport, industry or residential. **Hydrogen offers a centralized or decentralized source of primary or back-up power.** In addition, electrolyzers may provide ancillary services to the grid, such as frequency regulation. Fuel cells therefore, in combination with storage, are likely to be considered a cost-effective decarbonization alternative to diesel generation (currently often deployed for back-up power).

Hydrogen the natural successor of natural gas for diversification of energy supply in energy-intense industrial processes

Higher natural gas prices lead to green hydrogen cost parity with grey (natural-gas based) across key parts of Europe, pushing forward the first leg of the green hydrogen revolution: the substitution of grey hydrogen in existing industrial applications
Industrial use of natural gas accounts for c.30% of Europe's total natural gas consumption, as the commodity is used as both a fuel (for energy use) and as a feedstock (primarily for chemicals) across industrial processes. While many of these industrial sub-segments could potentially be electrified (machinery manufacturing, transport equipment, textiles, food, beverages & tobacco), >50% of the region's natural gas consumption stems from heavy industries, typically requiring high operating temperatures making direct electrification unfeasible. We therefore believe that renewable gases will be key in substituting natural gas in these sub-industrial segments. Among these are high temperature chemical and petrochemicals manufacturing, iron & steel, and non-metallic minerals (clay, limestone, cement).

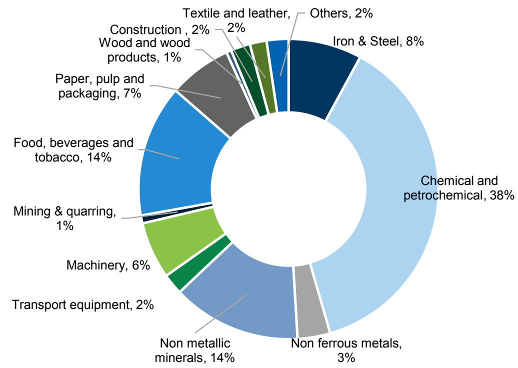
While green hydrogen's move towards cost parity with grey hydrogen is accelerating, and we expect this to be reached before 2030 across regions of low renewable power costs, **we note that the current macro environment of higher commodity prices, in particular for European natural gas, combined with carbon prices is creating a unique green hydrogen cost parity dynamic in Europe.** With most currently produced hydrogen being sourced from natural gas in the region, the notably higher natural gas price to which the region is currently exposed is **tilting the scale in favour of green hydrogen from an economic standpoint**. We estimate that the carbon price implied by the current higher natural gas price environment in the region is equivalent to >US$200/tnCO2eq (when accounting for the scope 1,2,3 carbon intensity of natural gas) even without considering European ETS carbon prices, which are currently above US$50/tnCO2eq despite their recent correction from the peak. This is more than sufficient to bridge the cost of grey hydrogen with green across regions of Europe where green hydrogen is produced with dedicated RES and a renewable power LCOE lower than US$70/MWh.

Exhibit 43: Rising European gas prices have now entered demand rationing territory for industrial uses of natural gas...
EU ETS carbon prices and carbon prices implied by natural gas prices in Europe (TTF) in US$/tnCO2eq



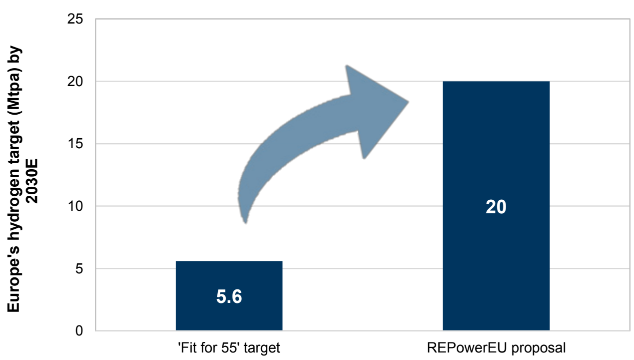
Source: Thomson Reuters Datastream, Goldman Sachs Global Investment Research

Exhibit 44: ...with >50% of natural gas consumption in Europe's industry attributed to heavy industrial sub-segments which are tough to electrify, including steel, cement, chemicals
EU27 final consumption of natural gas in industry split by sub-industry



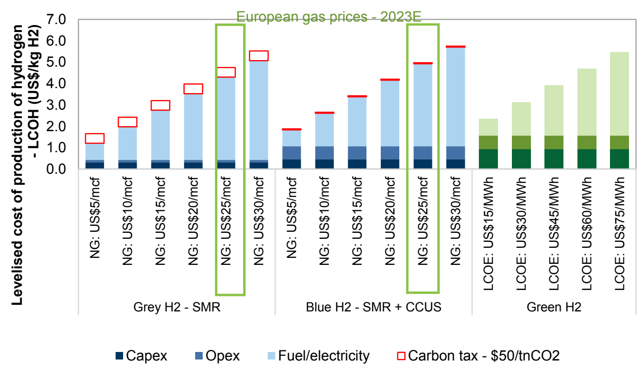
Source: Eurostat

Exhibit 45: The EU Commission's proposed 20 Mt of hydrogen by 2030 represents a notable upgrade of the 5.6 Mt included as part of 'Fit for 55'...
Europe's hydrogen aim (Mtpa) by 2030E



Source: EU Commission, Goldman Sachs Global Investment Research

Exhibit 46: ...with green hydrogen already at cost parity with grey hydrogen across key parts of Europe (for LCOE <US$70/MWh)
Levelized cost of production of hydrogen (LCOH - US$/kg H2)



Source: Goldman Sachs Global Investment Research

Currently, H2 is primarily used as a feedstock in a number of key industrial processes and therefore plays a very limited role in the energy transition as we are still to unlock hydrogen's potential as an energy vector and fuel, the direction in which the EU wishes to move. According to the IEA, global hydrogen demand was around 90 Mt in 2020. This includes more than 70 Mt H2 used as pure hydrogen, primarily in oil refining and ammonia production, and less than 20 Mt H2 mixed with carbon containing gases, primarily in methanol production and steel manufacturing. This excludes around 20 Mt H2 that is present in residual gases from industrial processes used for heat and electricity. **We believe the clean hydrogen revolution begins with the de-carbonization of existing hydrogen end markets given cost parity only needs to be reached at the point of hydrogen production in these industries.** Therefore, we see the starting point of the clean hydrogen economy as the decarbonization of the 70 Mt pa of current dedicated fossil fuel-based hydrogen production.

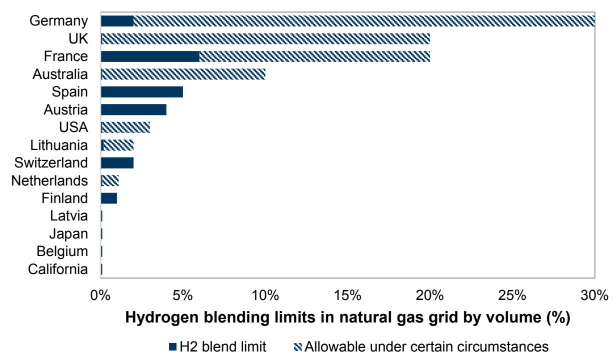
Grid blending: A major potential addressable market for hydrogen that is important for various existing natural gas end-users and benefits from existing infrastructure

To diversify Europe's industrial and heating demand (residential and commercial), we believe that another powerful tool is the **blending of hydrogen in the natural gas grid,** also offering a unique **opportunity to utilize existing assets that face the risk of becoming stranded in a net zero world.** Furthermore, grid blending can **aid the decarbonization of a broad range of natural gas customers** currently, including **industry**, **buildings** and **power generation,** leading to a much larger addressable market than buildings' heating alone would suggest. Overall, on our estimates, hydrogen blending in existing infrastructure would likely increase costs by around US$0.2-0.5 $/kg H2 on top of the costs of hydrogen production due to the need for injection stations on the transmission and distribution grids as well as higher operational costs. Nonetheless, even small hydrogen blending volume rates can have a major impact on the addressable market. However, a number of challenges have to be addressed: (a) the low energy density per unit volume of hydrogen compared to gas (around a third), which would imply greater required gas volumes, (b) the smaller size of hydrogen molecules, which would imply higher risk of leakage through steel pipeline networks, suggesting the need for polymer-based retrofitting at blending rates that exceed 20%-30%, (c) the increased risk of flammability and the odorless, colorless nature of the gas leading to rising need for flame detectors and monitoring, (d) variability of the volume of hydrogen blended into the stream, which could have an adverse impact on the operation of the equipment, which is often designed with a narrow range of adaptability to different gases.

Europe is one of the leading countries when it comes to setting the regulatory framework for hydrogen blending. Germany, for instance, specifies a maximum of 10% provided there are no CNG filling stations connected to the network. There are currently many projects in Europe examining the potential for hydrogen blending in existing gas networks including GRHYD in France, and HyDeploy, H21 and Hy4Heat in the UK. The 'European Hydrogen Backbone', a dedicated hydrogen infrastructure study published in 2020, authored by eleven gas infrastructure players, described the vision of how dedicated hydrogen infrastructure can be created in a significant portion of Europe. This describes a 6,800 km pipeline network by 2030 and its further scale-up to 23,000 km by 2040, requiring an estimated EUR27-64 bn based on the assumption of 75% natural gas pipelines converted and 25% new pipeline stretches. Assuming the backbone is equipped with a robust compression system, the proposed network should be able to meet 1130 TWh annual hydrogen demand in Europe by 2040.

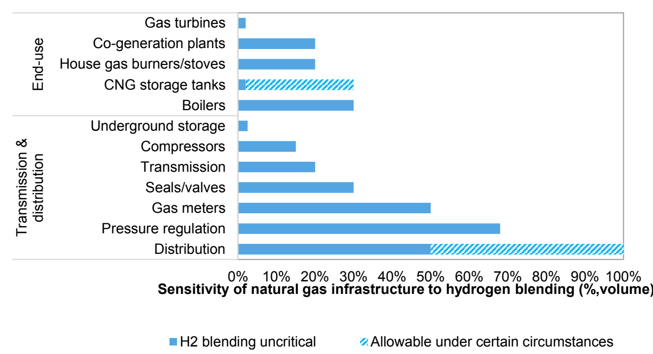
More recently, in December 2021, the **European Commission proposed a new EU framework to de-carbonize gas markets, promote hydrogen and reduce methane emissions.** The market rules will be applied in two phases, before and after 2030, and notably cover access to hydrogen infrastructure, separation of hydrogen production and transport activities, and tariff setting. A new governance structure in the form of the European Network of Network Operators for Hydrogen (ENNOH) will be created to promote dedicated hydrogen infrastructure, cross-border coordination and interconnecting network construction, and elaborate on specific technical rules. The new rules will make it easier for renewable and low-carbon gases to access the existing gas grid, by removing tariffs for cross-border interconnections and lowering tariffs at injection points. They also create a certification system for low-carbon gases, to complete the work started in the Renewable Energy Directive with the certification of renewable gases. In its most recent proposal, REPowerEU, the Commission will, according to the document, further develop the relevant regulatory framework to promote a European market for hydrogen and **support the development of an integrated gas and hydrogen infrastructure, hydrogen storage facilities and port infrastructure, and has highlighted that new cross-border infrastructure should be hydrogen compatible.**

Exhibit 47: Grid blending of hydrogen in existing natural gas infrastructure could be a quick way to reduce gas consumption, yet would require further testing and an upgrade of global hydrogen blending limits...
Hydrogen blending limits in natural gas grid by volume (%)



Source: S&P Global Platts

Exhibit 48: ...with higher blending volumes of hydrogen (>10%-20%) also likely to require upgrades of key components of the natural gas grid system
Sensitivity of natural gas infrastructure components to hydrogen blending



Source: S&P Platts, PG&E, IEA

Disclosure Appendix

Reg AC

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The Survivor's Guide to Disruption

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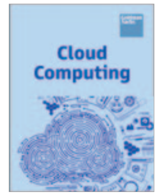
Artificial Intelligence

Cloud Computing



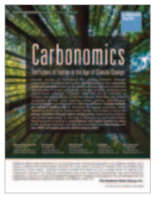
The Post-Pandemic Cycle

Gene editing

5G: From Lab to Launchpad

Climate Change

Carbonomics



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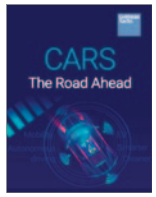


ESG Sector Roadmaps

The Rise of Renewables

Shale Scale to Shale Tail

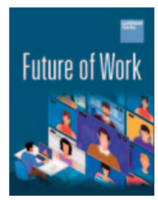
IMO 2020

The Genome Revolution

Digital Health

Sustainable ESG Investing

Future of Work



Drones

Space

Factory of the Future

eSports: From Wild West to Mainstream

Music in the Air

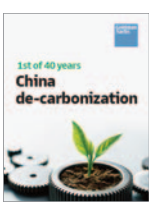
EVs: Back to Reality

Venture Capital Horizons

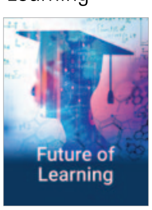
ESG

Womenomics

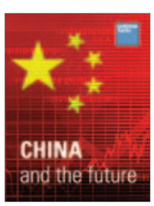
China de-carbonization



Future of Learning



New China, Old China



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China's Credit Conundrum

Top Projects

Made in Vietnam

What the Market Pays For

The Competitive Value of Data

What Matters for IPOs

Top of Mind

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