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Carbonomics

Re-Imagining Europe's Energy System

Can Europe strengthen its energy independence in the face of the Russia-Ukraine crisis without compromising its climate change goals? We use our Carbonomics framework to model the **evolution of Europe's energy system towards a lower cost, lower imports, lower carbon system**. Our analysis leads to five main conclusions:

1) **Cumulative infrastructure investments of €10 trn** will be needed by 2050 for Europe's energy transformation, reaching the equivalent of >2% of GDP by 2030. This incremental investment is **fully offset by a €10 trn reduction in net energy imports**, reducing the net **energy import dependency rate of the region from 58% to 15% by 2050**. Efficient financing and a reliable regulatory environment are key to bridge the 10-year time gap between the two flows.

2) Europe's new energy system would improve affordability. We estimate the **direct energy cost to the average European consumer could be reduced by c.40% vs 2021 and c.60% from the peak** (2022) owing to improved energy efficiency, lower cost LNG, cheaper renewables and better regional connectivity.

3) **Natural gas remains key to Europe's energy supply for the next two decades** and we **believe it is in Europe's interest to sign up to an additional 40 mtpa of 15-yr LNG contracts, and potentially up to another 50 mtpa of 10-yr LNG contracts,** to improve security of supply and drive a new cycle of LNG construction. We identify 15 new LNG projects for a total of 155 mtpa that can deliver gas to Europe at <$12/mcf.

4) Renewable power will be at the heart of Europe's future energy system, but seasonality, heavy industry and transport will require a major **green hydrogen economy to complement the ecosystem, reaching 15% of Europe's final energy mix** long term.

5) **An inter-connected European system of power networks and hydrogen pipelines** will be required to substitute hydrocarbon imports with clean energy flows from **low cost producers such as Iberia, parts of Southern Europe and the UK** to the rest of Europe.

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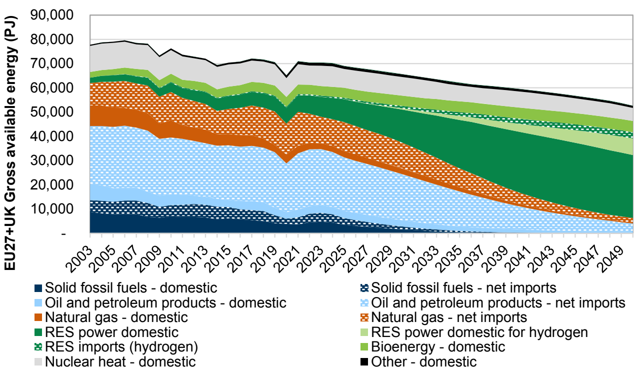
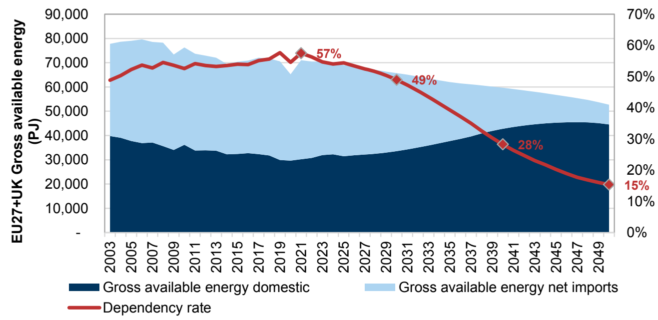


Source: Eurostat (historical), Goldman Sachs Global Investment Research

Exhibit 2: ...driving overall a more secure, independent energy system, with rising domestic energy production and lower energy import reliance bringing the energy dependency rate to 15%.
EU27+UK Gross available energy (PJ)



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

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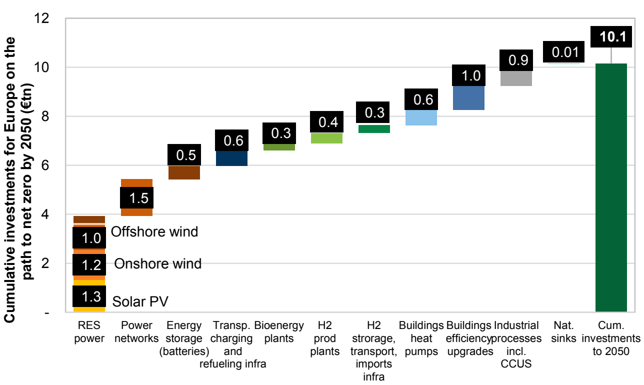

Source: Goldman Sachs Global Investment Research

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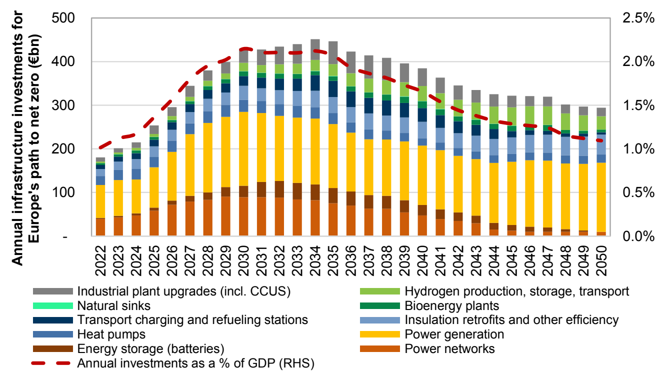

Source: Goldman Sachs Global Investment Research

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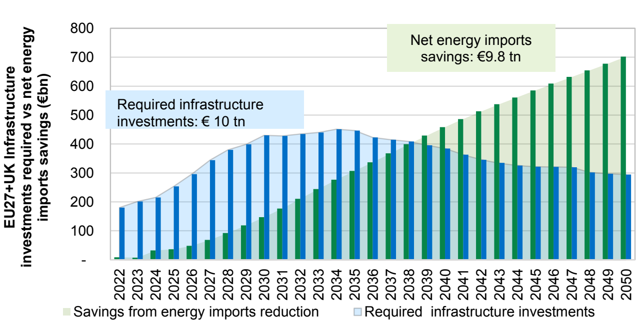

Source: Goldman Sachs Global Investment Research

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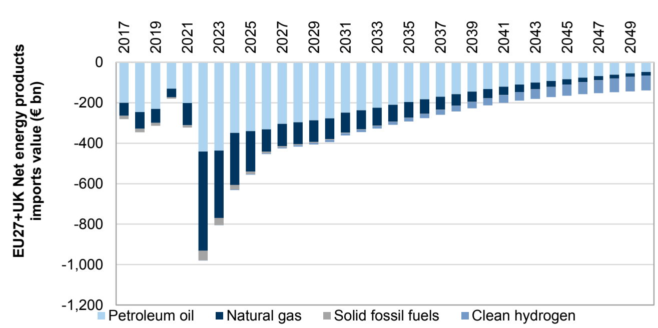

Source: Eurostat (historical), Goldman Sachs Global Investment Research

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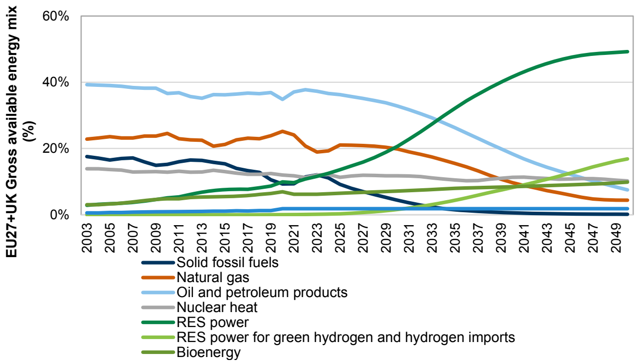
EU27+UK Gross available energy mix (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

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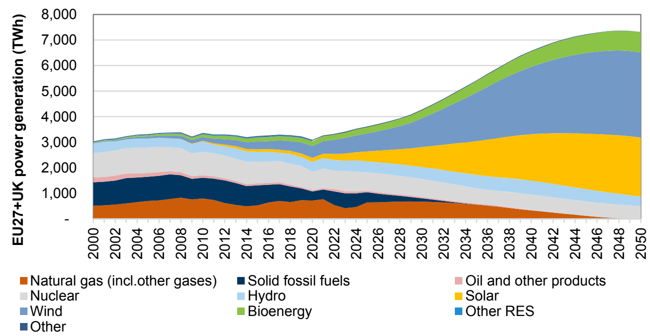

Source: Eurostat (historical), Goldman Sachs Global Investment Research

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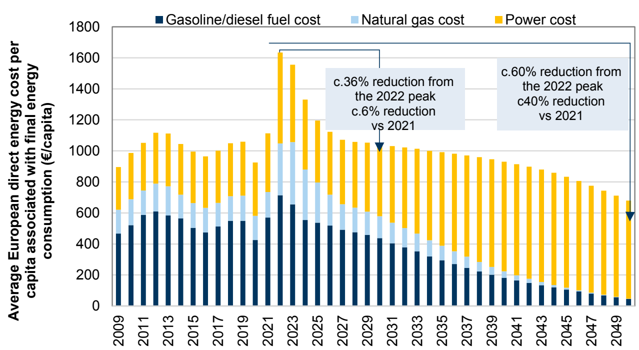

Source: Eurostat, Goldman Sachs Global Investment Research

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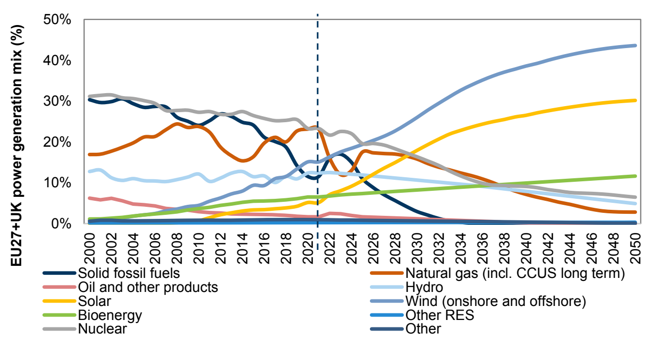
EU27+UK power generation mix over time (%)



Source: Eurostat, Goldman Sachs Global Investment Research

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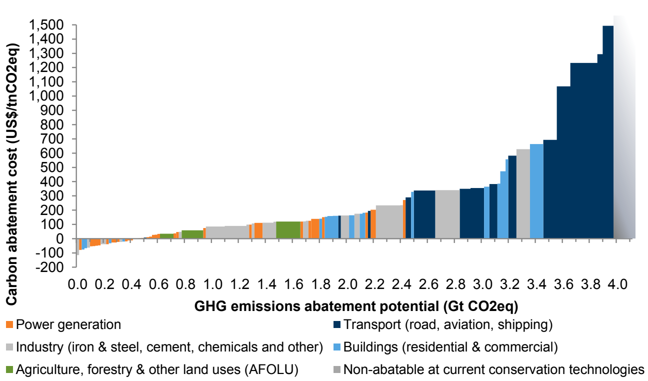
Europe Carbonomics cost curve of de-carbonization



Source: Goldman Sachs Global Investment Research

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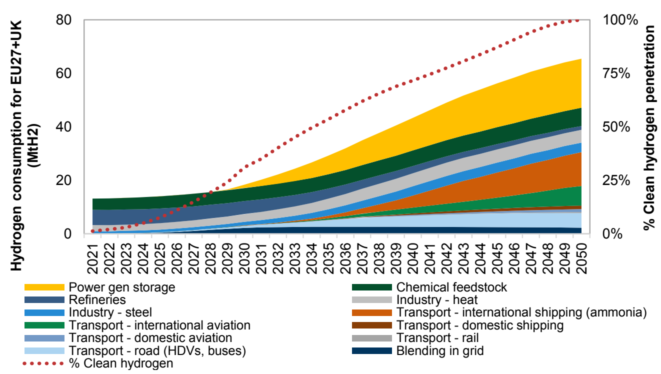

Source: Goldman Sachs Global Investment Research

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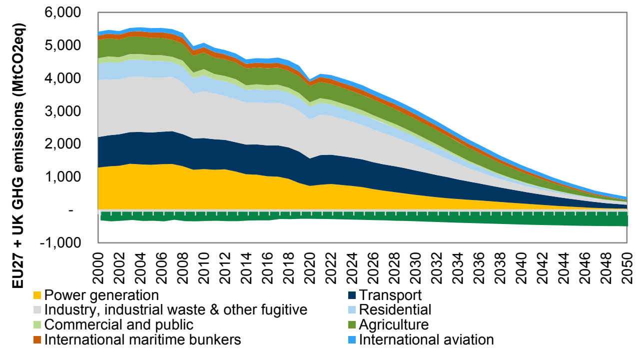

Source: Eurostat, EEA, Goldman Sachs Global Investment Research

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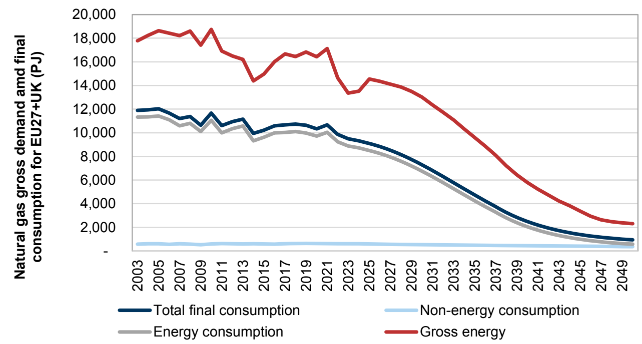
Natural gas gross energy and final consumption for EU27+UK (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

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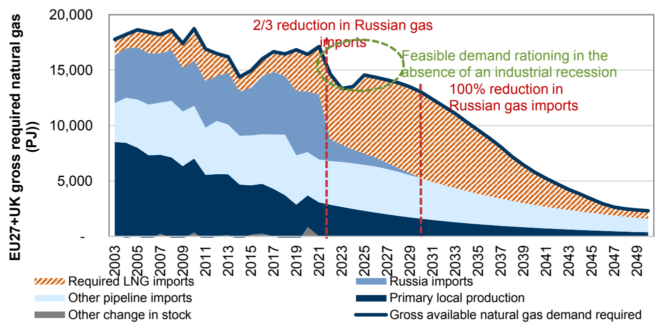
EUR27+UK gross natural gas demand vs sourcing (domestic, imports)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 16: ..leading to our estimate of c.40Mtpa of new 15-yr long-term LNG contracts requirement until 2040.

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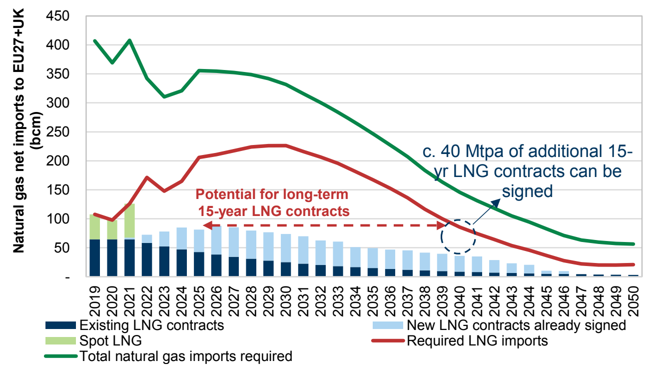

Source: Eurostat, Goldman Sachs Global Investment Research

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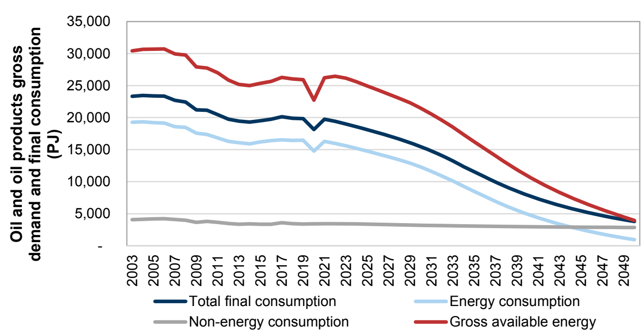
Oil and oil products gross energy and final consumption, EU27+UK (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

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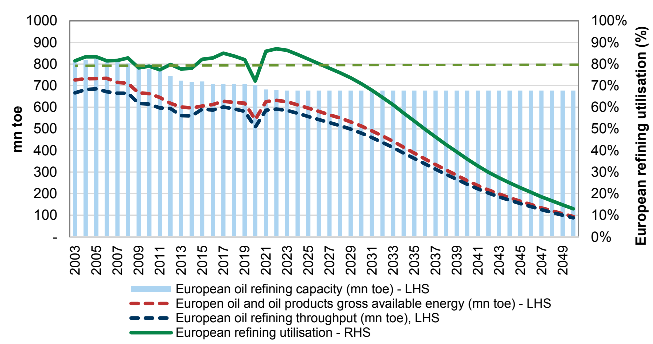
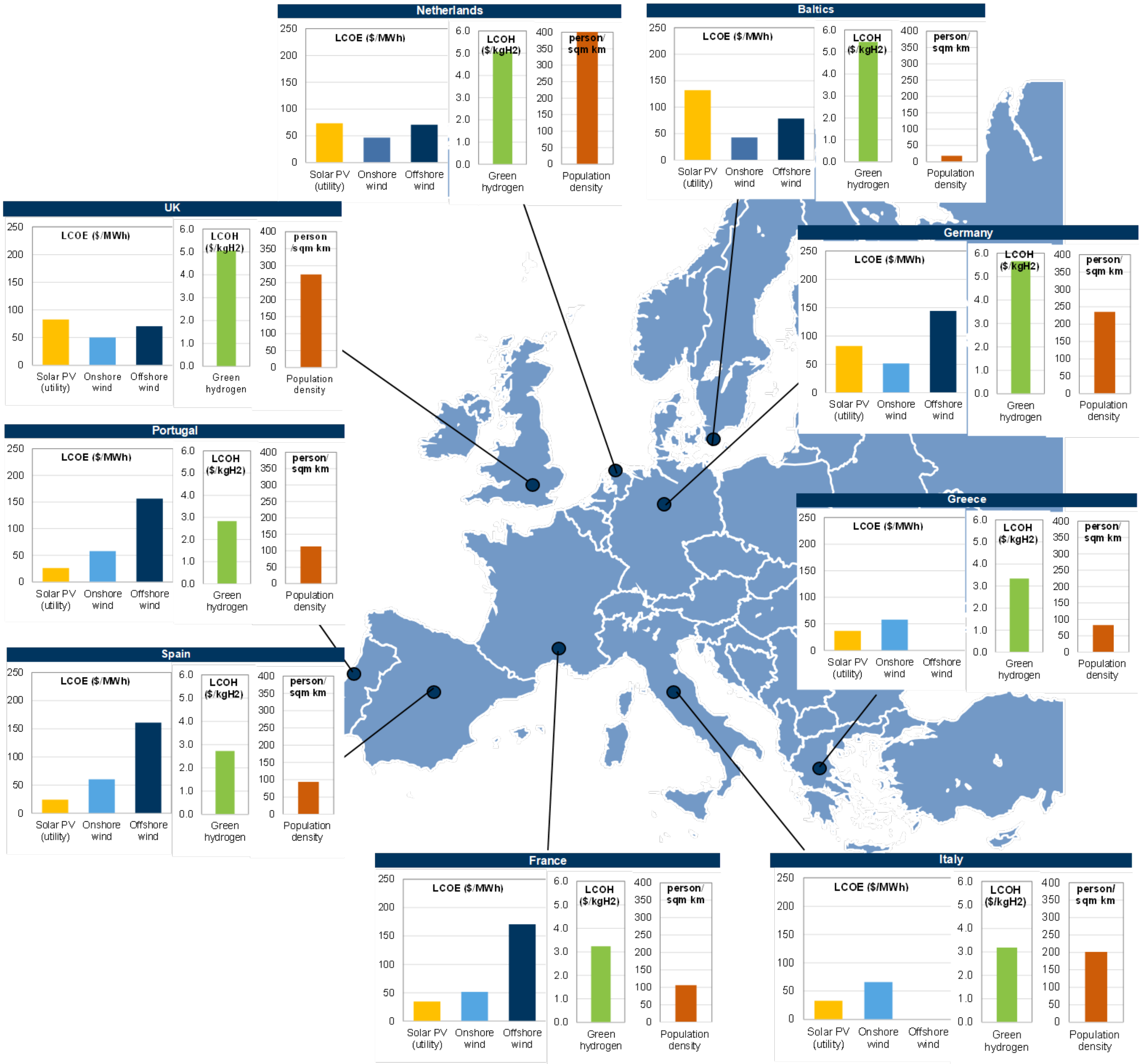


Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 19: The map of energy flows is transformed by emerging low cost renewables and green hydrogen exporters including Iberia, parts of Southern Europe (Southern France, Italy, Greece) and the UK (wind).

LCOE for solar, onshore wind and offshore wind, LCOH for green hydrogen and population density for key European regions



*LCOEs are estimated at the country average level, acknowledging that different parts of a region will have various solar, wind and LCOE profiles. We use consistently 7% cost of capital for solar and onshore wind, 9% cost of capital for offshore, 8% cost of capital for green hydrogen. **Population density data are for 2019.

Source: Eurostat (population density), Goldman Sachs Global Investment Research

Reference to the Europe region throughout this report refers to the EU27 countries plus the UK (previously referred to as EU28), unless otherwise indicated.

PM Summary: Re-imagining Europe's energy system – lower cost, lower imports, lower carbon

Europe's current energy system is unsustainable on three key metrics: costs (c. €980 bn of net energy imports in 2022E on our estimates), security of supply (58% energy dependency rate) and carbon intensity (3.7 GtCO2eq net GHG emissions pa). Our utilities team has addressed the deep impact on the European industrial system and consumer disposable income of Russian gas flows curtailments in the report 'What happens if Russian gas flows fall to zero: our assessment'. **In this report, we look at Europe's opportunity to leverage on the current challenging environment to build a more sustainable energy system for the future**, improving affordability, balance of payments, security of supply and creating domestic employment in key clean tech innovation areas. **We use our Carbonomics framework to model the evolution of Europe's energy system over the coming decades by sector**, aiming for Net Zero Carbon by 2050, through a path of least cost, maximizing domestic production and the continent's energy interconnectivity. The GS model for Europe's energy evolution is consistent with achieving net zero by 2050 for the region and with the key ambitions laid out by the European Commission as part of the 'Fit for 55' package (at least 55% net emissions reduction by 2030 vs 1990 level, at least 40% renewable energy sources in the overall energy mix by 2030).

Cumulative infrastructure investments of €10 trn will be needed by 2050 for Europe's energy transformation, reaching the equivalent of >2% of GDP by 2030

We estimate **a total infrastructure investment opportunity of €10 trn by 2050** for the transformation of Europe's energy system (EU27+UK) on the path to net zero carbon, implying an average annual green infrastructure investment opportunity of €350bn pa. We note that this figure focuses solely on incremental infrastructure investments and does not include maintenance and other end-use capex. We estimate that **this infrastructure investment can be entirely recouped from the savings of net energy imports**. Our model sees **a material reduction in the energy dependency rate of the region, from c.58% currently to <50% by 2030, <30% by 2040 and c.15% by 2050**. **We estimate that close to €10tn can be recouped from lower net energy imports by 2050**, **sufficient to fully cover the infrastructure investments required, although with a decade of time lag**. Efficient financing and a reliable regulatory environment are key to bridge this time gap. We further note that whilst the energy independence of Europe will improve substantially, the region will likely still need to import c.15% of its gross energy needs, accounting for fossil fuels used as feedstocks (such as for chemicals manufacturing) and around half of the green hydrogen volumes it requires. This energy evolution will likely be **very accretive to the overall Balance of Payments, even when considering the rising volumes of imported equipment**. We estimate that including the impact of net imported clean tech equipment (mostly solar panels and batteries), c.75% of the infrastructure investments can be recouped, with c.€7.5 trn in net imports savings.

We estimate the direct energy cost to the average consumer in Europe could be reduced by c.40% long term vs 2021 and c.60% from the peak (2022E)

Improved energy efficiency, but also lower cost long-term LNG contracts, cheaper renewable power and better seasonality management through batteries and hydrogen can substantially reduce the European consumer's energy spending in the long term. We estimate that the direct energy cost to the average consumer in Europe could fall by c.40% long term vs 2021 and c.60% from the peak (2022E). Our analysis focuses on the direct cost to the average European energy consumer of the electricity, fuel and gas that they use in their residential buildings and for their passenger vehicles, calculated at the retail price, including all relevant taxes and levies.

Natural gas remains key to Europe's energy supply for the next two decades and we believe it is in the interest of Europe to sign new long-term LNG contracts to improve security of supply

Natural gas remains a core part of the European energy system for another 20 years, in our analysis, being the most versatile energy source for the region with a broad use across applications. Despite its key importance across industries, power gen and buildings, Europe's reluctance to sign long-term LNG contracts over the past 15 years has resulted in an over-concentration of natural gas imports reaching the region via pipeline, with Europe importing >80% of its natural gas needs and with that supply largely dominated by a handful of regions: Russia, Norway, Algeria, Nigeria, the US, and Qatar. This is no longer sustainable, in light of the current geopolitical landscape. **We incorporate 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) into our modelling**, concluding that the shortfall between gross natural gas demand and available domestic supply plus other ex-Russian pipelines imports has to be met with incremental LNG imported volumes. This analysis suggests **it is in Europe's interest to sign up to an additional 40 mtpa of 15-yr LNG contracts, and potentially up to another 50 mtpa of 10-yr LNG contracts,** to improve security and diversification of supply – and allow a new generation of LNG projects to be developed for Europe. **We leverage our Top projects database to identify 15 projects that could supply up to a total of 155 mtpa pa to Europe with a long-term LNG price of $8-12/mcf**. On the oil side, our European energy system evolution model shows oil demand increasing to the middle of this decade, largely driven by the ongoing recovery of aviation, before starting a gradual decline which accelerates post 2030, driven by the higher penetration of EVs and better charging infrastructure. **We estimate that the next major cycle of refinery closures in Europe will only be needed by 2027,** when the refining utilisation rate falls below the historical average for the region.

Renewable power is at the heart of Europe's energy system re-invention, with power demand more than doubling by 2050, and green hydrogen accounting for c.15% of Europe's energy mix long term.

Electrification is the most important driver of lower emissions and lower energy import dependence in our modelling, with a more than doubling of European power demand by 2050. However renewable power intermittency and seasonality create the need for large-scale energy storage solutions, of which green hydrogen will be the most important, in our view. Hydrogen currently has a niche role, mostly in chems and refining. **However, we see hydrogen emerging as a critical technology in the long term, addressing the seasonal discrepancy between renewable power supply and power demand and aiding the de-carbonization of heavy industry and transport**. 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, while on the industrial side, hydrogen is the natural successor of natural gas and coal for diversification of energy supply in energy-intense industrial processes. Overall, we believe hydrogen demand for Europe will **surpass 60 Mtpa long term, in a scenario consistent with 'Fit for 55', reaching c.15% of the region's final energy consumption and creating a c.€0.74 tn cumulative investment opportunity in the direct hydrogen supply chain in Europe.**

The map of energy flows is transformed by emerging low cost renewables and green hydrogen exporters including Iberia, parts of Southern Europe and the UK

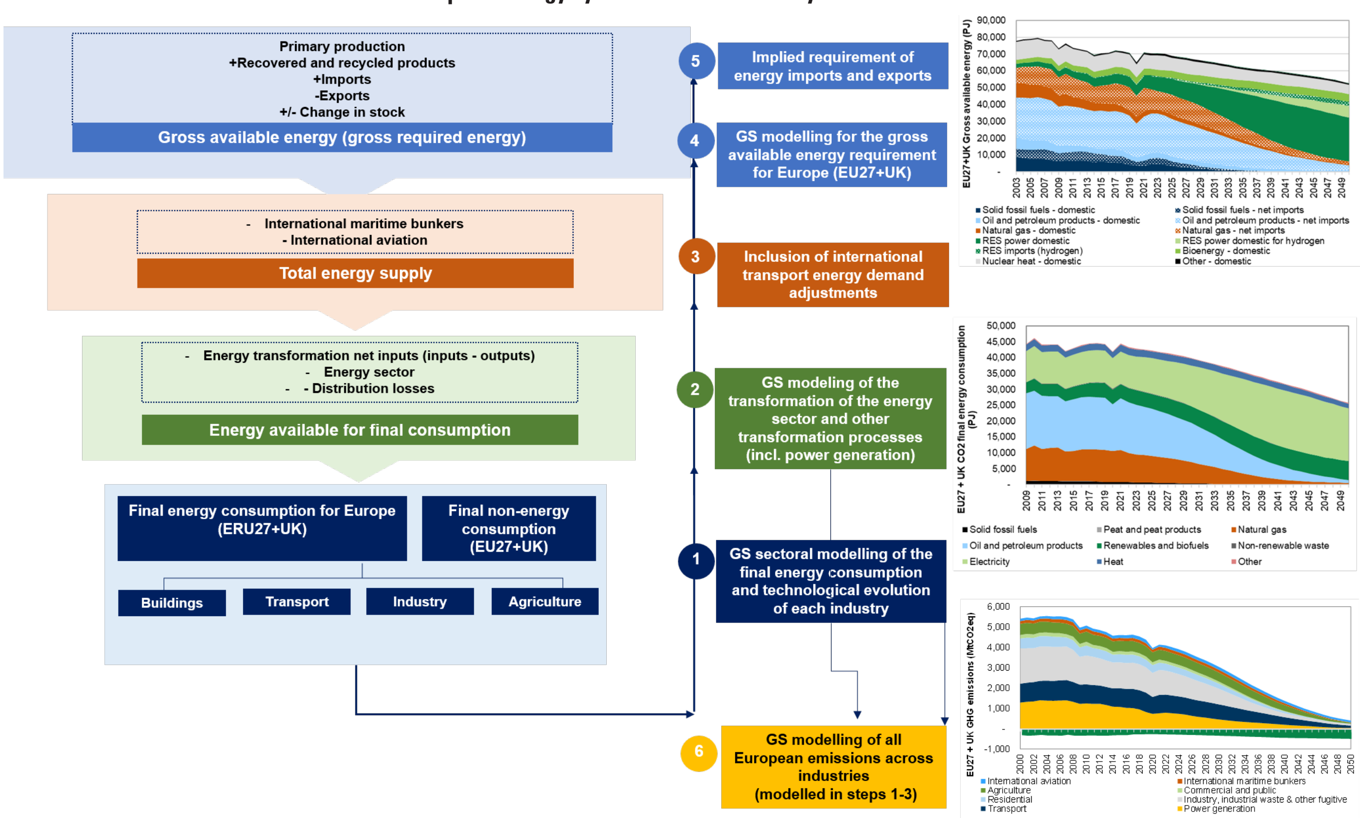
The energy import dependency of Europe can be reduced materially, with inter-regional hydrocarbon flows between Europe and the rest of the world being substituted by clean energy intra-regional flows between European countries – in **a more inter-connected European system of power networks and hydrogen pipelines**. We conduct an analysis to address the competitive positioning of key European countries across the most critical energy technologies of the future: solar, onshore wind, offshore wind, green hydrogen. We also note the inclusion of the population density measure for context regarding the potential space constrains associated with the scale-up of these technologies onshore. **The map of European energy flows can be transformed by emerging low cost renewables and green hydrogen exporters including Iberia, parts of Southern Europe (Southeastern France, Italy, Greece) and the UK (offshore wind)**. Iberia in particular screens very attractively on the potential of solar energy and low cost production of green hydrogen (both in terms of the implied solar PV LCOE and with regards to space availability and population density) whilst the UK screens attractively in terms of its cost positioning in offshore wind.

Re-Inventing Europe's energy system: A sectoral modeling approach consistent with the de-carbonization ambitions of the region

Laying out the path for Europe's energy evolution: A sectoral modeling approach leveraging our Carbonomics framework

In this report, **we introduce our model for the evolution of the European energy system** over the coming decades towards a more secure, more affordable and more sustainable system, **consistent with achieving net zero by 2050 and the key ambitions laid out by the European Commission as part of the 'Fit for 55' package** (at least 55% net emissions reduction by 2030 vs 1990 level, at least 40% renewable energy sources in the overall energy mix by 2030). For the purpose of this modeling and analysis, reference to the Europe region throughout this report refers to the EU27 countries plus the UK (formerly referred to as EU28), unless otherwise indicated. The methodology we adopted with regards to our energy modeling is summarized in Exhibit 20 below, and explained in detail in the section following this exhibit. The key terminology and definitions of the terms outlined in the exhibit and throughout this report are consistent with the energy balances terminology adopted by Eurostat (the European Statistical Office, a directorate-general of the European Commission).

Exhibit 20: A method overview for the GS European energy system models and analysis



Source: Goldman Sachs Global Investment Research

Step 1: As a first step, **we leverage our Carbonomics framework and adopt a sectoral approach to model** the **final energy consumption evolution** of each key **energy consuming sector in Europe** (denoted as Step 1 in Exhibit 20): **buildings** (residential, commercial/services and public), **transport** (light and heavy-duty road transport, aviation, shipping, rail), **industry** (including industrial combustion, industrial processes, fuel extraction, other fugitive and waste) and **agriculture**. The final energy consumption is defined as the total energy consumed by the end users in each of these sectors, the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself. As mentioned, overall, for the modeling of the final energy consumption, we leverage our Carbonomics framework to construct this model, and we adopt a sectoral approach, using our de-carbonization cost curve introduced in this report specifically for Europe, to determine the relative pace of de-carbonization and energy transformation in each industry on the basis of the current cost and technological readiness of the available alternative energy and de-carbonization technologies. This sectoral modelling provides two critical outputs: the final energy and non-energy (energy sources used as feedstock) consumption for Europe over time, we model to 2050.

Step 2: As a second step, we **model the evolution of the energy sector itself**, which bridges the gap between the final energy consumption obtained from Step 1 and the required total supply for Europe. This includes the modeling of the power generation system, as well as other energy transformation inputs and outputs (fuel conversions) and distribution losses.

Step 3: In Step 3, we add to the total European energy supply the energy required for international maritime bunkers and international aviation (vessels which are involved in international activities for which the demand for energy is stemming from Europe). This bridges the gap between total required energy supply and gross available energy.

Steps 4 & 5: Gross available energy is obtained from Steps 1 through 3 and is defined as the overall supply of energy for all activities on the territory of the European region considered in our analysis (EU27+UK). It includes energy needs for energy transformation (including generating electricity from combustible fuels), support operations of the energy sector itself, transmission and distribution losses, final energy consumption (industry, transport, buildings including households and services, agriculture) and the use of fossil fuel products for non-energy purposes (e.g. in the chemical industry). It also includes fuel purchased within the country that is used elsewhere (e.g. international aviation, international maritime bunkers). **Gross available energy for the total of all products (fuels) is the most important aggregate in energy balances and represents the quantity of energy necessary to satisfy all the energy demands.**

Gross available energy = Primary production + Recovered & Recycled products + Imports – Export + Stock changes

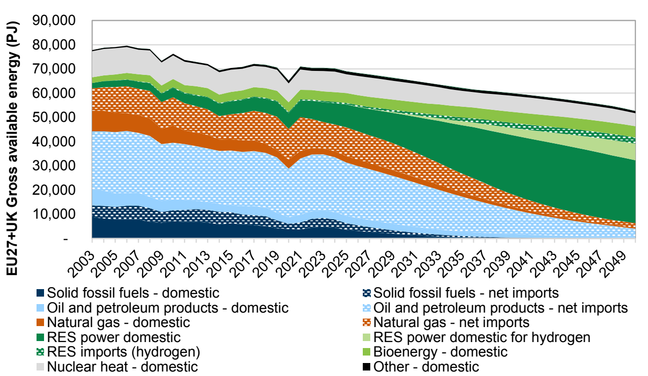
Step 6: Utilising our sectoral modeling of the energy and process technological mix evolution over time for each key emitting industry (both final energy consuming sectors and energy producing sectors such as power generation, fuel extraction, refining), we model the overall net GHG emissions of the region over time.

Re-Inventing Europe's energy system: A more secure, sustainable and resilient energy system

The outputs of our model for Europe's energy system evolution and transformation are presented throughout the exhibits of this report. Overall, Europe's gross energy evolution (gross available energy has been defined in the previous section of this report), modeled across sectors and fuels, is presented in the Exhibit 21 below, and the final energy consumption (also defined in the previous section of this report) with its mix evolution is shown in Exhibit 22.

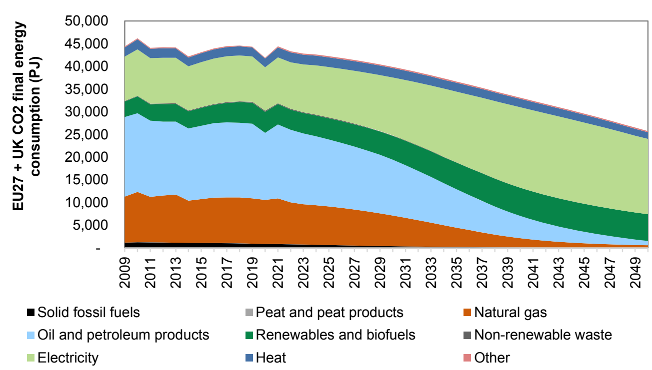
We see the region (EUR27+UK) gradually reducing its overall gross energy consumption and energy intensity, a result of ongoing improvements in efficiency and switch to alternative cleaner and more, on aggregate, efficient sources of energy (such as electrification). More importantly, we expect the mix of the gross European energy to completely transform in the coming years from largely relying on imported hydrocarbons (oil and oil products, solid fossil fuels and natural gas) to predominantly relying on domestic renewable energy sources and fuels (renewable power, bioenergy, hydrogen, nuclear). A combination of more sustainable but also largely domestically produced energy sources will lead, in our view, to both a **more sustainable, secure and independent energy system, with a lower reliance on imported energy and lower carbon footprint.** This section of the report addresses how the European energy system could evolve to be (1) more sustainable with a lower carbon footprint, (2) more secure and independent through a reduced reliance on imported energy sources, (3) more resilient through an ecosystem of technologies extending beyond renewable power especially with regards to energy storage to support seasonal and intraday imbalances in such a system, and (4) more affordable.

Exhibit 21: We present in this exhibit the resulting European gross available energy evolution over time, consistent with the region's de-carbonization ambitions..
Europe's (EU27+UK) gross available energy under the GS Europe energy evolution model (PJ)



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

Exhibit 22: ..as well as the evolution of the final energy consumption of European energy end-users (buildings, industry, transport, agriculture)
Europe's (EU27+UK) final energy consumption under the GS Europe energy evolution model (PJ)



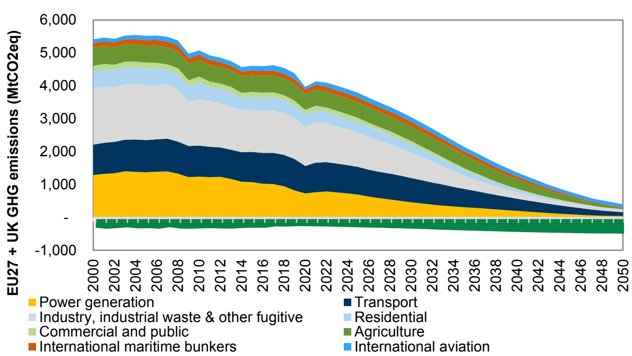
Source: Eurostat, Goldman Sachs Global Investment Research

A more sustainable energy system: A path consistent with the emission reduction ambitions laid out in 'Fit for 55', net zero by 2050, leveraging our Carbonomics cost curve across emitting sectors

The GS model for Europe's energy evolution is consistent with achieving net zero by 2050 for the region and the key ambitions laid out by the European Commission as part of the 'Fit for 55' package (at least 55% net emissions reduction by 2030 vs 1990 level, at least 40% renewable energy sources in the overall energy mix by 2030). Our European model addresses all key emitting sectors in the region: power generation, buildings (residential, commercial/services and public), transport (light and heavy-duty road transport, aviation, shipping, rail), industry (including industrial combustion, industrial processes, fuel extraction and other fugitive and waste emissions) and agriculture. This enables us not only to model the energy and process technological evolution by industry but also track and estimate the resulting overall emissions (both energy and process) stemming from each of these industries and the broader European region considered in our analysis.

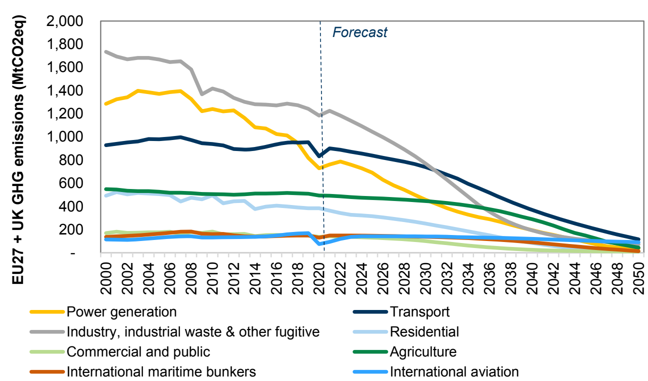
The resulting emissions profile resulting from our GS model of Europe's energy evolution is shown in Exhibit 23 and is resulting in c.55% GHG emissions reduction vs 1990 level for the region by 2030 and net zero by 2050. With regards to emissions accounting, we include in our emissions profile the international transport elements (defined earlier in this report) as well as the contribution of the land use, land-use change and forestry (LULUCF) sector, consistent with the Commission's proposal to strengthen the contribution of that sector to reverse the current declining trend of carbon removals and enhance the natural carbon sink throughout the EU. Specifically, the revision of the current legislation proposes to set an EU-level target for net removals of greenhouse gases of at least 310 million tonnes of CO2 equivalent by 2030, which is distributed among the member states as binding targets.

Exhibit 23: Our model of Europe's energy evolution is consistent with the ambitions laid out in 'Fit for 55' (reducing emissions by c.55% vs 1990) and net zero by 2050..
EU27+ UK GHG emissions (MtCO2eq), including LULUCF



Source: Eurostat, EEA, Goldman Sachs Global Investment Research

Exhibit 24: ..adopting a sectoral approach, modelling the emissions across all key emitting sectors
EU27+UK GHG emissions by key emitting sector (MtCO2eq)



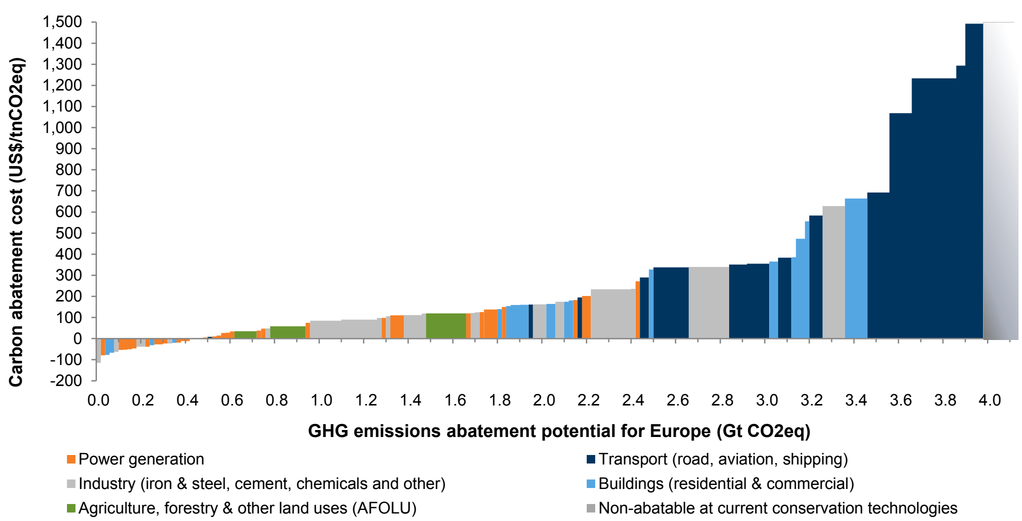
Source: Eurostat, EEA, Goldman Sachs Global Investment Research

The pace of the energy transformation and de-carbonization achieved for each sector is correlated to the sector's positioning on our Carbonomics cost curve. In our deep-dive de-carbonization report, we had introduced in detail our Carbonomics carbon abatement cost curves. The Carbonomics cost curves show the reduction potential and carbon abatement cost for anthropogenic GHG emissions through >100 different applications of GHG conservation and sequestration technologies across all key emitting sectors in the region the cost curve is addressing. In this report, **we introduce the first Carbonomics de-carbonization cost curve for Europe (EU27+UK)**, presented in Exhibit 25 below.

Overall, we expect all the key technologies addressed in our de-carbonization cost curve to play a role in facilitating the path to net zero, each in their respective sector. The speed of de-carbonization in each sector is largely dependent on the current carbon abatement cost and state of readiness of the available clean technologies presented in our Carbonomics cost curve. As such, in our models for Europe's energy and emissions evolution on the path to net zero, different sectors de-carbonize at different speeds and have a different carbon budget allocation, depending on their relative cost positioning and readiness on our de-carbonization cost curve. We note that our Carbonomics cost curve of de-carbonization **is not static, and is expected to evolve over time as the costs of existing technologies continue to change and as technological innovation leads to the addition of further de-carbonization technologies across sectors.** As such, **our energy evolution and net zero models are also dynamic, and are expected to evolve over time** as technological innovation and focus on de-carbonization continues.

Exhibit 25: Our GS European energy evolution and net zero model incorporates a transformation path across sectors that is largely dependent on the carbon abatement cost and readiness of the available de-carbonization technologies, as shown in our Carbonomics cost curve

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

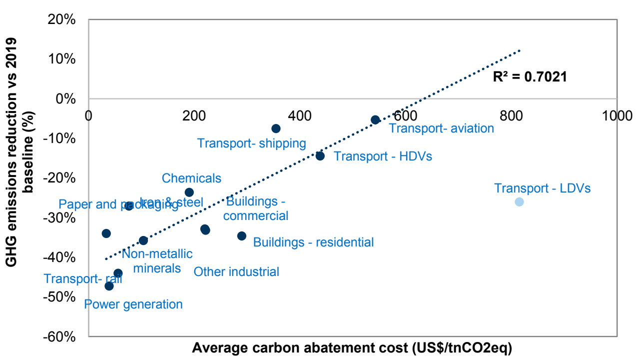


Source: Goldman Sachs Global Investment Research

As mentioned previously, the pace of de-carbonization varies by sector and sub-sector, depending on the carbon abatement cost and technological readiness, as addressed by our Carbonomics cost curve shown above. Exhibit 26 shows that **the pace of de-carbonization to 2030 for each sub-sectors in our European energy evolution model is correlated with the sub-sector's current average carbon abatement cost, as described previously.** Harder-to-abate sectors with limited alternative energy and de-carbonization technologies currently at large scale such as aviation, heavy industry, shipping with a higher carbon abatement cost, de-carbonize slower, compared to sectors such as power generation, buildings and efficiency measures, which are associated with a lower carbon abatement cost.

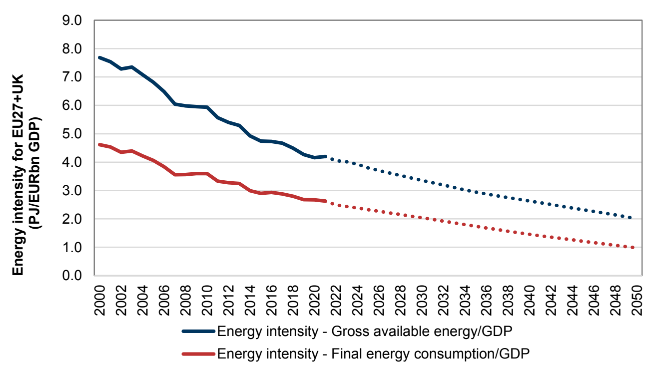
In addition to a higher energy sustainability, we also expect the **energy efficiency of the region** to improve notably in the coming years and we present in Exhibit 27 the energy intensity evolution for Europe based on our model. Energy intensity is an indicator used to measure the energy needs of an economy and it is often employed as a proxy for energy efficiency. Energy intensity is calculated as units of energy per unit of GDP. We note nonetheless that many factors can influence energy intensity, as it reflects on structure of economy and its cycle and general standards of living in the reference area. More interestingly, over the period 2000-19, the overwhelming majority of the energy intensity reduction was driven by the rise in GDP for the region (driving c.90% of the energy intensity reduction), whilst from here (2022-50) we expect the energy intensity reduction to be largely driven by the overall energy efficiency improvement of the system as opposed to the rise in GDP.

Exhibit 26: The pace of energy transformation and de-carbonization in each sector and sub-sector is correlated to the average carbon abatement price of the available clean technologies in that sector.
GHG emissions reduction in 2030 vs. 2019 by sub-sector vs. average carbon abatement cost



Source: Goldman Sachs Global Investment Research

Exhibit 27: We expect the energy intensity (energy per unit GDP) of the European energy system to continue to improve over time, mostly driven by higher energy efficiency as opposed to higher GDP growth which has been the case over 2000-19.
Energy intensity for EU27+UK (PJ/EURbn GDP)



Source: Eurostat, Goldman Sachs Global Investment Research

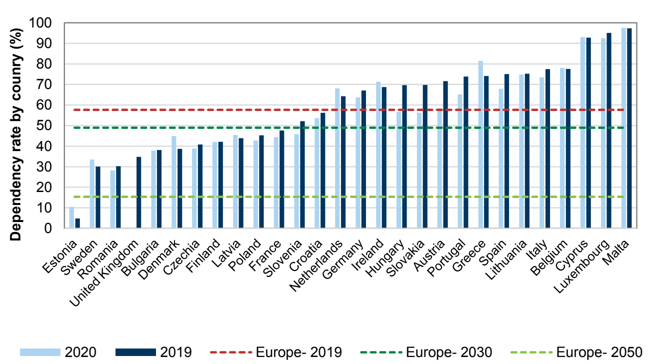
A more secure and independent energy system: The energy dependency rate for Europe falls from c.58% to c.15% by 2050 on our estimates with the emergence of local, low cost renewable power and green hydrogen exporters

Our model of the European energy system evolution sees a **material reduction in the dependency rate of the region, from c.58% currently to <50% by 2030, <30% by 2040 and c.15% by 2050.** The energy dependency rate shows the proportion of energy that an economy must import. It is defined as net energy imports divided by gross available energy, expressed as a percentage. A negative dependency rate indicates a net exporter of energy while a dependency rate in excess of 100% indicates that energy products have been stocked. It can be defined for all products total as well as for individual fuels.

In 2020, every single country within the EU27 and the UK has been a net importer of energy, as shown in Exhibit 28, with dependency rates as low as 10% to as high as 98%. Whilst we do not take a view on a country by country basis, we note that the energy import dependency of the **overall region** (EU27+UK) will reduce materially with **energy flows dominated by intra-regional flows between European countries rather than inter-regional hydrocarbon flows between Europe and the rest of the world.** In that context, we conduct an analysis to address the competitive positioning of key European countries across the most critical energy technologies emerging as the dominating energy pillars: solar, onshore wind, offshore wind, green hydrogen. We also note the inclusion of the population density measure for context regarding the potential space constrains associated with the scale-up of these technologies and which extends beyond economic considerations. We note that this analysis is not exhaustive (does not address every single country in the region) and adopts average cost figures for these technologies across these regions. Our results are summarized in Exhibit 32.

Exhibit 28: The dependency rate for Europe quantifies the share of net energy imports as part of the total gross available energy for the region, currently at c.58% for Europe..

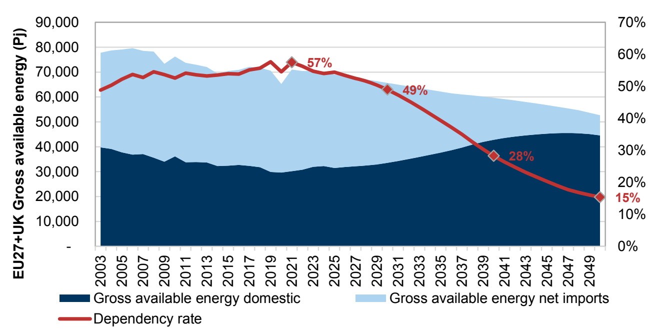
Europe's energy dependency rate by country (2019, 2020 and GS projections for the overall region to 2030 and 2050), %



Source: Eurostat, Goldman Sachs Global Investment Research

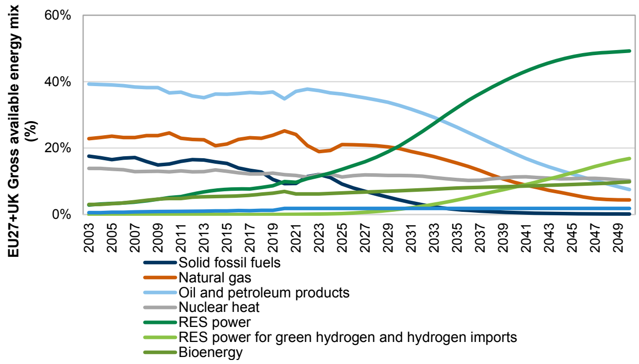
Exhibit 29: ..yet we expect it to reduce materially to <50%/<30%/c.15% by 2030/40/50 based on our model, enhancing the region's energy security and independence...

Europe gross available energy split between net imports and domestic energy (PJ)



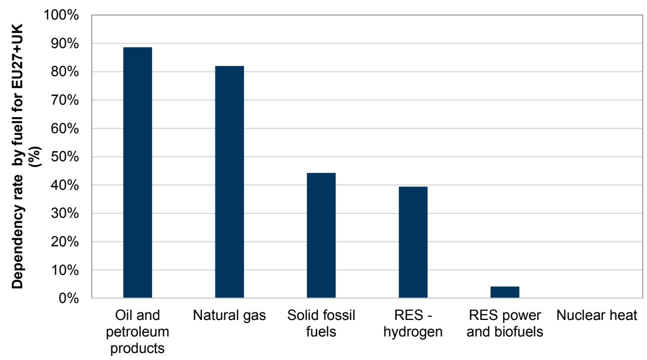
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 30: ..driven by a higher share of domestically produced energy sources, primarily renewable power, nuclear, bioenergy..
EU27+UK gross available energy mix evolution (%)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 31: ...all of which have an overall lower energy dependency rate compared to the hydrocarbon sources they are displacing.
Energy dependency rate by energy source for EU27+UK (%)



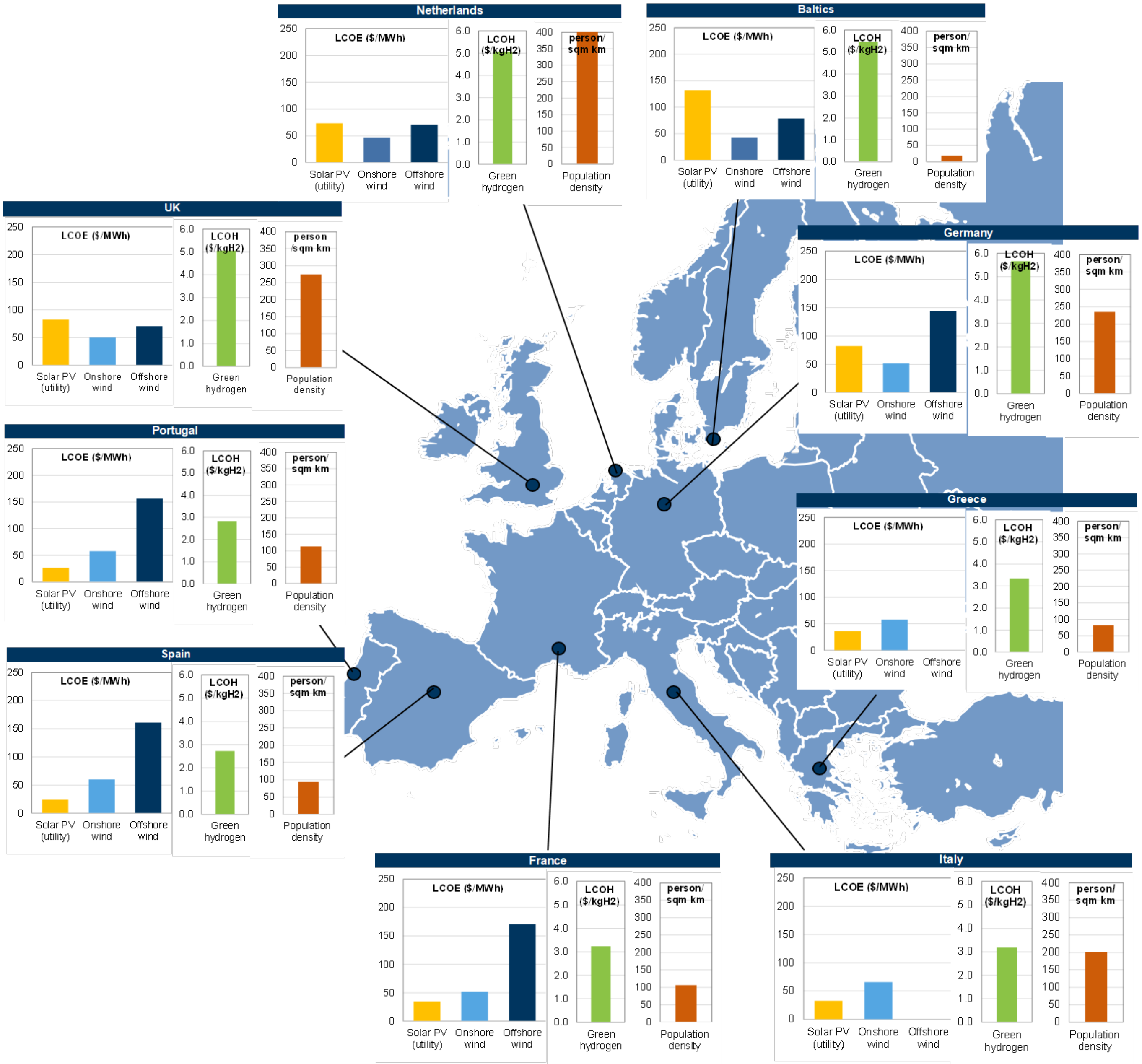
Source: Eurostat, Goldman Sachs Global Investment Research

The map of energy flows is transformed by emerging low cost renewables and green hydrogen exporters including Iberia, parts of Southern Europe and the UK

The map of **European energy flows** is transformed by emerging **low cost renewables and green hydrogen exporters including Iberia, parts of Southern Europe** (Southeastern France, Italy, Greece) and the **UK** (offshore wind). Iberia in particular screens very attractively on the potential of solar energy and low cost production of green hydrogen (both in terms of the implied solar PV LCOE and with regards to space availability and population density) whilst the UK screens attractively in terms of its cost positioning in offshore wind. Exhibit 32 summarizes the key comparative metrics across key regions of Europe with regards to domestically produced clean energy.

Exhibit 32: The map of energy flows is transformed by emerging low cost renewables and green hydrogen exporters including Iberia, parts of Southern Europe (Southern France, Italy, Greece).

LCOE for solar, onshore wind and offshore wind, LCOH for green hydrogen and population density for key European regions



*LCOEs are estimated at the country average level, acknowledging that different parts of a region will have various solar, wind and LCOE profiles. We use consistently 7% cost of capital for solar and onshore wind, 9% cost of capital for offshore, 8% cost of capital for green hydrogen. **Population density data are for 2019.

Source: Eurostat (population density), Goldman Sachs Global Investment Research

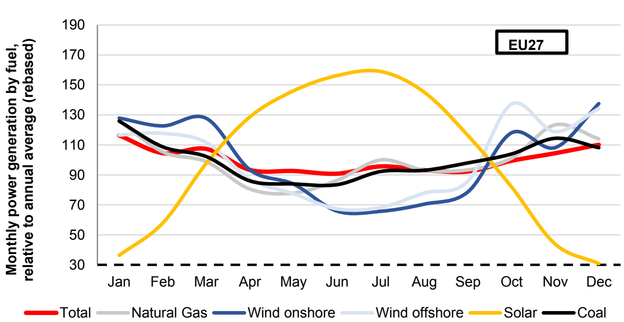
More resilient energy system: An ecosystem of clean technologies supporting a resilient system and filing the pivotal need for energy storage

As we have highlighted numerous times in our Carbonomics research series and our global net zero models, we believe that the energy evolution and path to net zero calls for an evolution of the de-carbonization process **from one dimensional (renewable power) to a multi-dimensional ecosystem**. Four more technologies are emerging as transformational in our view in addition to renewable power: **hydrogen**, **bioenergy** (including the role of biogas), **battery energy storage**, **carbon sequestration** (both natural sinks and carbon capture). All of these will, in our view, be required to help the stability and resilience of the energy path we envisage for the European region.

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. We incorporate both of these technologies in our energy evolution path for Europe. This low carbon infrastructure however will require time to be built. **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.**

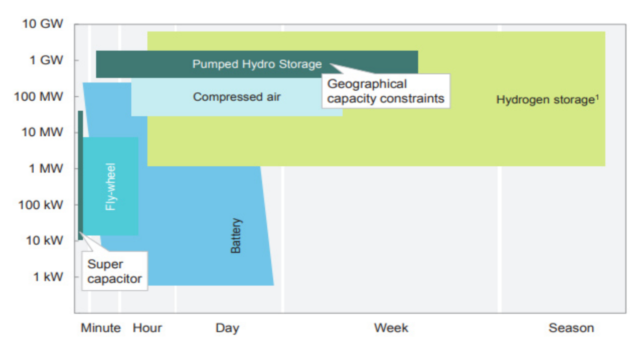
Exhibit 33: European natural gas consumption in winter months is on average c.2.5x that of summer months in order to meet growing seasonal power demand and address the counter-seasonality of renewable power.

EU27 average monthly power generation by fuel type relative to annual average, rebased



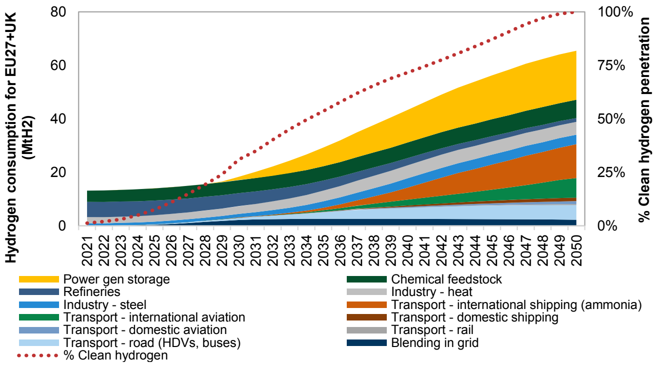
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 34: Hydrogen could be the optimal solution for large-scale, long-duration energy storage, particularly for discharge durations beyond 50 hours



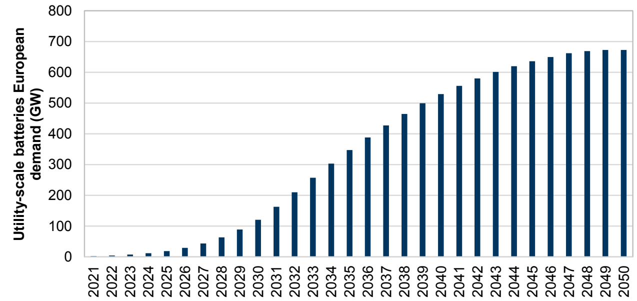
Source: Hydrogen Council

Exhibit 35: ..and we expect European hydrogen consumption to rise multi-fold on the path to net zero.
Hydrogen consumption for EU27+UK (MtH2)



Source: Goldman Sachs Global Investment Research

Exhibit 36: ..complementing the rising need for utility-scale batteries to support an increasingly intermittent renewable power-dominated grid.
Utility-scale batteries European demand (GW)



Source: Goldman Sachs Global Investment Research

With regards to energy storage, 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.

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: see section *Europe's energy evolution and the need for molecular energy sources: Hydrogen and Bioenergy* later in this report.

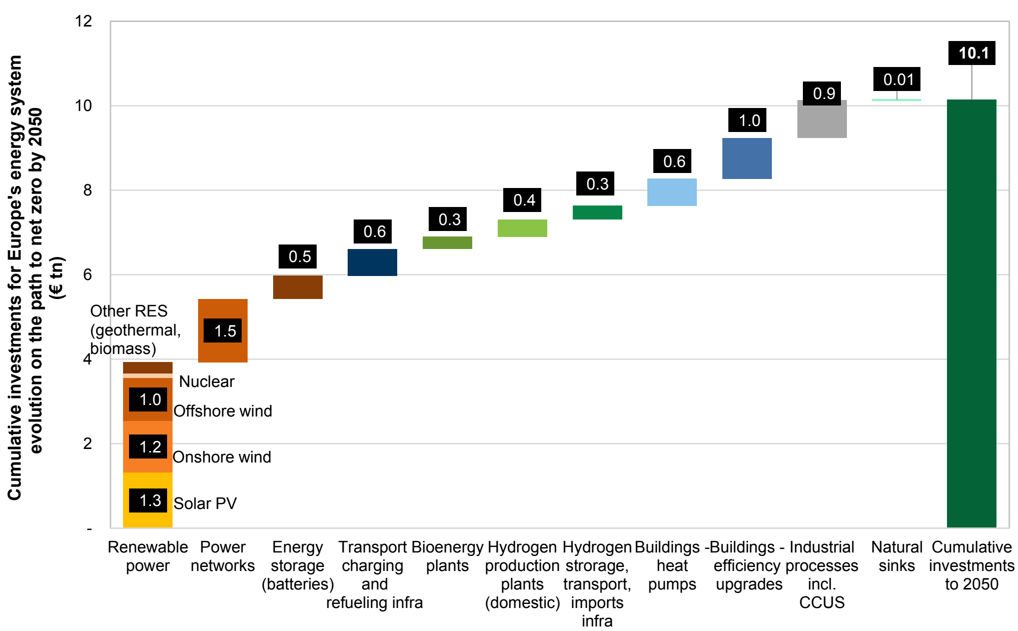
The investment path: €10 tn investment opportunity, largely recouped by lower net energy imports

The re-invention of the European energy system and path to net zero by 2050 has the potential to transform not only the local energy ecosystem but also the economy and society's standard of living. Exhibit 37 shows the wide range of investment opportunities associated with what we believe are the key infrastructure milestones required to transform Europe's system. These include, among others, the increasing uptake of renewable power, battery energy storage, hydrogen, bioenergy, as well as an increasing focus on infrastructure investments for power networks and charging stations that will enable a new era of electrification, an upgrade and/or retrofit of industrial plants, retrofitting of buildings and other existing heating infrastructure enabling greater efficiency and uptake of electrification, and finally a greater focus on carbon sequestration (natural sinks and carbon capture).

In aggregate, we estimate a total infrastructure investment opportunity around €10 trn by 2050 for the transformation of Europe's energy system (EU27+UK) on the path to net zero, which implies an **average annual green infrastructure investment opportunity of c.€350bn pa.** We note that this figure focuses solely on incremental infrastructure investments and does not include maintenance and other end-use capex.

Exhibit 37: We estimate that there exists in aggregate a €10 trn infrastructure investment opportunity for the transformation of Europe's energy system on the path to net zero

Cumulative investment opportunity across sectors for the re-invention of Europe's energy system to net zero by 2050 (€tn)

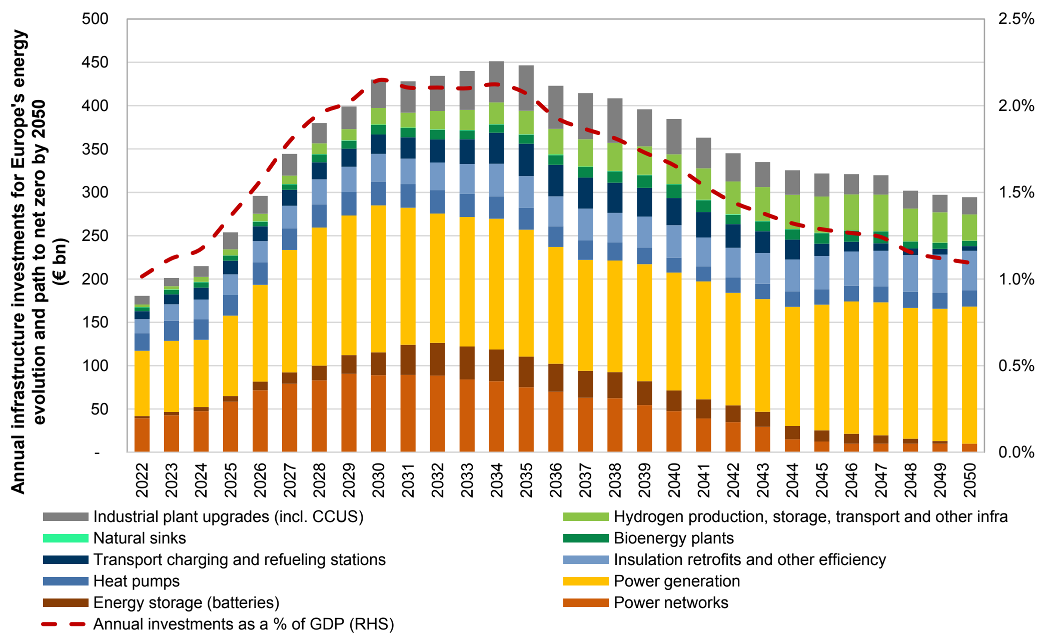


Source: Goldman Sachs Global Investment Research

The re-invention of Europe's energy system requires, on our estimates, c.€350 bn pa of infrastructure investments, representing >2% of the region's GDP by 2030 and peaking in the mid-2030s

As highlighted in Exhibit 37, we estimate a total investment opportunity of c.€10 tn by 2050 for an energy transformation path consistent with the long-term net zero and 'Fit for 55' ambitions, for a more secure, independent and sustainable energy system. We note however that we would not expect this to be evenly distributed annually to 2050. Instead, we anticipate an annual de-carbonization investment profile similar to that shown in Exhibit 38, with an acceleration of investments to 2035, the years when we expect investments to peak, driven largely by the initial infrastructure expansion required for power networks, charging networks, the massive expansion of renewable power, buildings upgrades and heating pipeline infrastructure to accelerate the penetration of electrification and clean hydrogen, and fuel substitution in transport and industry. Overall, the average annual investments in de-carbonization that we estimate over 2022-50 are c.€350 bn, with the peak in the 2030s (c.€450 bn) representing >2% of the region's GDP (EU27+UK).

Exhibit 38: We expect an annual investment profile similar to the one presented here, for the transformation of Europe's energy system on the path to net zero by 2050, with investments reaching >2% of the region's GDP by 2030 and peaking around the mid-2030s



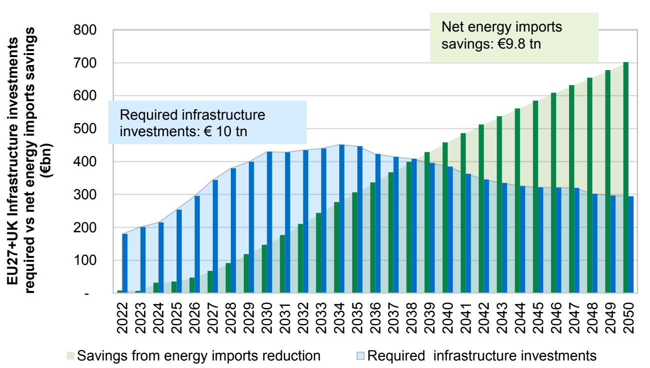
Source: Goldman Sachs Global Investment Research

We estimate that the infrastructure investments required can largely be recouped from the savings of net energy imports contributing to a material improvement in the balance of payments for the region

As mentioned in the previous section of this report, the evolution of the European energy system we envisage will lead to a notable reduction of its net energy imports dependency rate, as the share of domestic production overtakes and dominates energy supply long term (driven largely by the rise of electrification supported by domestic renewable power production). The reduction of net energy imports dependency of the region will subsequently result in a notable improvement to Europe's net energy imports balance.

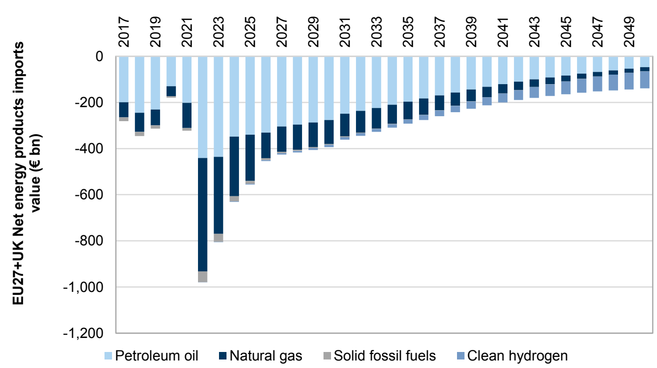
We estimate that €10tn can be recouped from the savings associated with the reduction of net energy imports, sufficient to fully cover the infrastructure investments required. We highlight nonetheless that the **annual evolution and profile of these savings and required infrastructure investments differs, with the former lagging the latter by more than a decade.** Efficient financing and a reliable regulatory environment are key to bridge the time gap. We further note that whilst the energy independence of Europe will improve substantially, the region will likely still need to import c.15% of its gross energy needs, accounting for fossil fuels used as feedstocks (such as for chemicals manufacturing) and around half of the green hydrogen volumes it requires (mostly from advantageous regions with low cost, excess renewable power such as the Middle East, North Africa, parts of Latin America, Australia).

Exhibit 39: The infrastructure investment can be largely recouped through lower net energy imports, yet with more than a decade lag...
EU27+UK annual required infrastructure investments vs net annual energy import savings (€bn)



Source: Goldman Sachs Global Investment Research

Exhibit 40: ...contributing to a material improvement in the balance of payments for the region.
EU27+UK net energy product imports value (€bn)

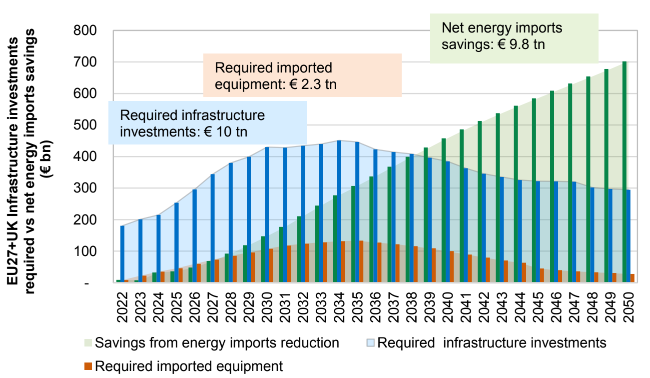


Source: Eurostat (historical), Goldman Sachs Global Investment Research

Extending the analysis beyond the changes in energy imports, and incorporating the potential net imports of clean tech equipment required for Europe's energy transformation (primarily solar panels, stationary and road transport batteries), we still view that **Europe's energy shift will likely be accretive to its overall Balance of Payments**. We estimate that even **including the impact of net imported equipment, c.75% of the infrastructure investments can be recouped through net import savings**, with c.**€7.5 trn in net imports savings for the region**, as shown in the exhibit below.

Exhibit 41: Even when considering the impact of rising imported equipment volumes (solar panels, stationary and transport batteries), we estimate a c. €7.5 trn net improvement in Europe's balance of payments cumulatively to 2050...

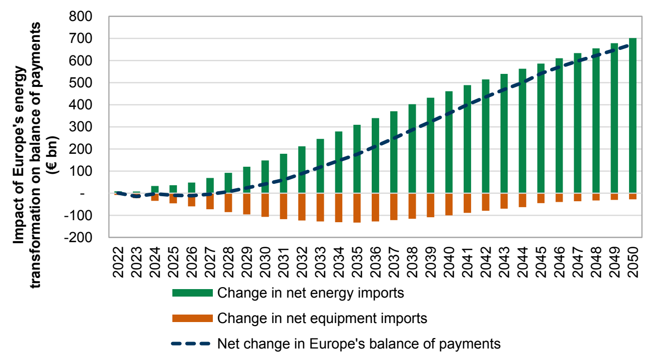
EU27+UK infrastructure investments vs net energy imports savings and required equipment imports (€ bn)



Source: Goldman Sachs Global Investment Research

Exhibit 42: ..with the improvement mostly seen from 2028

Net change in Europe's balance of payments as a result of the European energy evolution we envisage (€ bn)



Source: Goldman Sachs Global Investment Research

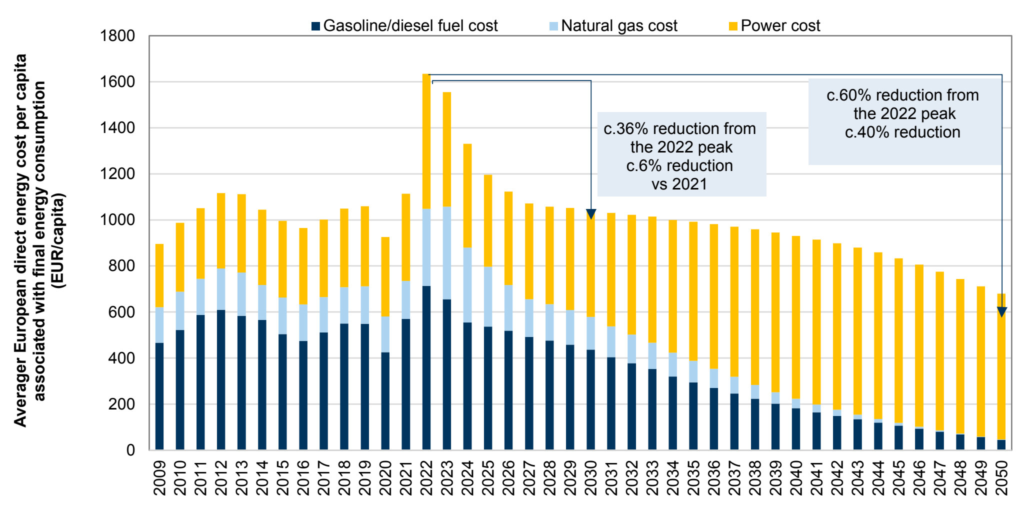
A more affordable energy system: c.40% reduction in the average European direct energy cost per capita vs 2021 and c.60% vs the peak

We believe the average European direct energy cost per capita can be reduced by c.40% to 2050 (vs 2021) and c.60% vs the peak in 2022

In addition to the more sustainable, secure and resilient energy system we envisage for Europe, we believe this energy system could prove to also be more affordable. We estimate the **direct energy cost to the average consumer in Europe (done on a per capita basis) could be reduced by c.40% long term (by 2050) vs 2021 figure and c.60% from the peak (2022).** Our analysis focuses on the **direct cost the average European 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 electricity final 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 43. 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) before gradually reducing to the 2021 level by the middle of the decade, on our estimates. **Thereafter, the higher share of power in the average European consumer's energy spending as well as the improved energy efficiency of Europe drives 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.**

Exhibit 43: We estimate the direct energy cost to the average energy consumer in Europe (done on a per capita basis) could be reduced by c.36% long term (by 2050) vs 2021 figure and c.60% vs the peak in 2022.
Average European direct energy cost per capita associated with final energy consumption (EUR/capita pa)



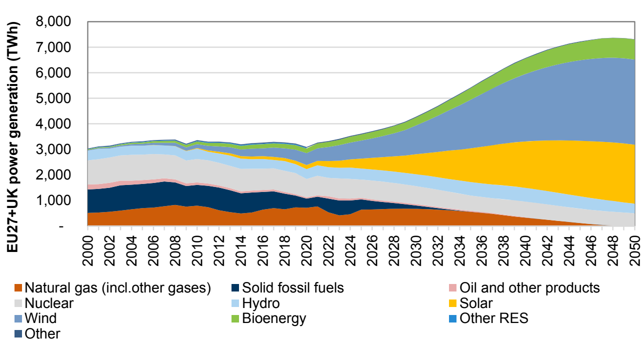
Source: Eurostat, Goldman Sachs Global Investment Research

Power generation: At the heart of Europe's energy evolution, affordability and security

Power generation is the most vital component for any European energy evolution and net zero path, with the sector contributing to >20% of the total anthropogenic GHG emissions for the region. The role of power generation is, in our view, only likely to increase in the coming decades, as the penetration and pace of electrification is rapidly increasing across sectors as these progressively follow their own energy evolution and de-carbonization path, including, amongst others, the electrification of road transport, buildings, industrial manufacturing processes and low-temperature industrial heat. Overall, we expect **total European demand for electricity generation to more than double** (vs. that of 2019) **and surpass 7,500 TWh** as the de-carbonization process unfolds and **electricity forms c.65% of the overall European final energy consumption mix.**

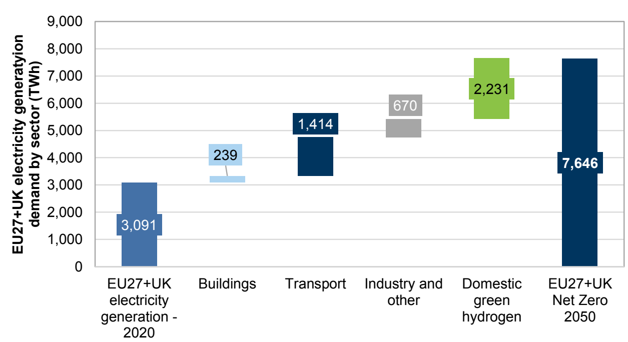
Based on our European Carbonomics cost curve analysis, power generation currently dominates the low end of the carbon abatement cost spectrum, with renewable power technologies already developed at scale and costs that have fallen rapidly over the past decade making them competitive with fossil fuel power generation technologies across key European regions. As such, we believe that **power generation will likely be amongst the sectors that transform their mix and de-carbonize at a faster pace than others**, as shown in Exhibit 26 earlier in this report. In fact, as shown in Exhibit 47, it can be argued that the transformation of power in Europe has already started and accelerated over the past decade with renewable power the most critical component of the mix moving forward. Based on our European energy evolution model, consistent with the 'Fit for 55' ambitions, we estimate that **the share of renewables in the European power mix will rise from c.40% currently** (2021, including in addition to solar and wind, hydro, bioenergy and renewable waste) **to >60% by 2030 and >90% by 2050.**

Exhibit 44: We estimate that total demand for power in Europe will increase almost three-fold to 2050..
EU27+UK electricity generation (TWh)



Source: Eurostat, Goldman Sachs Global Investment Research

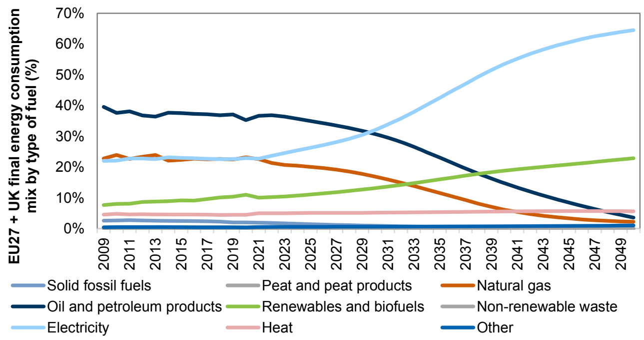
Exhibit 45: ..as it forms a critical part of the energy evolution and de-carbonization route for other sectors such as the electrification of transport, buildings, industry, production of green hydrogen..
EU27+UK electricity bridge to 2050E (TWh)



Source: Goldman Sachs Global Investment Research

Exhibit 46: ..and its share in the European final energy mix is rising, reaching c.65% of the European final energy consumption, from c.23% currently.

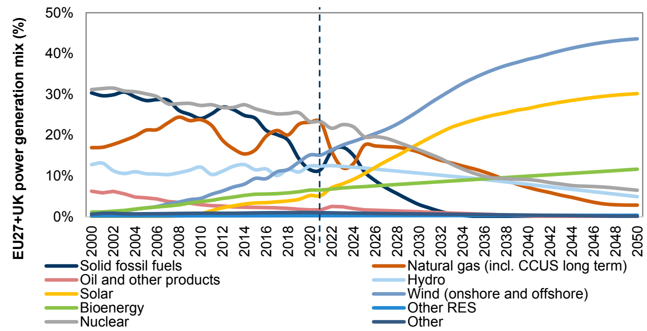
Europe's (EU27+UK) final energy consumption mix under the GS Europe energy evolution model (%)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 47: The transformation of the power generation mix has already started and we only expect it to accelerate from here with renewable energy having the most critical role to play...

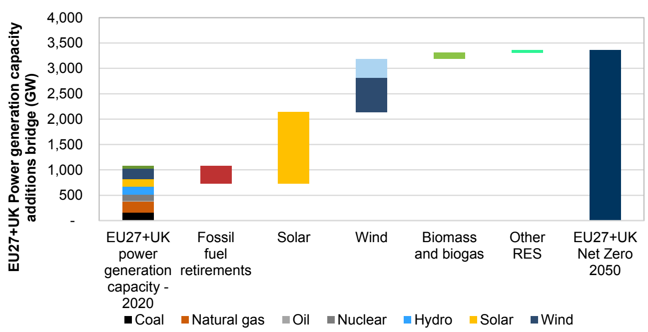
EU27+UK electricity generation mix (%)



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

Exhibit 48: ...and dominating capacity additions from here, with total installed renewable capacity reaching 3,000 GW by 2050..

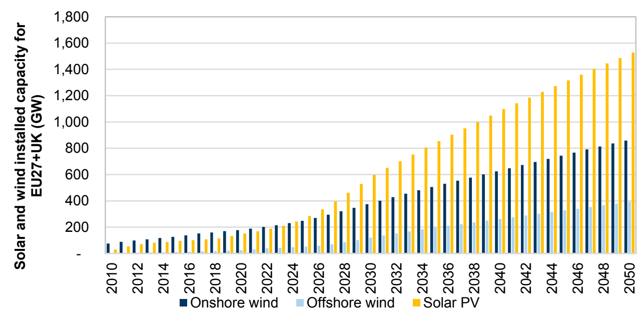
EU27+UK generation capacity additions bridge (GW)



Source: Eurostat (2020), Goldman Sachs Global Investment Research

Exhibit 49: ...driven predominantly by solar and wind (onshore and offshore)

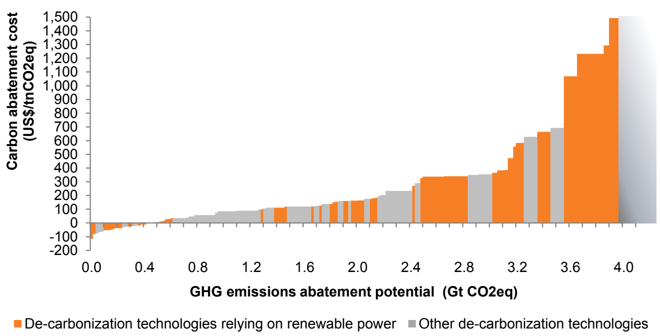
Solar pv and wind installed capacity for Europe (GW)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 50: Access to renewable power is the most critical de-carbonization component, being broadly vital for the de-carbonization of c.50% of the current European emissions

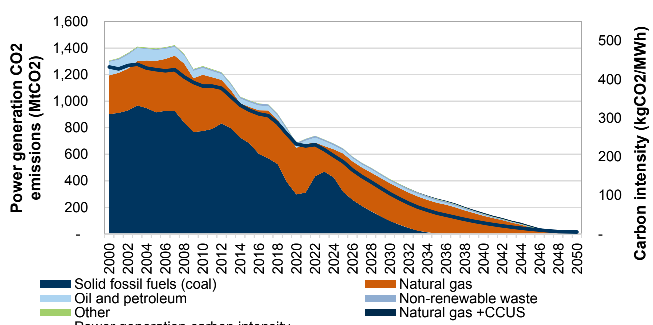
Europe (EU27+UK) GHG emissions de-carbonization cost curve with orange indicating technologies reliant on access to renewable power (clean electricity)



Source: Goldman Sachs Global Investment Research

Exhibit 51: Power generation emissions have been on a downward trajectory in Europe for most of the last two decades and we expect that to continue to 2050, despite the slowdown in 2022-23

Power generation CO2 emissions (LHS) and carbon intensity (RHS)



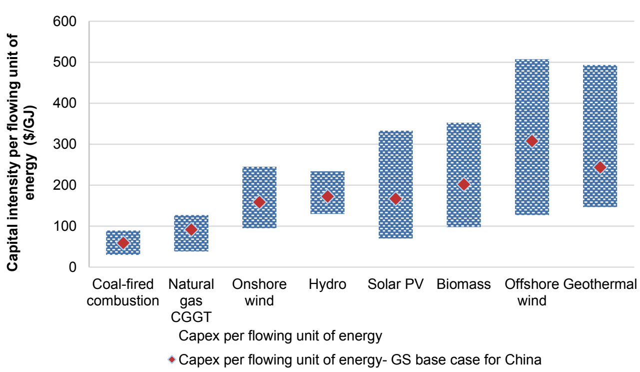
Source: Eurostat, Goldman Sachs Global Investment Research

The power generation investment opportunity: Higher capital intensity of renewable power and the rising importance of energy storage and networks infrastructure pave the way for a c.€6 tn investment opportunity

Earlier in this report, we highlighted the substantial potential investment creation opportunity associated with Europe's energy evolution path. Renewable power generation acts as a major contributor to this infrastructure investment opportunity (Exhibit 37). This is mainly attributed to the higher capital intensity of these technologies and their associated infrastructure, compared with traditional fossil fuel energy developments. In the exhibits that follow, we present the capital intensity (capex) per unit of output energy for each type of power generation technology. 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. However, **this does not necessarily translate into higher costs for the consumer, thanks to the availability of very cheap financing (under an attractive and stable long-term regulatory framework) and lower opex, compared with traditional hydrocarbon developments.** In fact, in the current commodity price landscape, **renewable power on aggregate improves the affordability of power.**

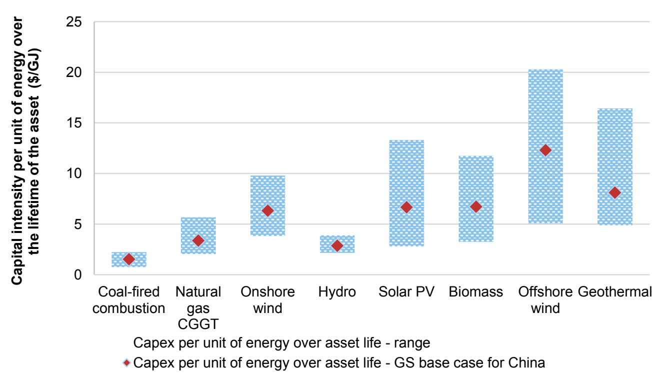
As the growth in renewable power accelerates, intraday and seasonal variability has to be addressed through energy storage solutions, as highlighted in an earlier section of this report. To reach full de-carbonization of power markets, we believe two key technologies will likely contribute to solving the energy storage challenge: **utility-scale batteries and hydrogen**, each having a complementary role. We incorporate both of these technologies in our model for Europe's energy evolution. **Energy storage and the need for extensive network infrastructure** is a particularly **important consideration as demand for power generation growth accelerates, to ensure a resilient global energy ecosystem.**

Exhibit 52: Renewable clean technologies in power generation have higher capital intensity compared with traditional fossil fuel sources, based on per flowing unit of energy...
Capex per flowing unit of energy (US$/GJ)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 53: ...and over the lifetime of the asset
Capex per unit of energy over the life of the asset (US$/GJ) for each technology



Source: Company data, Goldman Sachs Global Investment Research

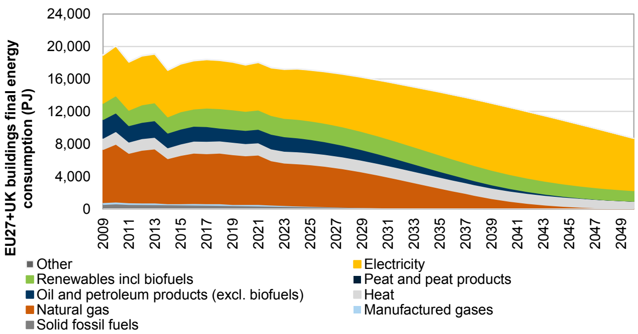
Buildings: Electrification and efficiency likely to govern the energy evolution path

Buildings, both residential and commercial (including services and public), account for c. 42% of the final energy consumption in Europe, with the energy mix currently dominated by electricity and natural gas (primarily for heating). Whilst the key technologies that govern the energy evolution and de-carbonization of buildings in the near and medium term are readily available, including electric heat pumps (air and ground source) and residential solar, geothermal, and bioenergy, the long lifespan of buildings makes the need for comparatively costly retrofits essential to achieve net zero emissions by 2050, particularly for residential buildings where the switch is largely reliant on consumer preference. As such, any aspiration for gross zero emissions in buildings has to come with the need for an accelerated pace of retrofits.

Our energy evolution model for Europe incorporates a step change in the **pace of acceleration of energy efficiency, as well as the flexibility of the stock and a shift away from fossil fuels**. The former can be achieved by a combination of measures, including the switch to best-available technology (BAT) across appliances with heat pumps in particular being very energy efficiency accretive (as shown in Exhibit 58), insulation (cavity wall, floor), automation and smart meters, and will largely be governed by underlying building codes and standards. The latter is largely dependent on the cost and availability of clean alternative technologies.

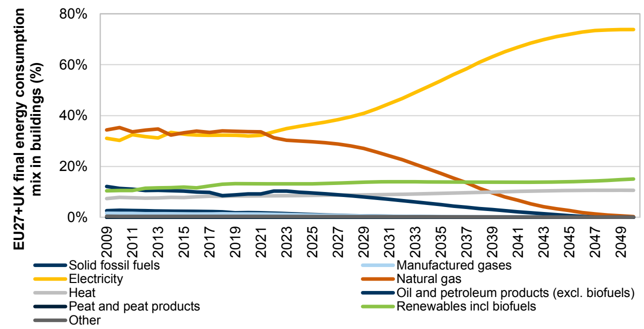
Overall, as shown in Exhibit 55, **electricity accounts for around one third of the total final energy consumption of buildings, and we expect its share to more than double, reaching c.74% by 2050**, whilst the share of direct renewable energy, such as residential solar, geothermal and bioenergy, is also increasing over time, reaching >15% by 2050. This implies, on our estimates, **more than 40 million heat pumps installed across Europe by 2030.** Increasing heat pump installations coupled with increased spending on efficiency and insulation contribute to **c.€1.6 trn of cumulative infrastructure investments for buildings in Europe** (mostly retrofits).

Exhibit 54: The current final energy consumption of buildings is dominated by electricity and natural gas consumption, each accounting for c.32%/34% of the final energy consumption across total buildings (residential, commercial/ services and public)..
EU27+UK Buildings final energy consumption (PJ)



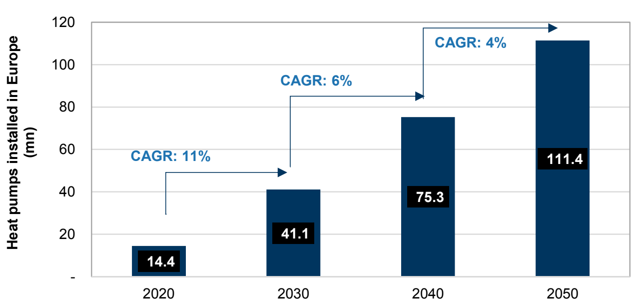
Source: Eurostat (historical), Goldman Sachs Global Investment Research

Exhibit 55: ...with electrification and direct renewables however dominating the energy mix longer term, each representing c.74%/15% of the mix respectively...
EU27+UK final energy consumption mix in buildings (%)



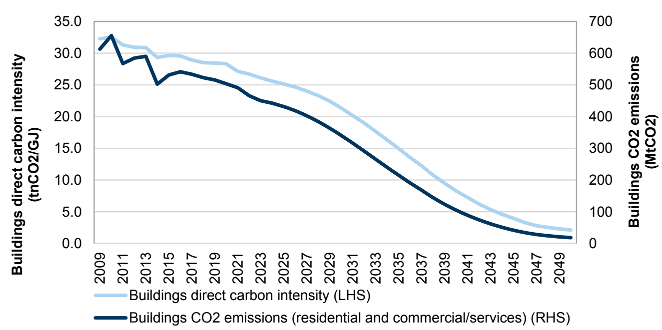
Source: Eurostat (historical), Goldman Sachs Global Investment Research

Exhibit 56: ..and heat pump installations surpassing 40mn by 2030 and 75 mn by 2040
Cumulative heat pumps installations (mn)



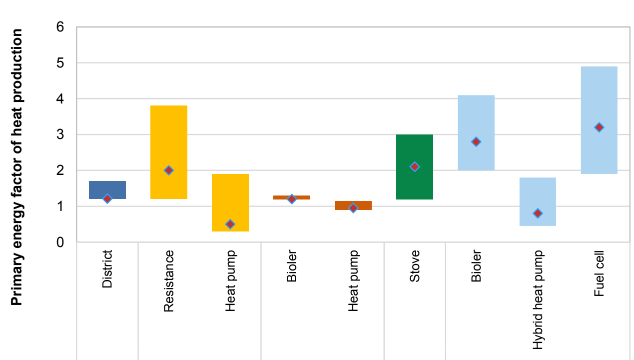
Source: EHPA, REHVA, Goldman Sachs Global Investment Research

Exhibit 57: Switch to electrification and accelerated efficiency improvements drive the buildings' carbon intensity and emissions lower
EU27+UK buildings' direct carbon intensity (LHS) and total direct CO2 emissions (RHS)



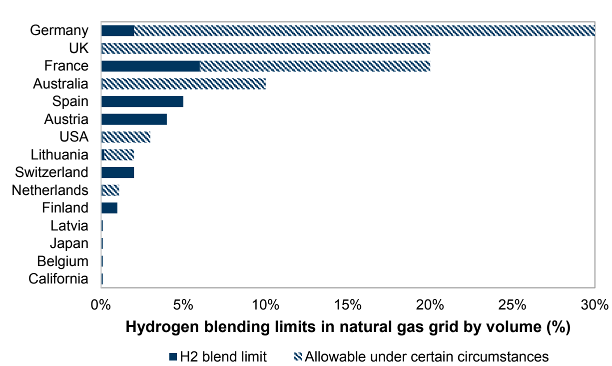
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 58: Heat pump technologies have a distinct advantage for buildings where they can be successfully deployed, given their relatively high efficiency (low primary energy factor)..
Primary energy factor of heat production across technologies and fuels



Source: IEA

Exhibit 59: ..yet the infrastructure investment and time it takes for a broad retrofit and adoption may prove to be a transition opportunity for blending hydrogen in the natural gas grid, subject to further testing and an upgrade of global hydrogen blending limits
Hydrogen blending limits in natural gas grid by volume (%)



Source: S&P Global Platts

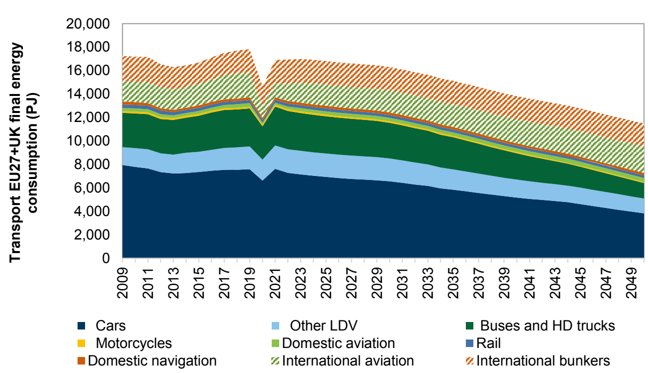
Transportation: The rise of NEVs and alternative fuels drive differing energy evolution profiles across transport modes

Transportation, in contrast to power generation, mostly sits in the 'high-cost' area of the de-carbonization cost curve, with the sector responsible for c.30% of the European final energy consumption and c.25% of the net European GHG emissions (excluding international bunkers and aviation). As part of our analysis, we lay out the energy evolution and de-carbonization path for Europe's transportation, as shown in Exhibit 60, addressing all key transportation modes: short and medium-haul road transport, heavy long-haul transport, rail, domestic aviation and navigation. We highlight that the speed of the energy transformation and de-carbonization varies depending on the transport mode, largely driven by the difference in costs and technological readiness of the available clean alternatives required for each sub-sector. Light-duty vehicles and rail (which is already largely de-carbonized through electrification) are the two transport modes with a faster relative de-carbonization, given the readiness and rising scale of the clean technologies for both (electrification). Conversely, aviation and shipping de-carbonize at a slower pace, given the still largely undeveloped or early stage development de-carbonization alternatives in both (sustainable aviation fuels, synthetic fuels, clean hydrogen and ammonia/methanol), which we expect to enjoy a large uptake in adoption and account for a notable part of the fleet only post 2030. We further address how the fuel mix of the energy consumption of transport evolves over time in our European energy evolution model and present the results in Exhibit 61.

Overall, electricity increases its share in total transport energy consumption to c.40% by 2050 (>60% if we exclude international transport). Bioenergy, clean hydrogen & hydrogen-derived fuels (synthetic fuels, ammonia/methanol) all emerge as important energy sources for transportation, particularly for shipping, aviation and heavy long-haul heavy transport (lorries).

Exhibit 60: In our European energy evolution model, we address the energy evolution of each transport mode...

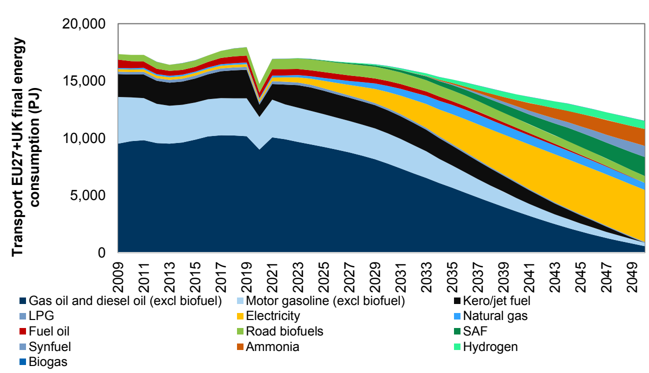
EU27+UK transport final energy consumption by transport mode (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

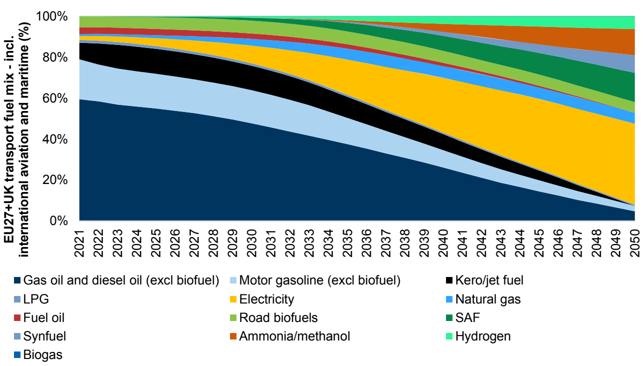
Exhibit 61: ...and of each fuel, including international aviation and shipping (where fuel demand stems from Europe)

EU27+UK transport final energy consumption by fuel (PJ)



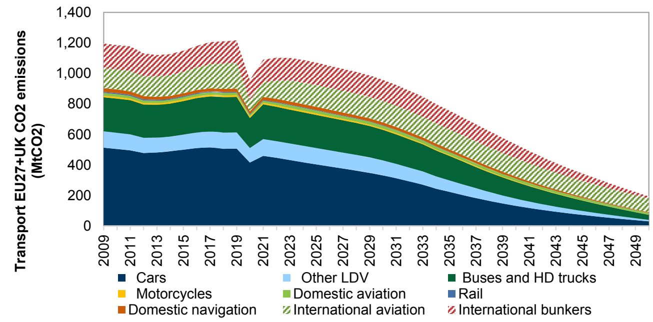
Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 62: Electricity, bioenergy, hydrogen and hydrogen-derived fuels (ammonia, synfuels, methanol) dominate Europe's transportation energy mix in the coming decades...
EU27+UK transport fuel mix - incl. international aviation and transport (%)



Source: Goldman Sachs Global Investment Research

Exhibit 63: ..and drive the required emissions reduction, mostly accelerating from 2030.
EU27+UK transport CO2 emissions (MtCO2)



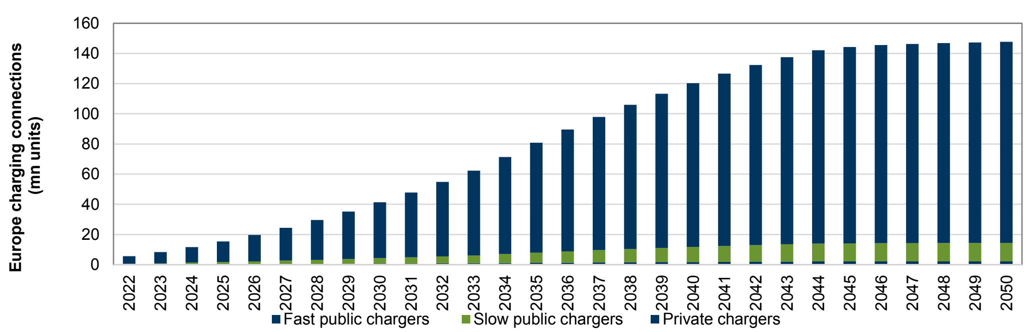
Source: Eurostat (EEA), Goldman Sachs Global Investment Research

We note that whilst fuel demand for international aviation and maritime bunkers (defined in a section earlier in this report) is not typically included in the definition of 'final energy consumption' but is rather part of 'gross available energy' for Europe, we include it in the exhibits which follow to provide a better overview of the ultimate transportation fuel demand stemming from the region (even if that fuel demand is ultimately used for international trip activities).

Charging and refueling infrastructure critical for the transformation of transport: We estimate a c.€0.6 trn infrastructure investment opportunity in Europe

The ability to facilitate the energy evolution of transport envisaged, with rapid uptick of electrification and alternative fuels, calls for substantial infrastructure investments, which we estimate at €0.6 tn cumulatively to 2050. This is imperative for the increasing number of public but also private chargers as well as alternative fuels refueling stations.

Exhibit 64: The energy evolution of transport requires on our estimates c.€0.6 tn in charging and refueling infrastructure investments
Charging connections for Europe (mn units)



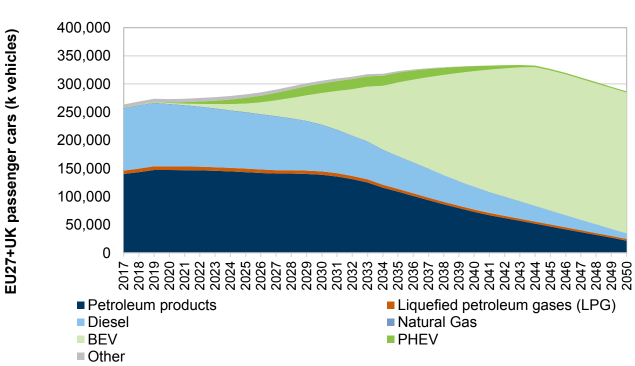
Source: Goldman Sachs Global Investment Research

Light-duty road transport vehicles: Electrification at the heart of the transport evolution

We believe road transport is at the start of its most significant technological change in a century, with electrification, autonomous driving and clean hydrogen at the core of the de-carbonization challenge. For light-duty vehicles (LDVs) transport (primarily constituting passenger vehicles, special purpose vehicles, motorcycles, commercial vehicles and short/medium-haul trucks), we consider **electrification the key de-carbonization technology.** Overall, we estimate that the total LDVs European road fleet (including passenger vehicles, short and medium-haul trucks) will increase c.5% by 2050 (from a 2019 base), with new energy vehicles – NEVs (including all of BEVs, PHEVs and FCEVs) reaching almost 100% penetration in the road transport fleet, as shown in Exhibit 67, for a path consistent with net zero emissions by 2050. Our modeling of the LDVs energy evolution for Europe is consistent with the region's ambitions laid out in 'Fit for 55', which had introduced EU-wide reduction targets for 2030 and set a **target of 100% carbon intensity reduction for car and van vehicle sales by 2035**. This implies all sales from 2035 (100%) in Europe will be NEVs and our models assumes >65% of new LDV sales will be net zero by 2030, as presented in Exhibit 66.

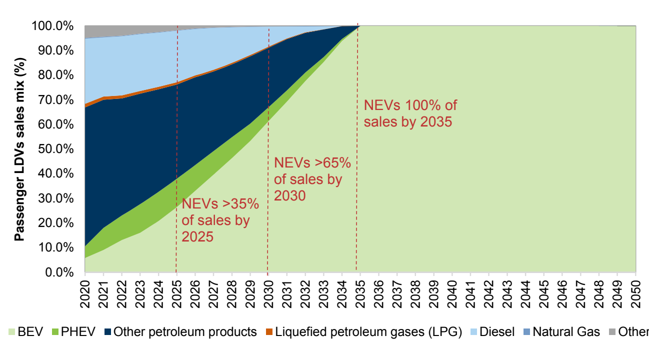
While we project considerable growth in pure battery vehicles in the ultimate de-carbonization solution for light road transport (essential for a net zero path), we expect multi-energy powertrain to also play a role in the facilitation of this transition, accounting for a considerable portion of sales and the fleet over the next 20 years. Multi-energy vehicles include plug-in hybrid EV (PHEVs), range-extended EVs, and light emission hybrid cars (HEVs). Overall, considering all NEV types, our net zero path requires a NEV penetration in the light-duty road transport fleet to reach >25% by 2030, close to >65% by 2040, and almost 100% by 2050. NEVs sales make up >35%/>65% and 100% of total LDV sales by 2025/30/35E respectively, effectively reaching zero carbon intensity in LDV sales by 2035, as shown in Exhibit 66. We primarily focus on the evolution of the fleet for the purpose of emission accounting in this analysis, with the fleet evolution reliant on both vehicles sales and retirements, as it is ultimately the penetration in the fleet that directly translates into transport emissions.

Exhibit 65: Europe's energy evolution model calls for a transformational shift in the mix of the LDVs fleet to 2050..
EU27+UK passenger LDVs fleet (k vehicles)



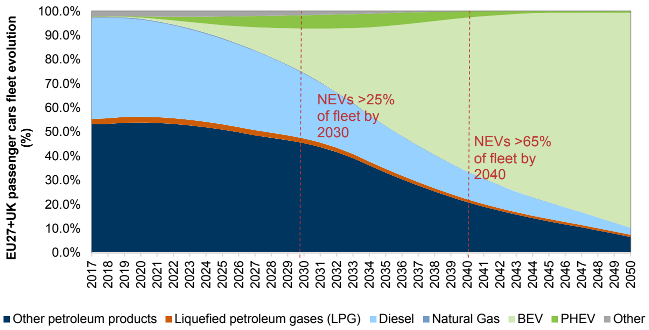
Source: Goldman Sachs Global Investment Research

Exhibit 66: ..with the share of NEVs in the sales mix reaching 100% by 2035 and >60% by 2030..
EU27+UK passenger LDVs sales mix (%)



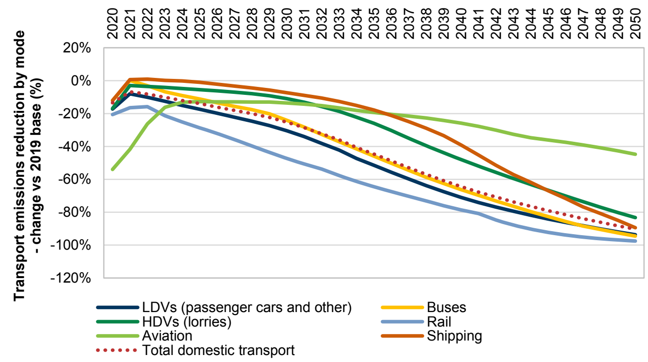
Source: Goldman Sachs Global Investment Research

Exhibit 67: ...and driving the transformation of the fleet with a c. 12-15 year delay given the replacement cycle of average vehicles.
EU27+UK passenger LDVs fleet mix evolution (%)



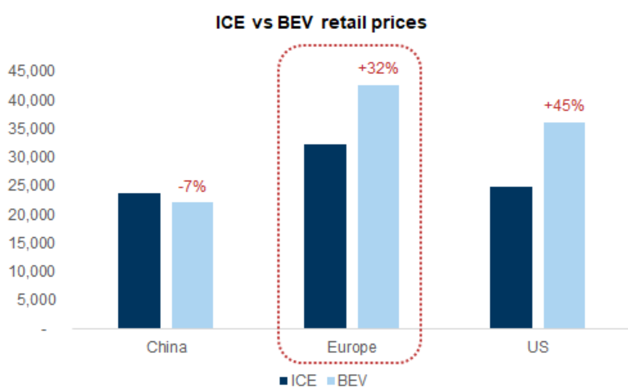
Source: Goldman Sachs Global Investment Research

Exhibit 68: LDVs and rail are achieving the most rapid energy transformation and de-carbonization relative to other transportation modes given the technological readiness and cost of the available technologies
EU27+UK transport emissions reduction by mode relative to the 2019 base (%)



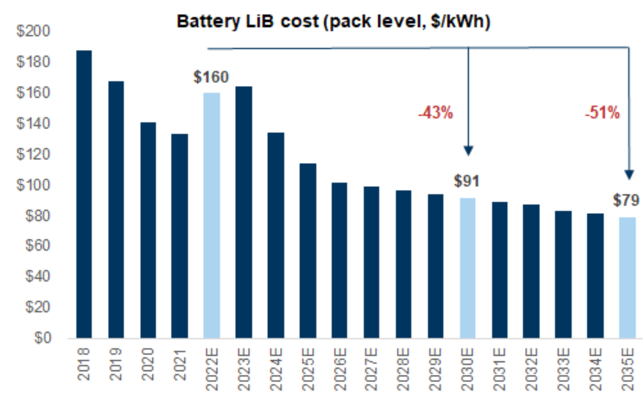
Source: Goldman Sachs Global Investment Research

Exhibit 69: Despite their de-carbonization and efficiency improvement potential, we note that in Europe, the average BEV retails for >30% more than ICE vehicles
Average retail price ICE vs BEV (€), 2021



Source: Goldman Sachs Global Investment Research

Exhibit 70: ..and we forecast a gradual improvement in battery cell costs will materialize post 2023



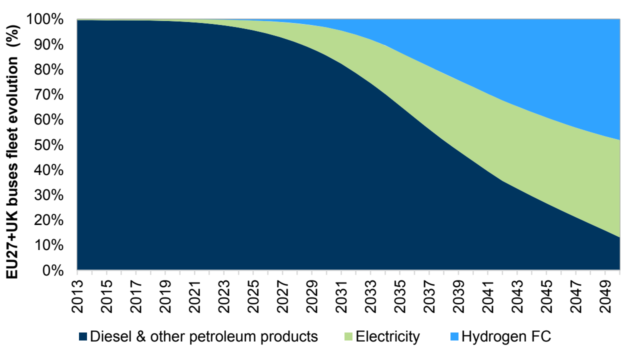
Source: Goldman Sachs Global Investment Research

Heavy-duty road transport: A comparatively smaller part of the European transport energy system with a more competitive landscape encompassing electrification, bioenergy and potential clean hydrogen

While we believe that electric vehicles screen as the most attractive de-carbonization solution for LDV applications, including short and medium-haul transport, we believe that the space becomes more competitive once we look to address heavier segments of the transportation market, primarily buses and lorries. We acknowledge however, that the share of heavy-duty transport in the case of Europe is comparatively small compared to light-duty given required mileage stoppage and recharging/refueling frequency. Nonetheless, we note that both bioenergy and clean hydrogen could be key competing technologies when long-haul heavy transport is considered (primarily lorries), given its high energy content per unit mass and shorter refueling time. Although the FCEVs (fuel cell electric vehicles) global stock was estimated (by IEA) to be around 25,000 at the end of 2019, owing to a limited product offering, non-competitive price points and little infrastructure, we see the recent policy drive towards de-carbonization as a reason to reconsider the potential for FCEVs. Despite small absolute volumes, the growth of FCEVs could accelerate notably, particularly in heavy long-haul transport applications, buses and forklifts.

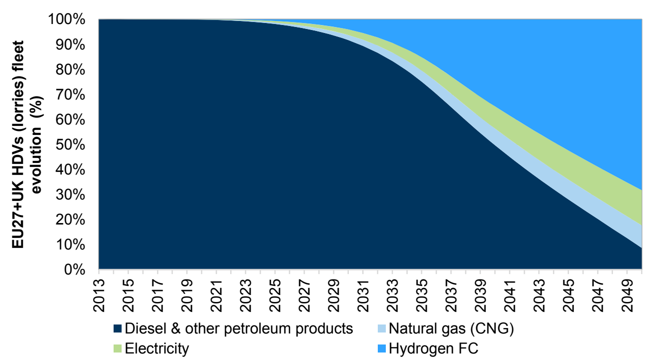
Overall we model considerable growth in both electric vehicles and FCEVs as the penetration of both overtakes internal combustion engine vehicles in the coming decades for buses and heavy-duty lorries, as presented in Exhibit 71 and Exhibit 72. However, the shift in the fleet mix for heavy-duty vehicles starts later than the transition in LDVs, given the lower product offering and the need for further technological innovation (in the case of long-haul large capacity batteries) and cost deflation (in the case of fuel cells).

Exhibit 71: We expect the evolution of the buses fleet in Europe to be dominated by electrification and clean hydrogen...
EUR27+UK buses fleet evolution (%)



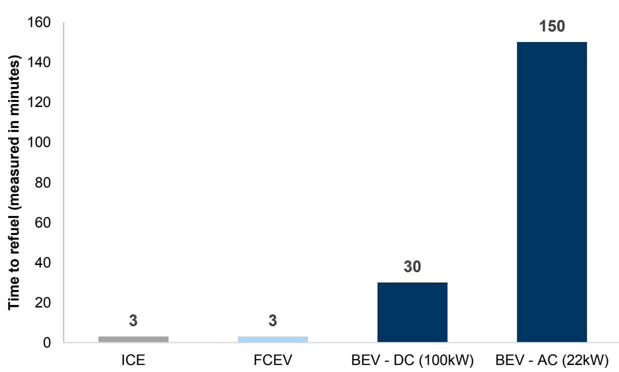
Source: Goldman Sachs Global Investment Research

Exhibit 72: ...with a similar trend observed in heavy-duty lorries, with a greater role for clean hydrogen in a more niche transportation end market in Europe
EU27+UK HDVs (lorries) fleet evolution (%)



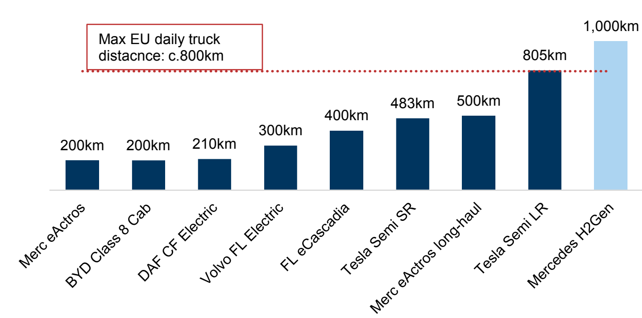
Source: Goldman Sachs Global Investment Research

Exhibit 73: Hydrogen outperforms significantly when we compare the refueling times of FCEVs versus BEVs at different kW charging ratings...
mins to refuel/recharge



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 74: ...and also provides a range advantage, particularly useful for long-haul truck applications
ZEV Class 8 trucks and range (km)



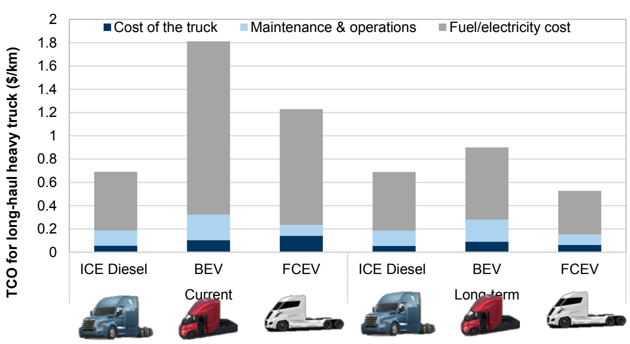
EU max daily driving time at 9 hours (assuming average speed of 90km/h)

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

In the exhibits below, we compare the total cost of ownership for ICE, BEV and FCEV, for heavy-duty long-haul trucks. As we look into heavy-road long-haul transport, we find the hydrogen proposition potentially competitive, with a TCO that is similar to that of BEV but benefiting from lower weight and faster refueling times. While both options remain more costly than conventional diesel ICE trucks, we expect technological innovation and cost deflation that generally comes on the back of economies of scale to reduce the costs of both technologies over time.

Exhibit 75: Long-haul heavy transport could be a new potential end market for hydrogen, with FCEV trucks becoming cost competitive, yet we note the share of long haul HDVs in European transport is relatively small

Total cost of ownership of a Class 8 truck (15 years assumed useful life)

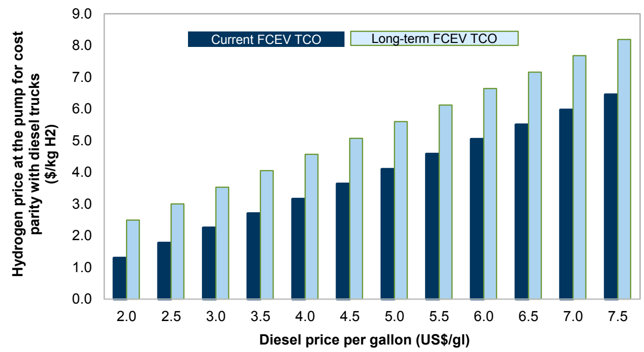


* Diesel price assumption of US$6.5/gl, retail power price assumption of $0.6/kWh ($0.4/kWh long-term), hydrogen price at the pump of $12/kg ($5/kg long-term)

Source: Company data, Goldman Sachs Global Investment Research

Exhibit 76: Longer term, we estimate a hydrogen price around US$4-4.5/kgH2 would be sufficient for cost parity with diesel (normalized diesel prices)

Hydrogen price at the pump required for cost parity with diesel



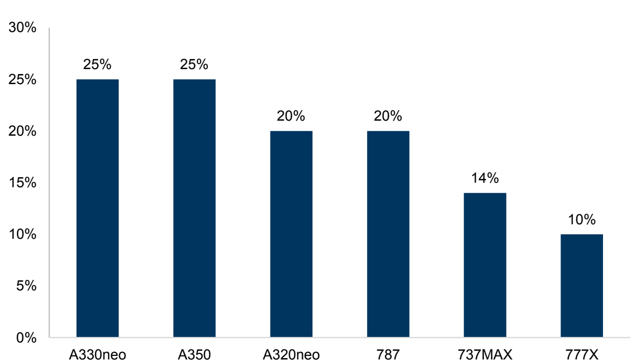
Source: Goldman Sachs Global Investment Research

Aviation & Shipping: Harder-to-abate sectors, with new generation aircraft/fleet renewal, sustainable aviation fuels (SAFs) and hydrogen-based fuels and new propulsion technologies paving the way for technological innovation and transformation

Aviation sits at the top of our Carbonomics cost curve for Europe, and is one of the toughest sectors to de-carbonize. We note that domestic aviation accounted for only c.2% of the total transport energy consumption for Europe; however, with the inclusion of international aviation, this share rises to c.14% (2019), making it an important and challenging part of the energy system to transform.

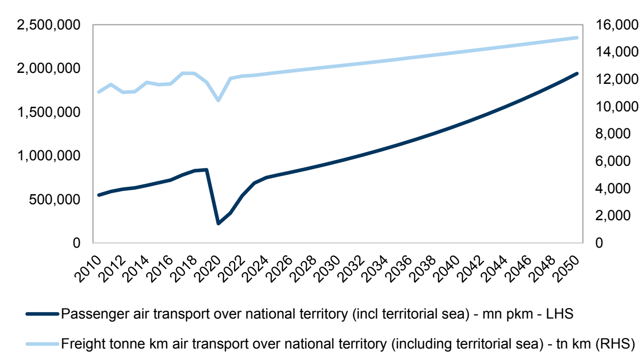
Sustainable aviation fuels (SAFs), synthetic fuels and improved aircraft efficiency are in our view all key parts of the solution. In the near term, we view the new generation of aircraft and fleet renewal as likely to achieve the lowest-cost aviation emissions abatement. New generation aircraft, which can burn c.15%-20% less fuel than their predecessors, currently have limited penetration across the global fleet, yet with fuel costs accounting for >30% of airlines fuel opex we believe the ongoing shift will accelerate in the coming years. Although lower investment capacity amid weakened balance sheets post Covid had resulted in aircraft deferrals, we do not expect medium- and long-term fleet renewal plans to change. From here, we see a gradual and ongoing improvement in aviation activity with efficiency an important pillar for the sustainability and ultimate energy demand progression of this sub-segment of transportation. Having said that, ultimately, in the medium and long term we expect the fuel switch from current kerosene and jet fuel into sustainable aviation fuel (SAF) and longer-term synthetic and other fuels to drive the most meaningful change in the energy evolution of the aviation industry in Europe, with the two fuels making up c.63%/37% of the mix longer term, respectively. Whilst the economics of SAF remain more challenging relative to traditional jet fuel at present, we note that the first leg of the energy switch will likely be driven by EU-wide blending mandates, with the ReFuelEU proposal incorporating the commencement from 2025 for 2% SAF, gradually increasing to 63% in 2050, consistent with our model.

Exhibit 77: The switch to more efficient aircrafts has the potential to lead to c.15%-20% fuel burn improvement...
Fuel burn improvement vs. previous generation as per company data



Source: Company data

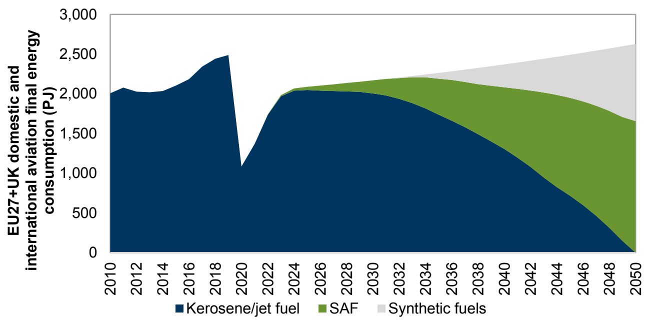
Exhibit 78: ...and is a key tool for the energy evolution of aviation in the near and medium term given the ongoing increase in activity we expect in the sector...
Aviation pkm and fuel consumption



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

Exhibit 79: ..but ultimately, fuel switch is necessary, with SAFs, synthetic and other fuels paving the energy evolution of aviation in the medium and long-term..

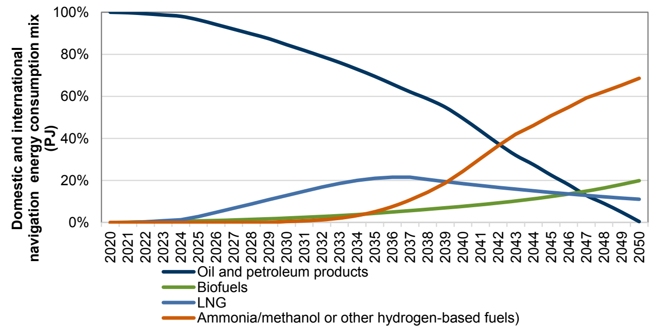
EU27+UK aviation (domestic and international) energy consumption (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 80: ..accounting for c.63%/37% of the aviation fuel mix respectively by 2050

EU27+UK aviation (domestic and international) energy mix evolution (%)

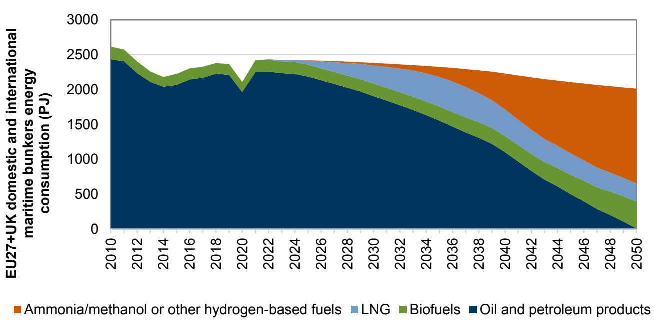


Source: Goldman Sachs Global Investment Research

Domestic navigation (covers the quantities delivered to vessels not engaged in international navigation) accounted for c.2% of the total European final energy consumption in transport, but similarly to aviation, considering also international marine bunkers, this share rises to c.11%. Shipping is another sector with hard-to-abate emissions given a lack of widespread adoption of the available low-carbon de-carbonization technologies at scale, and the relatively long operating life of vessels. Similar to aviation, we do not expect gross emissions in shipping to reach absolute zero in 2050, yet we do model a notable reduction in emissions, as alternative fuels become more widely adopted. Amongst these is liquefied natural gas (LNG), which, whilst not a zero-emitting fuel, can play a key role as a transition fuel for the shipping sector, as well as advanced biofuels, and clean hydrogen-derived fuels such as ammonia/methanol can play a larger role as the ultimate de-carbonization technologies for the sector. In our European energy evolution model, clean ammonia or alternative clean hydrogen-based fuels (such as methanol) account for c.69% of the total energy in shipping in 2050, sustainable biofuels provide c.20% of total shipping energy needs, with the remaining energy provided by LNG.

Exhibit 81: Fuel switching will be key for the energy evolution of maritime bunkers...

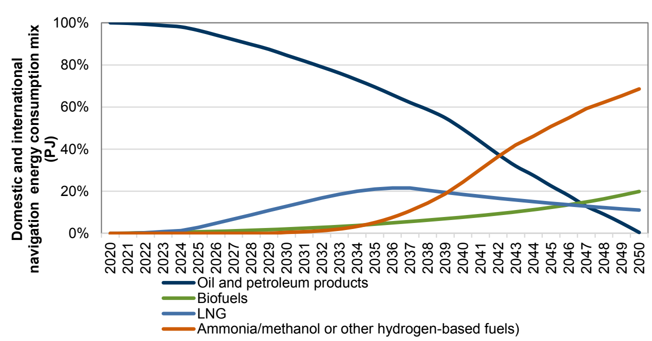
EU27+UK domestic and international maritime bunkers energy consumption (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 82: ..with clean ammonia/methanol, advanced biofuels and LNG all playing a role in the energy transition

EU27+UK domestic and international



Source: Goldman Sachs Global Investment Research

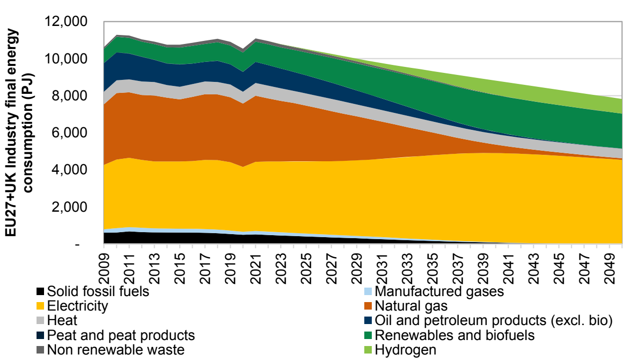
Industry: A new industrial technology revolution centered around efficiency, electrification, hydrogen, circular economy and CCUS

The industrial sector accounts for c.25% of Europe's final energy consumption, making it the third-largest energy consuming industry in the region (after buildings and transportation). The sector nonetheless contributes the highest European net GHG emissions, at c.33% in 2019. The industrial sector for the purpose of this analysis incorporates all of industrial combustion, industrial processes, waste and other fugitive emissions (including those associated with the extraction and refining of fossil fuels). While the exact split of all the different industrial sub-sector emissions is subject to uncertainty, with differences between sources, we estimate that c.50% of the European industry energy consumption stems from the key heavy industries as shown in Exhibit 85 (ferrous and non-ferrous metals manufacturing, non-metallic minerals such as cement and chemicals).

We believe European industry, similar to the transport and buildings sectors, will have to undergo a technological revolution on its path to net zero with the key levers of this transformation being energy efficiency, electrification, hydrogen, circular economy and CCUS (for sectors where an alternative energy source does not drive the complete abatement of emissions, such as in processes such as cement production). Overall, our model for European industry points to a long-term share of electricity of c.58%, direct renewables (renewable waste and bioenergy both in the form of biogas and biomass) c.24%, clean hydrogen c.10%, as shown in Exhibit 84, with the latter two (bioenergy and clean hydrogen) being vital for heavy industries where direct electrification is not possible given the high temperatures involved in these industrial processes.

Exhibit 83: We see energy efficiency, electrification, hydrogen, circular economy, bioenergy as key drivers of the energy transformation of European industry..

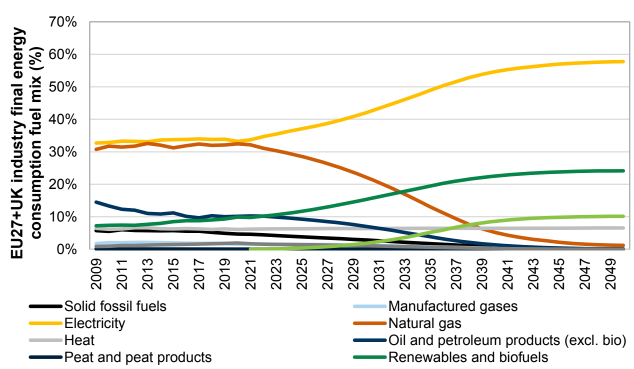
EU27+UK industry final energy consumption (PJ)



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

Exhibit 84: ..required to de-carbonize and diversify the energy of both low temperature conventional manufacturing processes but also heavy industry

EU27+UK industry final energy consumption fuel mix (%)



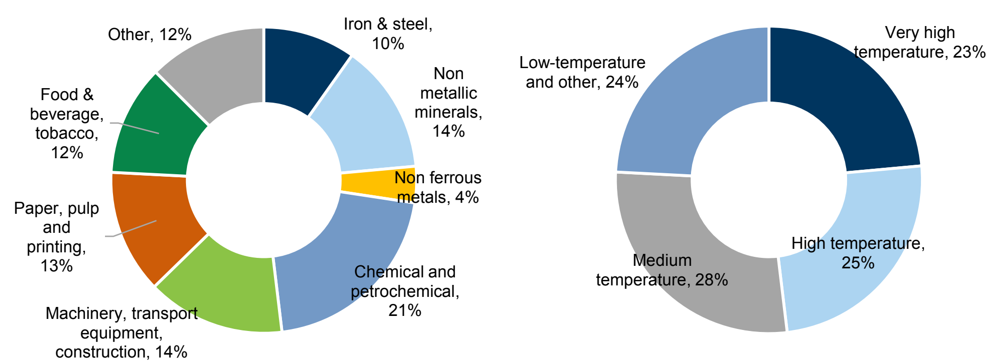
Source: Eurostat (historical), Goldman Sachs Global Investment Research

The energy evolution and technological mix of each sub-segment of industry will differ depending on the characteristics of the process involved, calling for the need of contributions from all of electrification, circular economy, efficiency, hydrogen, bioenergy, CCUS

The energy evolution of European industry will differ both in pace and in technological and fuel mix depending on the specific process and its characteristics. More broadly, European industrial energy consumption is split fairly evenly between low and medium temperature heat processes such as broader equipment manufacturing, and high temperature heat processes, primarily heavy industry such as iron & steel, non-metallic minerals and non-ferrous metals manufacturing, as well as petrochemicals, as shown in Exhibit 85. Whilst energy and material efficiency (including circular economy and waste management) will likely be relevant for all industrial sub-segments, we note that the dominant technologies and ultimate energy mix will differ for each type of industrial process. Overall, we view **electrification as likely to be the dominant source of energy for low temperature heat processes (such as broader equipment manufacturing)**, as those defined in Exhibit 85, whilst **molecular sources of energy including bioenergy, hydrogen and hydrocarbons retrofitted with carbon capture are likely to dominate high temperature processes** for which full electrification is not possible with existing technologies at scale.

Exhibit 85: European industry is split between low and high temperature processes, making the need for both electrification but also molecular energy sources for its de-carbonization and energy evolution

European industry final energy consumption split by sub-industry and type of process, 2019



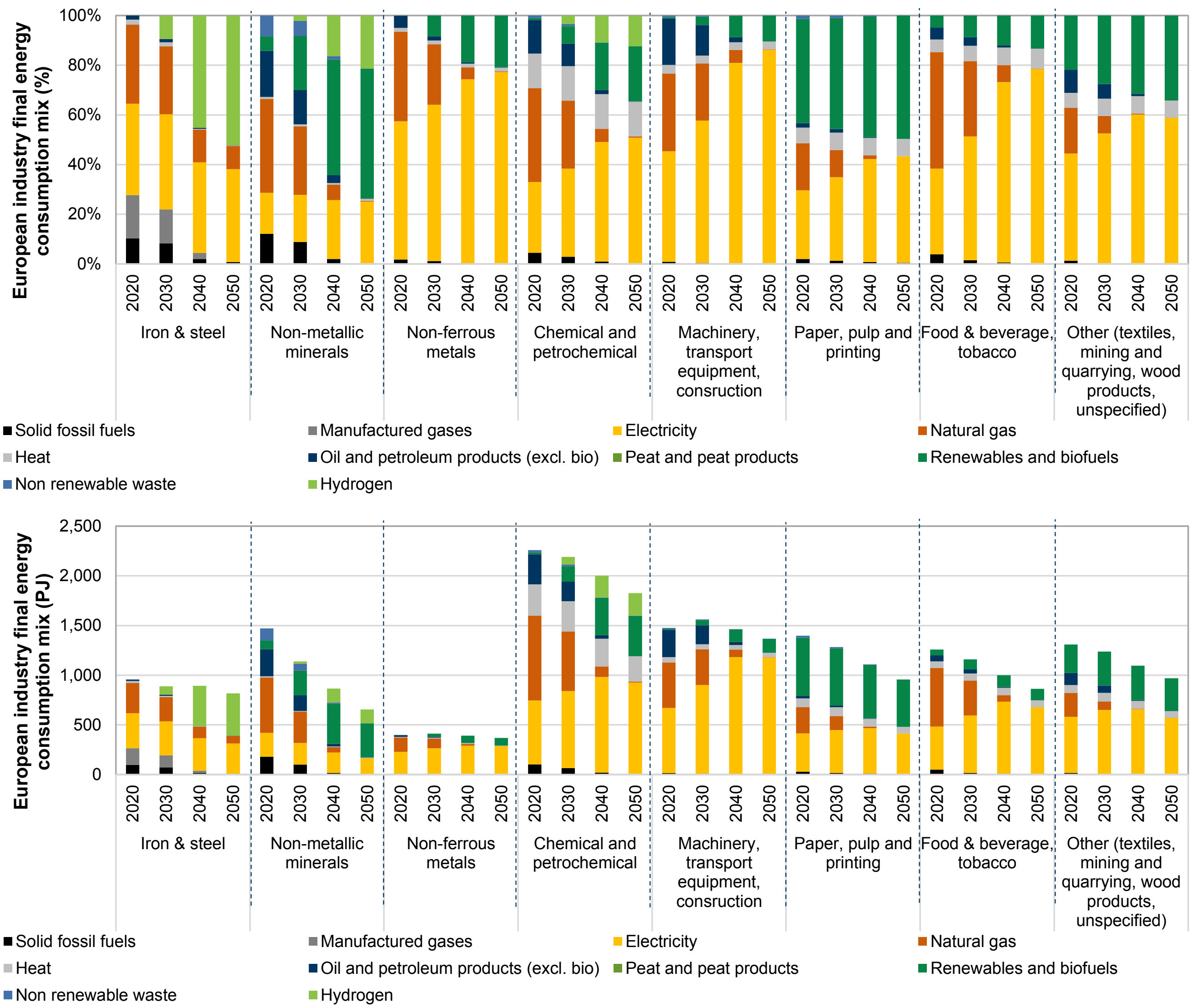
	Heat temperature	Examples of processes	Available clean technologies
c. 24%	**Very high-temperature heat >1,000 degrees**	Calcination of limestone for cement production Melting in glass furnace Reheating for slab in hot strip mill	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c. 25%	**High-temperature heat 400-1,000 degrees**	Steam reforming and cracking in petrochemicals (ammonia, methanol)	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c. 28%	**Medium-temperature heat 100-400 degrees**	Drying, evaporation, distillation activation Broader manufacturing	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity
c. 13%	**Low-temperature heat < 100 degrees and other unclassified**	Washing, rinsing, food preparation Broader manufacturing	Fossil fuels + CCUS Bioenergy Clean hydrogen Electricity

Applicable and currently available at large scale
Applicable but not yet at large scale
Not applicable

Source: Goldman Sachs Global Investment Research

Exhibit 86: The energy evolution of European industry differs depending on the specific process and its energy and heat requirements, with an ecosystem of energy sources and technologies required to address the full spectrum of processes

EU27+UK industry final energy consumption by sub-industry (% - top chart, PJ - bottom chart)

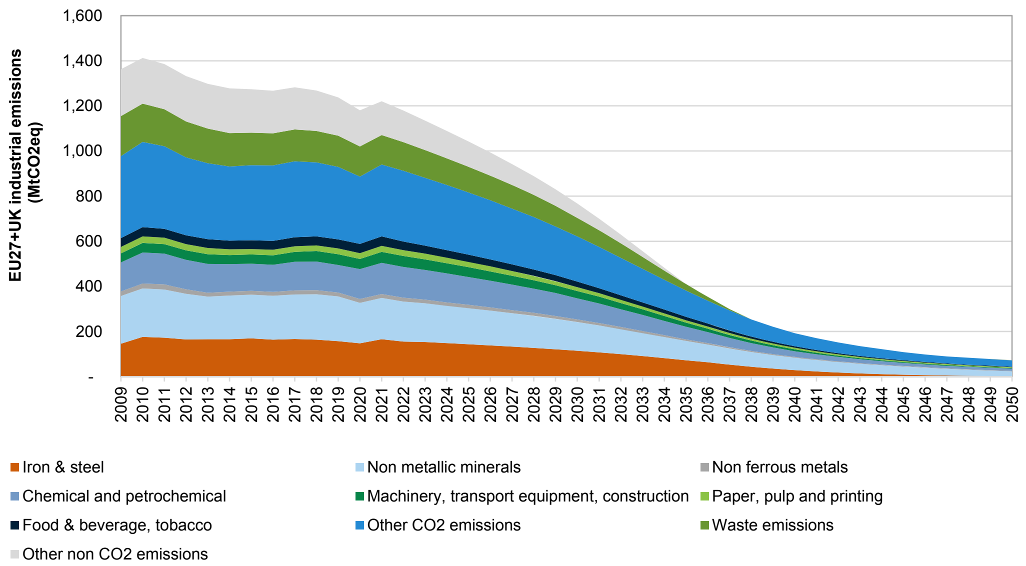


Source: Eurostat (historical), Goldman Sachs Global Investment Research

Overall, our European industry energy model is consistent with a notable acceleration of industrial GHG emissions reduction (including industrial combustion, processes, fugitive and waste emissions). We note nonetheless that gross industrial GHG emissions never reach absolute zero, given the harder-to-abate process emissions across key sectors, making the need for LULUCF (defined earlier in this report and including natural sinks) important for net zero for the region, consistent with the framework of emissions reduction suggested by 'Fit for 55'. The overall profile of European industrial emissions is presented in Exhibit 87, including fugitive and other waste emissions.

Exhibit 87: Industrial emissions stem from a very diverse range of sources and industries, requiring an ecosystem of de-carbonization technologies, including carbon offsets, to achieve net zero GHG emissions by 2050

EU27+UK industrial GHG emissions (MtCO2eq)



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

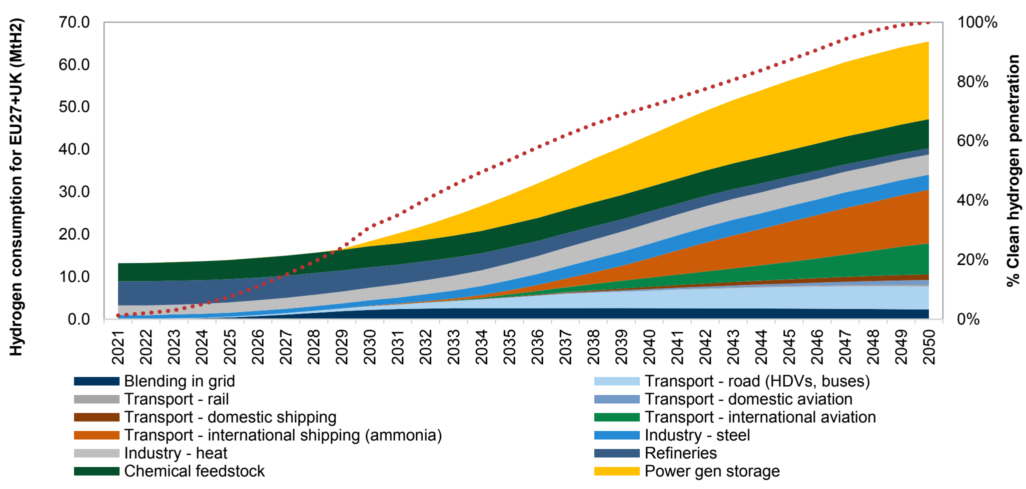
Europe's energy evolution and the need for molecular energy sources: Hydrogen and Bioenergy

As we have highlighted earlier in this report, we believe Europe's energy transformation and path to net zero calls for an evolution of the de-carbonization process from one dimensional (renewable power) to a multi-dimensional ecosystem. Whilst renewable power is the most critical part of the energy system we envisage (with c.50% of the de-carbonization of the region relying on access to clean power), we note that the nature of it poses two key challenges, intermittency and seasonality, **increasing the importance of molecular sources.** In this section of the report, we focus on **addressing the potential role and opportunity for the two molecular energy sources complementing renewable power: clean hydrogen and bioenergy.**

The rise of the European green hydrogen economy: Bridging the gap between energy sustainability and energy resilience

Hydrogen has a critical role to play in any aspiring energy evolution path which largely relies on the resilience of an increasingly electrified energy system dependent on renewable sources. Hydrogen has a wide range of applications across sectors including, but not limited to, its potential use as an **energy vector and storage (seasonal) solution that can extend electricity's reach, industrial energy source and industrial process feedstock** including its potential use in replacing coal in steel mills, serving as a building block for some primary chemicals and providing an additional clean fuel option for high temperature heat, and long-haul heavy transport. We estimate that clean hydrogen can constitute **c.15% of Europe's total final energy consumption with its addressable market, growing to c.66 Mtpa by 2050 in a scenario consistent with 'Fit for 55'.**

Exhibit 88: Our European energy evolution model sees total hydrogen demand increasing to c.66 Mtpa by 2050, with further potential upside from the 'REPowerEU' proposal
Hydrogen consumption for EU27+UK (Mtpa) and share of clean hydrogen (%)



Source: Goldman Sachs Global Investment Research

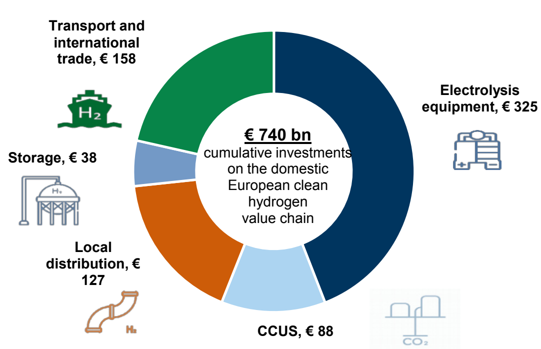
Furthermore, we believe recent geopolitical events have changed the EU's priority in relation to its energy policy, with the European Commission publishing the 'REPowerEU' plan outlining a set of joint actions to reduce Europe's dependence on Russian gas imports and unlock increased investments and reforms 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 and the proposal includes a **notable upgrade of the 'Fit for 55' target of 5.6 Mtpa** of renewable hydrogen by 2030 **to 20 Mtpa over the same timeframe** on a combination of locally produced and imported volumes. This **poses further upside potential for the technology than our European energy evolution model suggests (consistent with the 'Fit for 55' target).**

Clean hydrogen creates a c €0.74 trn cumulative investment opportunity for the direct domestic European clean hydrogen supply chain

Overall, our European energy path consistent with the 'Fit for 55' ambitions laid out for hydrogen calls for €0.74 tn of cumulative investments in the direct domestic European hydrogen value chain to 2050, even when accounting for c.50% of volumes being imported from neighboring regions. This figure captures investments in the direct supply chain of clean hydrogen, including investments required for its production (electrolyzers and CCUS for green and blue hydrogen, respectively), storage, distribution, transmission and global trade (regasification terminals). We note this is solely domestic European capex investments in the direct supply chain of clean hydrogen and does not include capex associated with end markets (industry, transport, buildings) or upstream capex associated with the power generation plants required for electricity generation for green hydrogen.

Exhibit 89: We estimate c.€0.74 tn of cumulative domestic European investments will be required in the clean hydrogen supply chain to 2050...

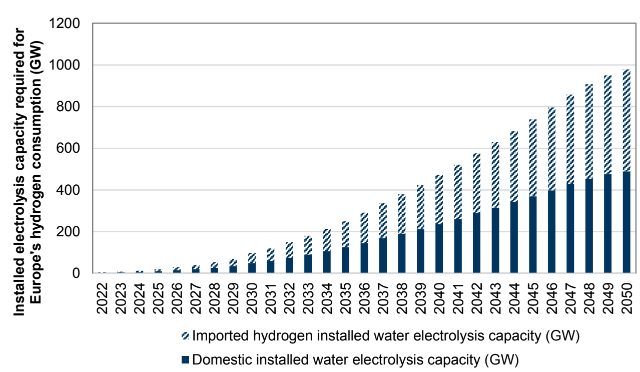
Cumulative investments in the domestic European clean hydrogen value chain to 2050 (EUR bn)



Source: Goldman Sachs Global Investment Research

Exhibit 90: ...with electrolysis capacity making up the largest share of these investments

Installed electrolysis capacity required for Europe's hydrogen consumption (split between domestic and that required for hydrogen imported volumes), (GW)



Source: Goldman Sachs Global Investment Research

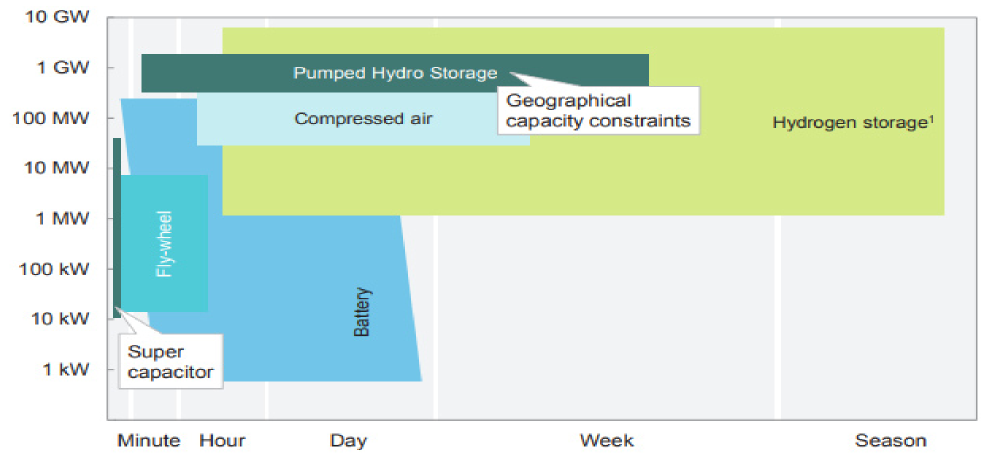
(1) Green hydrogen a key enabler of electrification, unlocking seasonal energy storage and having grid buffer capabilities

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 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 natural gas to be substituted with renewable power – especially solar power, which has opposite seasonality. As growth in renewable power accelerates, intraday and seasonal variability has to be addressed through energy storage solutions.

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 91. 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 91: 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

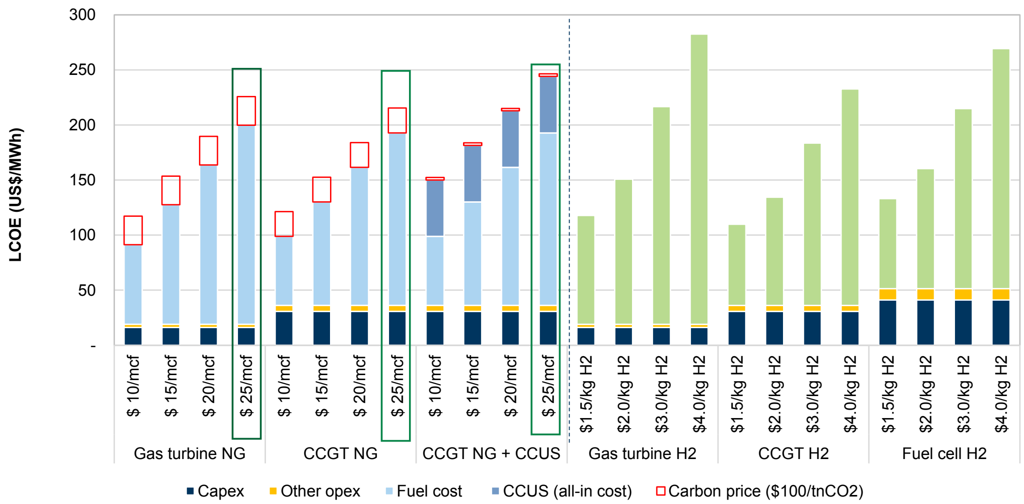


*1. As hydrogen or SNG

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$60/MWh).

Exhibit 92: 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: Goldman Sachs Global Investment Research

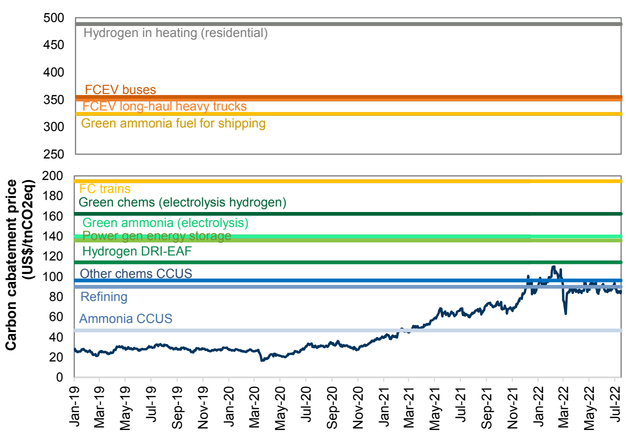
(c) Buffer, back-up and off-grid power supply: Hydrogen has valuable attributes that could make it a key solution for power generation system back-up as electrolysis can convert excess electricity into hydrogen during times of oversupply. The produced hydrogen can then be used to provide back-up power during power deficits or 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).

(2) Hydrogen is the natural successor of natural gas for diversification of energy supply in energy-intense industrial processes

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 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 industrial 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).

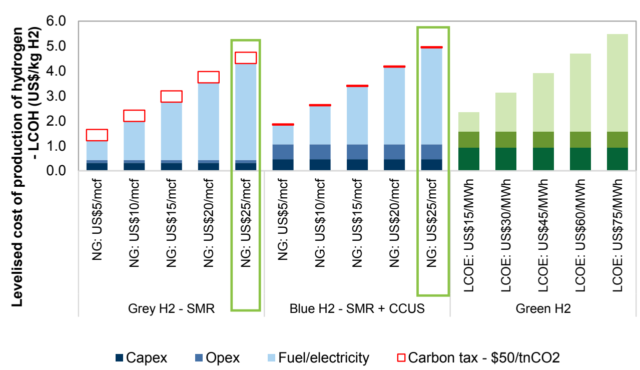
While green hydrogen's move towards cost parity with grey hydrogen is accelerating, and we expect this to be reached before 2030 across regions of low renewable power costs, **we note that the current macro environment of higher commodity prices, in particular for European natural gas, combined with carbon prices is creating a unique green hydrogen cost parity dynamic in Europe (as shown in Exhibit 94).** 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 well above US$50/tnCO2eq despite their correction from the peak. T**his 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 93: Whilst higher carbon prices are required at the point of use to encourage large-scale adoption and penetration of clean hydrogen in the hard-to-de-carbonize end markets (assuming normalized commodity prices)..
Carbonomics cost curve carbon abatement price (US$/tnCO2eq) for clean hydrogen applications



Source: Thomson Reuters Eikon, Goldman Sachs Global Investment Research

Exhibit 94: ..the current combination of carbon and commodity (natural gas) prices brings green (at LCOEs <$75/MWh) at cost parity with grey hydrogen in Europe at the point of production
Levelized cost of production of hydrogen - LCOH (US$/kg H2)

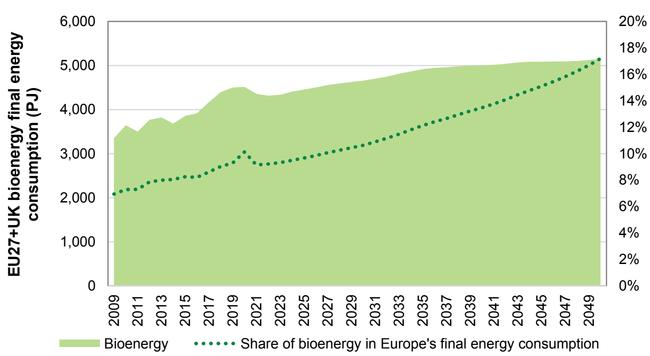


Source: Goldman Sachs Global Investment Research

Bioenergy: Biogas, advanced biofuels, renewable waste and biomass all have their key roles in the energy transition of specific industries

Bioenergy is already an important part of European energy consumption, mostly in the form of solid biofuels (primarily used in buildings and industry) as well as road biofuels blended in road transport. We see biogas, advanced biofuels (including both road biofuels and sustainable aviation fuel -SAF) as well as solid biofuels and RES waste as continuing to have an important role for Europe's energy system. As shown in Exhibit 95, we expect bioenergy and RES waste consumption in Europe to increase c.15%, with most of the increase driven by advanced biofuels (and in particular SAF) as well as biogas.

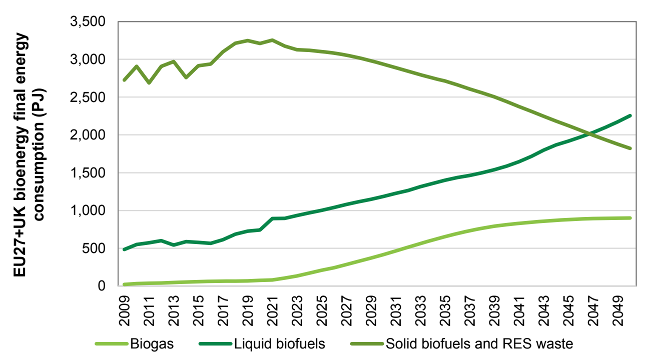
Exhibit 95: We expect European final bioenergy consumption to continue to increase from here on the path to net zero..
EU27+UK bioenergy final energy consumption (PJ)



*Including international aviation and international maritime bunkers

Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 96: ..primarily driven by growth in biogas and advanced biofuels (in particular SAF)
EU27+UK bioenergy final energy consumption split by bioenergy product (PJ)



*Including international aviation and international maritime bunkers

Source: Eurostat, Goldman Sachs Global Investment Research

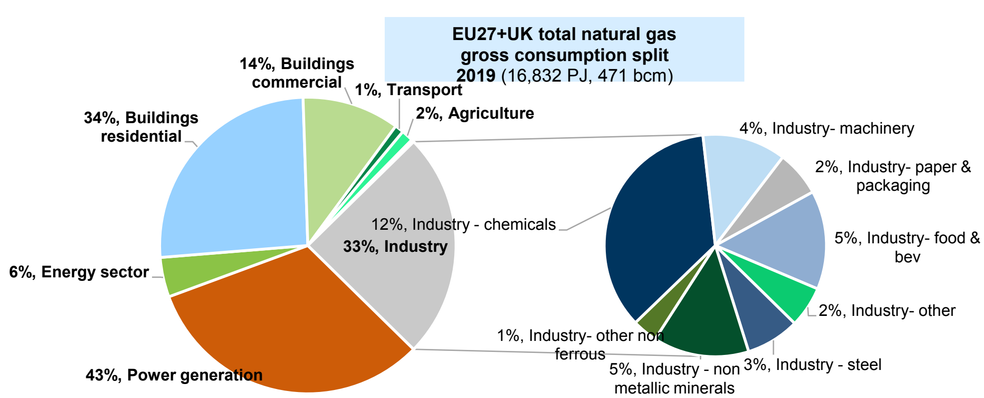
The role of hydrocarbons: Signing LNG contracts is consistent with Europe's de-carbonization ambitions and critical to its security and diversification of energy supply

Whilst Europe's energy transformation will undoubtedly 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. In this section of the report, we address the outlook and implications resulting from the energy consumption profiles for natural gas, oil and oil products and coal for the region, in light of the current geopolitical landscape and disruptions.

Natural gas: Remains key to Europe's energy supply for the next two decades with the potential for an additional 40 mtpa of 15-yr LNG contracts to improve security and diversification of supply

Whilst overall gross natural gas demand for Europe will gradually come down over time as the energy evolution of the European energy system unfolds, we note that natural gas remains a core part of the European energy system for another 20 years, being the most versatile energy source for the region with a broad use across applications (as shown in Exhibit 97). Despite its versatile consumption in the region across industries, the diversification of natural gas supply for Europe has been very low, with Europe importing c.83% (2019) of its gross natural gas needs and with that supply largely dominated by a handful of regions: Russia, Norway, Algeria, Nigeria, the US and Qatar. More importantly, **Europe's reluctance to sign long-term LNG contracts over the past years has resulted in an over-concentration of natural gas imports reaching the region via pipeline**. We believe that in light of the current geopolitical landscape and political disruptions this trend has to change.

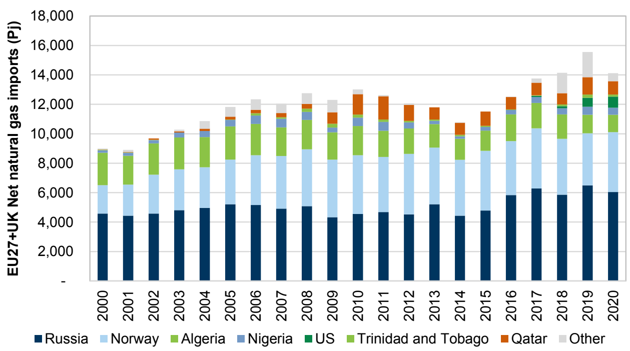
Exhibit 97: Natural gas is Europe's most versatile energy source, with its consumption in the region split amongst three key energy consuming sectors: power generation, buildings and industry (particularly heavy industry such as chemicals, steel, non metallic minerals and non ferrous metals)
EU27+UK total natural gas consumption split, 2019



Source: Eurostat

Exhibit 98: Despite the versatile use of natural gas and its core role for the European energy system, the imported supply has been largely concentrated in a few regions..

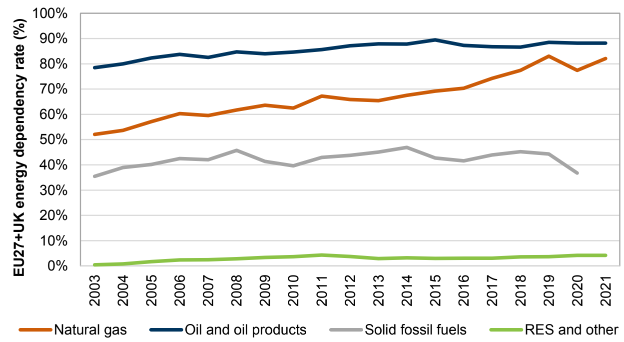
EU27+UK net natural gas imports by region (PJ)



Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 99: ..with the energy import dependency for the fuel trending upwards for the past two decades, more than any other energy source consumed by Europe.

EU27+UK energy dependency rate (%)

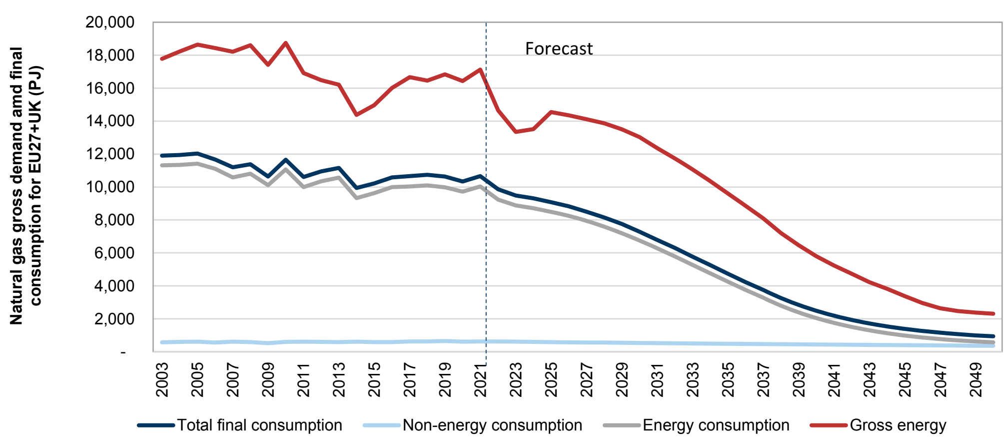


Source: Eurostat, Goldman Sachs Global Investment Research

Exhibit 100 presents our overall gross natural gas demand profile for Europe (EU27+UK). **Despite incorporating in our model an acceleration of the shift away from natural gas, particularly in industries where alternative existing technologies have available spare capacity,** such as coal in power generation, and also incorporating some degree of **natural gas demand rationing in gas intensive industries** (**yet not a large-scale industrial recession) for the near term**, **it becomes evident that demand for the fuel will likely persist for at least another two decades.** This is shown in Exhibit 100, with the reduction in the 2022-23 period incorporating our view of the currently feasible demand rationing in the absence of a large-scale industrial recession.

Exhibit 100: Natural gas remains a critical part of Europe's energy system for another two decades, even when incorporating some level of near-term rationing and acceleration of the shift away from it where technological readiness of alternatives is available.

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

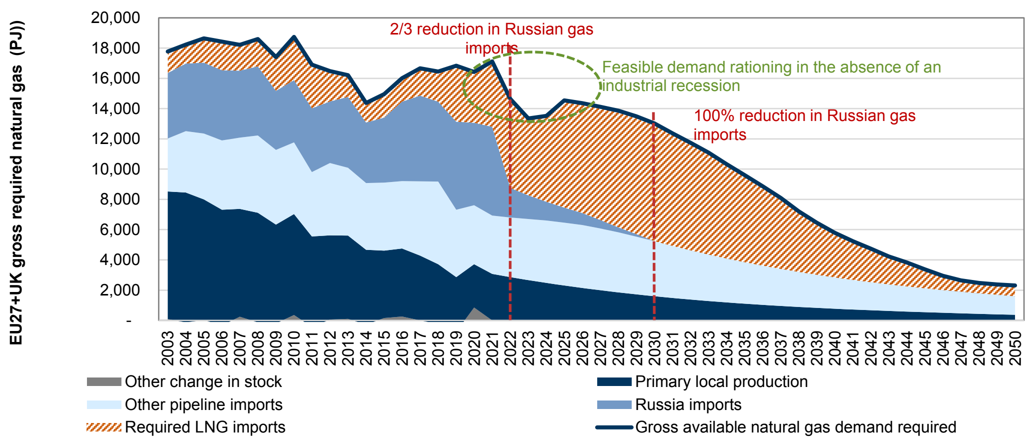


Source: Eurostat (historical), Goldman Sachs Global Investment Research

Overall, based on the natural gas demand profile that emerges as an output of our European energy model, **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), we conclude that the shortfall between gross natural gas demand and available domestic supply plus other ex-Russian imports has to be met with incremental LNG imported volumes, as shown in Exhibit 101. We believe it is in the EU+UK's interest to sign up to an additional 40 mtpa of 15-yr LNG contracts to improve security and diversification of supply, as shown in Exhibit 102 (and potentially up to another 50Mtpa of 10-yr LNG contracts).**

Exhibit 101: 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 has to be met with incremental LNG imports, potentially through 15-year LNG contracts

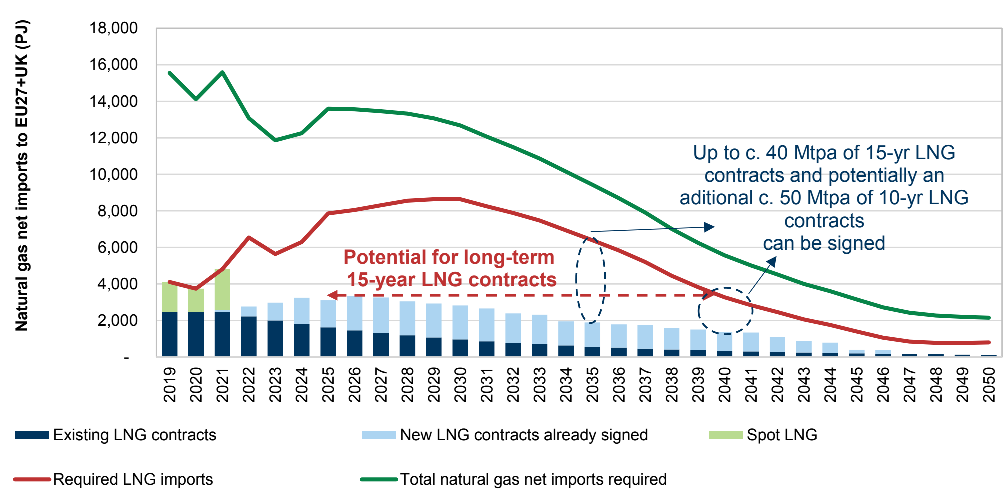
Natural gas gross energy demand vs domestic supply, pipeline imports and required LNG imports for EU27+UK (PJ)



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

Exhibit 102: We believe it is in the EU+UK interest to sign an additional 40 mtpa of 15-yr LNG contracts to improve the security and diversification of supply in natural gas

Natural gas net imports to EU27+UK (PJ)

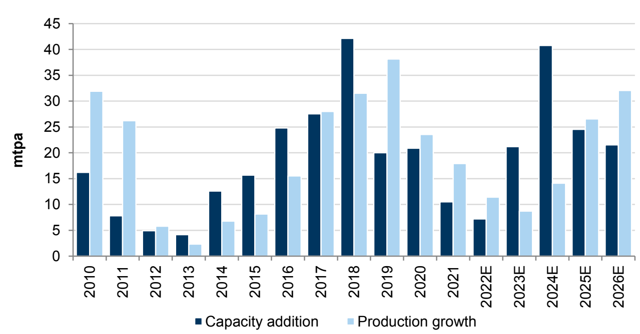


Source: Goldman Sachs Global Investment Research

The return of LNG with a strong pipeline of projects coming onstream economic at US$8-12/mcf which could aid Europe's energy security subject to the signing of necessary LNG contracts

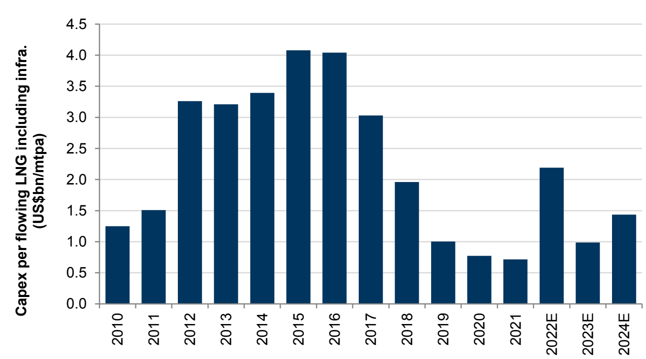
As we analyse in detail in our oil & gas sector deep-dive, Top Projects, the last two years have been characterized by capital discipline across the industry, with FID postponements and capital expenditure reductions as a result of COVID-19. Capex in 2021 remained at very low levels for the industry, 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. LNG benefits from a 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) with projects in Qatar, Canada and the US, among others, contributing to a significantly lower cost curve in 2022 vs 2014. There is a vast amount of LNG projects which could potentially be used to contract volumes to Europe, highlighted in Exhibit 105.

Exhibit 103: 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

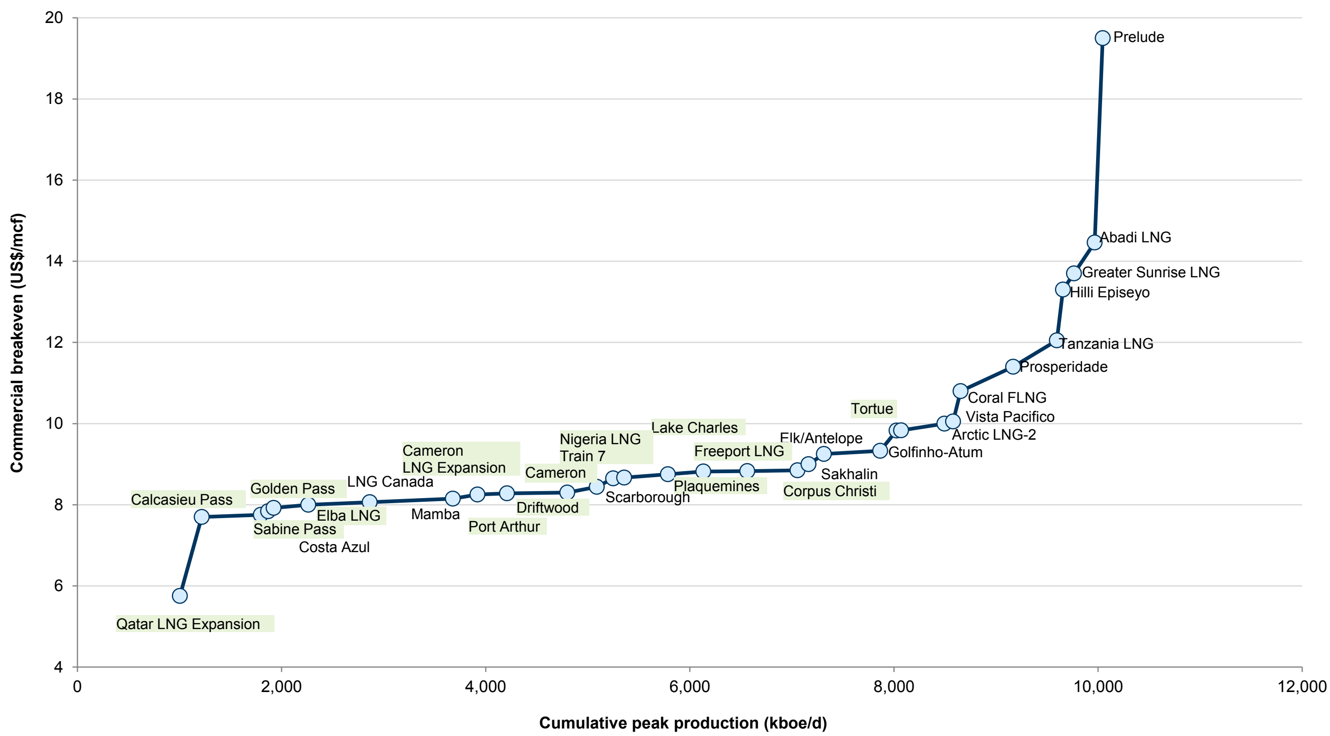
Exhibit 104: The new wave of LNG projects is coming at a very competitive cost relative to history.
Top Projects capex per flowing LNG output, US$ bn per mtpa



Source: Goldman Sachs Global Investment Research

Exhibit 105: There is a vast amount of LNG projects which could potentially be used to contract volumes to Europe, as highlighted in the exhibit below

Commercial breakeven by project (US$/mcf)

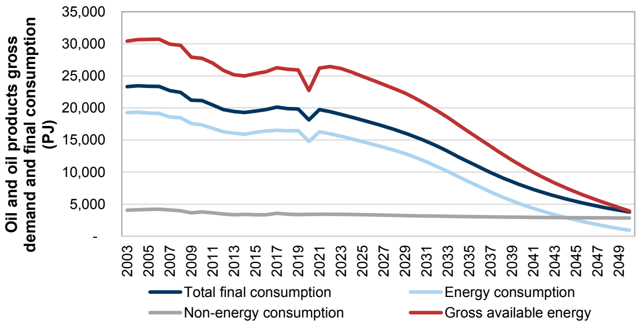


Source: Goldman Sachs Global Investment Research

Oil and petroleum products: Demand decline acceleration post 2030 with the next major refinery closures cycle only coming around 2027

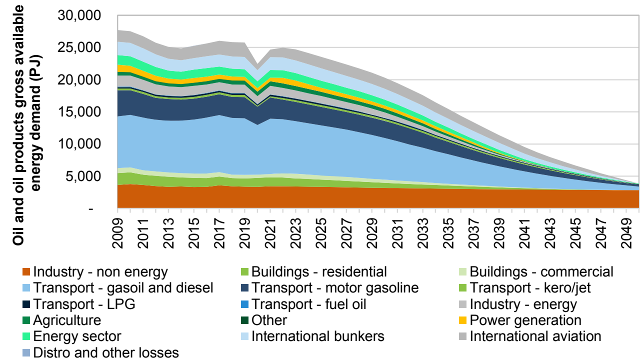
Our European energy system evolution model shows oil demand only increasing to the middle of this decade, largely driven by the ongoing recovery of covid-led reduction in transport (particularly aviation) and its higher share in the near term (2022-23) across applications where it can flexibly substitute natural gas with existing available capacity, as shown in Exhibit 106, **before starting a gradual decline which accelerates post 2030,** driven by the higher penetration of EVs and better charging infrastructure. It's worth noting, however, that oil demand does not reach absolute zero by 2050, given its uses in non-energy consumption applications, such as a feedstock for chemicals manufacturing, as shown in Exhibit 107.

Exhibit 106: European gross oil and oil products demand peaks by the middle of this decade with the decline accelerating post 2030..
EU27+UK oil and oil products gross demand and final consumption (PJ)



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

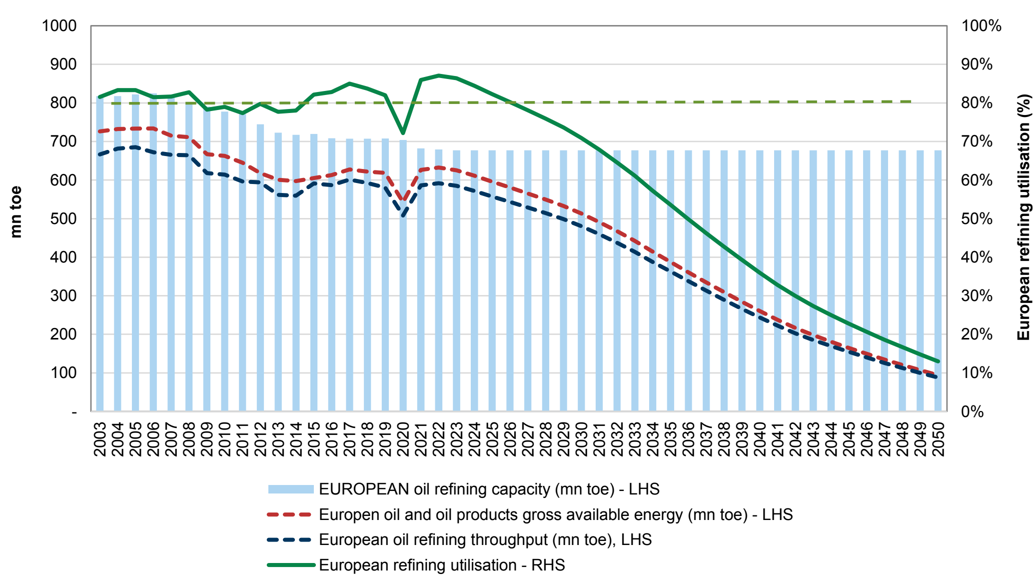
Exhibit 107: ...but never reaches absolute zero given its use in non-energy applications, primarily as a feedstock for chemicals manufacturing.
EU27+UK oil and oil products gross available consumption split by sector (PJ)



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

Based on our European energy model and resulting oil and oil products demand profile, in this section of the report we address the timing of the next potential major cycle of refinery closures for Europe. Overall, **we estimate that the next major cycle of refinery closures in Europe will only be needed by 2027, as shown in Exhibit 108, where the refining utilisation rate falls below the historical average European utilisation rate of c.80%.** For the purpose of this analysis, we only incorporate in the European (EU27+UK) capacity profile the already announced capacity closures for the coming years.

Exhibit 108: Based on our European energy model and resulting oil and oil products demand profile, we estimate that refining closures will likely be required around 2027, when the implied utilisation falls below the European historical utilisation rate average (c.80%)
European refining capacity, throughput, oil and oil products gross demand (LHS) and utilisation rate (RHS)

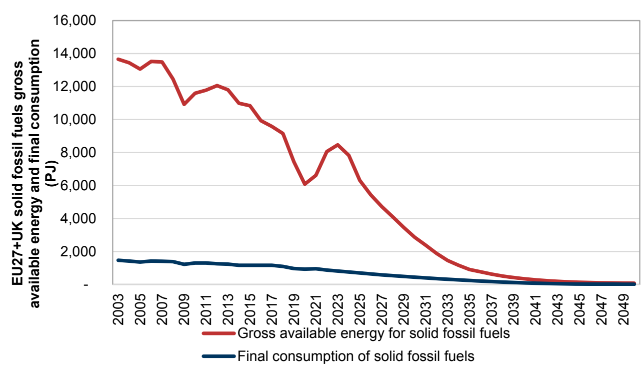


Source: BP Statistical Review, Goldman Sachs Global Investment Research

Coal: Near-term revival driven by power generation does not derail long-term structural decline

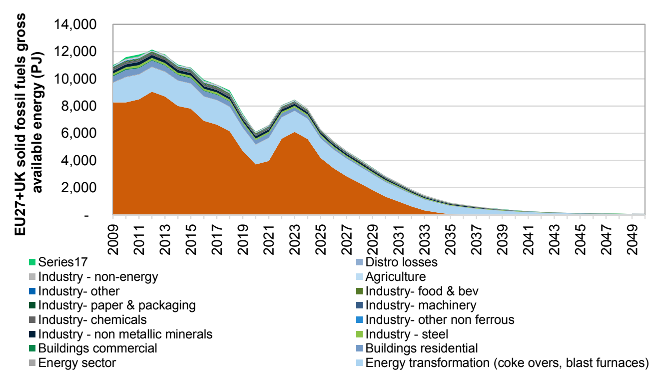
The gross demand for solid fossil fuels in Europe has been in structural decline for the past two decades on aggregate, as shown in Exhibit 109, and whilst we expect this to continue in the medium and long term, we note that in the near term (2022-23), solid fossil fuels (ie. coal) will potentially go through a short revival in order to support Europe's energy security. Specifically, we assume most of the natural gas demand switch in the near term occurs in power generation, the only key natural gas consuming sector with available spare capacity in other technologies such as coal which can provide near-term relief to some extent. Nonetheless, we do not expect the structural decline trend to reverse permanently, and we see the fuel returning to an accelerated structural decline thereafter. The impact of the near-term revival on Europe's de-carbonization path will likely be small, with the region still able to achieve the ambitions laid out in 'Fit for 55' based on our model.

Exhibit 109: Consumption of solid fossil fuels has been in structural decline in Europe for the past two decades, a trend we expect to continue long term..
EU27+UK solid fossil fuels gross demand and final consumption (PJ)



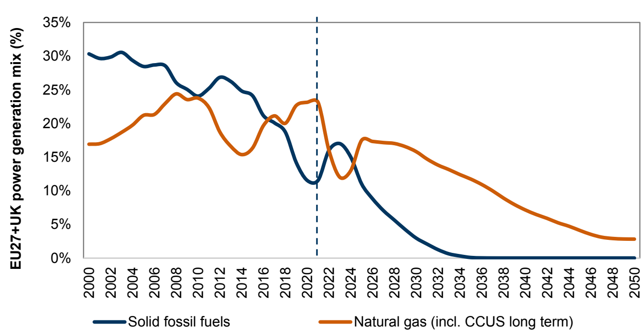
Source: Eurostat (historical), Goldman Sachs Global Investment Research

Exhibit 110: ..despite the near-term revival of the fuel in power generation,
EU27+UK solid fossil fuels gross energy demand (PJ)



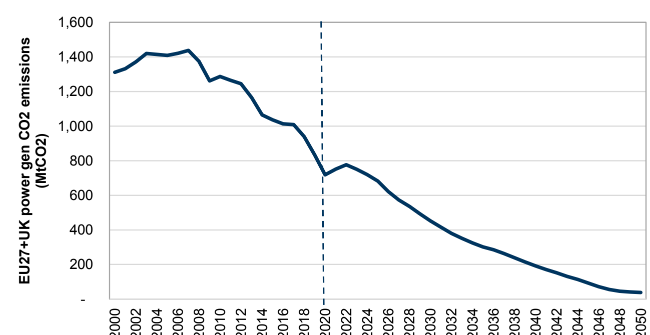
Source: Eurostat (historical), Goldman Sachs Global Investment Research

Exhibit 111: ..required to aid the energy security challenge facing Europe in light of the recent geopolitical natural gas disruptions...
EU27+UK power generation mix (%)



Source: Eurostat , Goldman Sachs Global Investment Research

Exhibit 112: ...which, whilst derailing the emission reduction profile in the sector by c.2 years, does not pose a material risk to Europe's climate ambitions based on our model
EU27+UK power generation CO2 emissions (MtCO2)



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

Appendix: Glossary of key terminology terms

Terminology used in this report	Definition
Gross available energy	**Gross available energy** is defined as the overall supply of energy for all activities on the territory of the European region considered in our analysis (EU27+UK). It includes energy needs for energy transformation (including generating electricity from combustible fuels), support operations of the energy sector itself, transmission and distribution losses, final energy consumption (industry, transport, households, services, agriculture) and the use of fossil fuel products for non-energy purposes (e.g. in the chemical industry). It also includes fuel purchased within the country that is used elsewhere (e.g. international aviation, international maritime bunkers). **Gross available energy for the total of all products (fuels) is the most important aggregate in energy balances and represents the quantity of energy necessary to satisfy all the energy demands.** Its interpretation for individual products (fuels) is varying and needs to take into consideration other parts of energy balances. ***Gross available energy = Primary production + Recovered & Recycled products + Imports – Export + Stock changes***
Final energy consumption	The final energy consumption is the total energy consumed by the end users in each of the energy consuming sectors (buildings, transport, industry, agriculture and other), the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.
International maritime bunkers and aviation	**Bunkers** includes all dutiable petroleum products loaded aboard a vessel for consumption by that vessel. **International maritime bunkers** describe the quantities of fuel oil delivered to ships of all flags that are engaged in international navigation. It is the fuel used to power these ships. International navigation may take place at sea, on inland lakes and waterways, and in coastal waters. International maritime bunkers do not include fuel oil consumption by: (a) ships engaged in domestic navigation; whether a vessel is engaged in domestic or international navigation is determined only by the ship's port of departure and port of arrival - not by the flag or nationality of the ship; (b) fishing vessels, (c) military forces.
Energy dependency rate	The **energy dependency rate** shows the share of energy that an economy is net importing. It is defined as net energy imports divided by gross available energy, expressed as a percentage. A negative dependency rate indicates a net exporter of energy while a dependency rate in excess of 100% indicates that energy products have been stocked. It can be defined for all products total as well as for individual fuels (for example: crude oil, natural gas).
Energy intensity	**Energy intensity** is one of the indicators to measure the energy needs of an economy and is often used as a proxy for energy efficiency. Many factors influence energy intensity. It reflects on structure of economy and its cycle, general standards of living and weather conditions in the reference area. Energy intensity is calculated as units of energy per unit of GDP.
LULUCF	The **LULUCF (Land Use, Land Use Change and Forestry)** sector is used to report the CO2 flows between different terrestrial reservoirs (biomass, soils, etc.) and the atmosphere that take place on the managed surfaces of a territory. It can thus constitute a net source or a net sink of CO2. This sector, defined within the framework of national greenhouse gas emission inventories, reflects in particular emissions and absorptions linked to land use (growth, biomass mortality and wood removal in forests; impacts of changes in agricultural practices on cultivated soils, etc.) and to changes in land use (deforestation, afforestation, soil artificialisation, etc.). The methods for calculating these emissions and removals are defined by the Intergovernmental Panel on Climate Change (IPCC), under the United Nations Framework Convention on Climate Change (UNFCCC).

Disclosure Appendix

Reg AC

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