CFA Institute
Research & Policy Center

Carbonomics: The Economics of Reaching Net Zero

CARBONOMICS: THE ECONOMICS OF REACHING NET ZERO

Michele Della Vigna, CFA
Managing Director and Head of Natural Resources Research in EMEA, Goldman Sachs Bank Europe SE, Milan

Yulia Bocharnikova
Associate, Goldman Sachs International, Dubai

Anastasia Shalaeva
Analyst, Goldman Sachs International, Dubai

Quentin Marbach
Analyst, Goldman Sachs International, London

In the last few years, many challenges have emerged on the path to net-zero carbon. Three of them are (1) direct hydrocarbon subsidies reaching $1 trillion in 2022, 4× the six-year average; (2) coal consumption resuming an upward trend; and (3) the nationally determined contributions (NDCs) still needing an extra 54% reduction of estimated 2030 CO_2 equivalent emissions to remain on track for 1.5°C. The impact of technological innovation, however, leaves room for optimism. By analysing more than 100 different applications of decarbonization technologies across all key emitting sectors globally, we arrive at five key conclusions. (1) We identify a re-emergence of cost deflation and improved affordability in some key technologies, such as solar panels and batteries. (2) The decarbonization of transport becomes 30% cheaper as batteries resume their deflationary trend. (3) The impact of higher interest rates on the overall cost curve is actually limited, although it is material for the carbon abatement cost in the renewable power sector. (4) Policy remains supportive, and we identify $500 billion of project announcements driven by the Inflation Reduction Act, which has reduced the decarbonization cost curve in the United States by 75% according to our estimates. (5) Bio-energy continues to grow its role, with renewable natural gas and sustainable aviation fuel gaining momentum in heavy transport, industry, and buildings.

Carbonomics Cost Curve

The Carbonomics cost curve—or carbon abatement cost curve—models the cost of achieving net-zero carbon emissions across more than 100 decarbonization technologies. The Carbonomics cost curve serves as a critical tool in the global effort to mitigate climate change by indicating the carbon price associated with a low-carbon technology that would make this technology affordable and in the money. Today, the lower part of the cost curve is still dominated by power generation or nature-based solutions, while industry and transport remain more expensive to decarbonize. For instance, electric vehicle incentives typically have an implied CO_2 cost of around \$500/ton, while shifting from gas to solar in power generation has a CO_2 cost of –\$50/ton to \$50/ton depending on the region.

Overall, our Carbonomics cost curve shows a consistent flattening since its 2019 inception, with technologies dominated by China moving lower and technologies that compete with natural gas moving higher. China has been leading the technology upgrade for clean tech innovations and continues to drive costs down, as it currently produces approximately 60% of electric vehicles, 86% of batteries, and 85%–97% of solar products. In 2023, we saw significant deflation in the prices of batteries and solar panels, which has moved the cost curve lower. On the other hand, lower conventional energy prices, higher interest rates, and clean tech inflation in areas such as offshore wind have moved the cost curve higher.

Carbonomics Cost Curve Shifts, 2022–23

Our 2023 Carbonomics cost curve shows a mix of technologies moving lower and higher relative to 2022. Overall, the cost curve has become more affordable—encouraging individuals and corporates to implement decarbonization technologies—thanks to the higher end moving lower despite the lower end of the curve moving higher. Movements in the cost curve were driven by contributions from (1) lower long-term energy prices (natural gas, coal, power, oil products) following 2022 peaks, increasing the implied cost of the switch to cleaner alternative technologies; (2) clean tech cost inflation for existing technologies (such as equipment costs in renewable power generation, especially in offshore wind); and (3) higher interest rates increasing the cost of capital for existing clean technologies (primarily in power generation); while (4) battery cost deflation and electric vehicle (EV) economies of scale have driven down EV costs and decreased the implied cost of switching to EVs from internal combustion engines (ICEs).

The net impact is that clean technologies at the low-cost end of decarbonization, dominated by renewable power, have become more expensive year over year (reflecting lower energy prices, higher interest rates, and cost inflation), while those at the high-cost end, dominated by transportation, have become cheaper as batteries resumed their deflationary trend. Further, lower raw material costs and simpler cell-to-vehicle integration have brought the target three-year payback in sight by mid-decade. According to our estimates, the evolution of the Carbonomics cost curve results in higher costs to reach 75% decarbonization but a decrease in the cost of achieving the remaining 25%.

The transformation of the cost curve brings with it a change in the global annual cost to achieve decarbonization from existing, large-scale, commercially available technologies. A combination of lower energy prices and higher clean tech costs (inflation) has had an unfavorable impact on the Carbonomics cost curve, while lower battery prices in EVs have had a favorable impact on overall cost.

We estimate that the initial ~50% of global anthropogenic greenhouse gas (GHG) emissions—what we classify as "low-cost decarbonization"—can now be abated at an annual cost of ~$1.0 trillion based on the 2023 cost curve ($0.3 trillion per annum higher than in 2022), largely driven by lower energy prices (~50%), cost inflation (~30%), and higher interest rates (~20%) primarily impacting sectors such as power generation.

The cost of achieving 75% abatement of global anthropogenic GHG emissions is approximately $3.2 trillion annually, based on our 2023 cost curve (~$0.1 trillion per annum higher than in 2022), with lower battery prices being offset by clean tech inflation, higher interest rates, and lower energy prices. At the same time, as we move toward 100% decarbonization, we enter into the "high-cost decarbonization" end of the spectrum, with the 2023 Carbonomics cost curve indicating that the cost to abate the last 25% of emissions is down ~$0.6 trillion per annum from 2022. At this end of the curve, lower battery prices in EVs are driving savings for the transportation sector.

Power Generation

Renewable power has transformed the landscape of the global energy industry and represents one of the most economically attractive opportunities in our decarbonization cost curve. We estimate that approximately 35% of the decarbonization of global anthropogenic GHG emissions is reliant on access to clean power generation, including electrification of transport and various industrial processes, electricity used for heating, and more. In 2023, the power generation switch from natural gas to renewables (and storage) became more expensive as cost inflation and higher funding costs in renewable power increased the cost of generating electricity for solar and wind year over year, while European and Asian gas prices decreased, making renewables relatively more expensive. Specifically, we highlight the following:

- The weighted average cost of capital (WACC) for new renewable power projects increased to 6.0%–6.5% in 2023 from 4.0%–4.5% in 2022, driven by the increase in risk-free rates in Europe and the United States.
- Equipment costs rose overall in renewable energy, although cost inflation has been most prominent in offshore wind, while solar module prices have been decreasing. Overall, higher interest rates and cost inflation raised the cost of generating electricity from renewable power (solar and wind) in Europe by ~11% year over year and by ~42% compared with the trough observed in 2020.
- Costs also increased in other forms of renewable generation, primarily hydro (largely owing to the development of more challenging and remote sites) and nuclear power.
- Gas prices eased from 2022 peaks as supply concerns receded, leading to roughly a 30% decline in the back end of the European gas forward curve, increasing the competitiveness of gas versus renewables.

We estimate that last year, the weighted average carbon abatement cost in power generation increased by ~3× year over year—from $20/ton in 2022 to $66/ton in 2023—with about 35% of this increase driven by cost inflation, 40% by lower gas prices, and 25% by higher interest rates. At the same time, the CO_2 cost for power generation remains the lowest on the Carbonomics cost curve in comparison with other sectors.

Offshore Wind and Solar

Solar power generation has been relatively less prone to cost inflation, with prices for solar modules—mostly produced in China—declining significantly since August 2023. The ongoing decline in equipment costs and somewhat stickier long-term clean energy prices suggest better economics for solar generation, which we estimate to be two times cheaper than offshore wind. Solar's competitiveness against other renewable technologies and its high deflationary impact in the context of current power prices (especially in Europe) suggest that it could gain incremental market share from other technologies.

Meanwhile, the steep cost inflation in offshore wind (especially in the United States, owing to an underdeveloped supply chain) could signal a setback in growth and a slowdown in future developments. Since its inception in the late 1990s, the offshore wind industry has benefited from a major improvement in economics. In Europe, we estimate that between 2008 and 2020, the electricity cost for offshore wind dropped by 65%. Yet, following a steep 20-year decline in costs, the more recent cost inflation in raw materials and an unprecedented spike in funding costs led to a marked increase in offshore costs of approximately 10% in 2023 year over year.

Transportation

Transportation, in contrast to power generation, mostly sits in the "high cost" area of the decarbonization cost curve, with the sector responsible for about 30% of global final energy consumption and about 15% of net GHG emissions. In 2023, we saw the transportation decarbonization cost curve shift downward significantly, driven by cost deflation and the technological innovation observed in EV batteries leading to a decrease in the carbon price of technologies dependent on EVs. At the same time, because of lower gasoline and jet fuel prices, some technologies, such as sustainable aviation fuel (SAF), have become relatively more expensive.

Overall, we estimate that these factors drove an approximate 30% year-over-year decrease in the weighted average carbon abatement cost in transport in 2023—to $422/ton CO_2 equivalent—because the material deflation in battery costs was partly offset by lower jet fuel and gasoline prices.

Electric Batteries and EVs

Battery technology and its evolution play a key role in the decarbonization of both transport and power generation. The high focus on electric batteries over the past decade has helped to reduce battery costs by more than about 30% in the past five years alone, owing to the rapid scale-up of battery manufacturing for passenger electric vehicles. Nonetheless, the technology is currently not readily available at large, commercial scale for long-haul transport trucks, shipping, or aviation, and it remains in the early stages for long-term battery storage for renewable energy.

Looking ahead, we expect declining battery prices, as well as EV economies of scale, to help narrow the cost gap between EVs and ICEs by 2030. As a rule of thumb, we see an EV premium payback period of around three years (i.e., the number of years needed for fuel savings from cheaper electricity vs. gasoline to cover the EV cost premium over a fossil fuel car) as a threshold for a new powertrain to be widely accepted by consumers, given the case of Toyota Prius. We expect this three-year target could be reached around mid-decade for EV makers in China, as well as in ex-China markets such as the United States. In our view, the main drivers for a decline in battery prices from here include lower lithium and other raw material costs and simpler cell-to-vehicle integration (e.g., cell-to-pack, cell-to-chassis).

Clean Tech Innovations

The ongoing product innovation and technology upgrade continues to drive cost reduction and expand the demand outlook for key decarbonization technologies, such as clean hydrogen, sustainable aviation fuel, renewable diesel, and carbon capture and storage, which are gaining momentum.

Bioenergy

Bioenergy is already the largest source of renewable energy in the world and has the potential to decarbonize road, marine, and air travel, as well as heating, industry, and power generation. In renewable diesel (RD), we forecast strong capacity growth of more than 3 million tons in 2024, as well as a tightening feedstock market. However, we also see potential upside from the implementation of the Renewable Energy Directive (RED) III regulation in the EU from 2026, which could generate 5 million to 6 million tons of additional RD demand by 2030 (see European Commission 2024).

SAF is emerging as the leading technology to decarbonize air transport, with blending becoming mandatory from 2025 in several countries. We expect a tight market dominated by a few players in 2025–27 and see an opportunity for healthy margins.

Renewable Diesel

On 4 September 2023, the Dutch government proposed an upward revision in its 2024 target for renewable use in transport from 19.9% currently to 28.4%, which could result in up to 500 kilotons of additional RD demand in the Dutch market. Also, on 13 September 2023, the EU adopted amendments to RED II that increased the binding share of renewables within final energy consumption in transport to at least 29% by 2030, up from 14% previously (see European Commission 2024).

Although a number of countries in the EU with the highest RD consumption already have higher or similar renewables target ambitions (e.g., Sweden, Finland, Germany, the Netherlands), we believe there is potential for an upward revision to country mandates. This is after the adoption of RED III in countries with lower targets (e.g., Italy and France), given that member states are required to implement EU-wide regulations within 12–18 months of RED adoption, which we think could benefit the supply–demand balance in the RD market from 2026. Unlike regulations, which are binding in their entirety and directly applicable in all EU countries, directives require integration into national law by a specified deadline. EU member states are required to incorporate RED III into their national legislation over the coming months.

Beyond that, amendments to the Low Carbon Fuel Standard (LCFS) program have been proposed that would increase the stringency of carbon intensity (CI) targets through 2030 and extend emissions targets through 2045. The California Air Resources Board (CARB) has proposed tightening the CI reduction target to 30% (compared with the 2010 baseline) by 2030 from the current target of 20%, with a 5% proposed step-up in the reduction by 2025 compared with the level targeted under the current regulation. The CARB expects the proposed tightening of the CI reduction target to support LCFS prices: Preliminary CARB estimates show that LCFS prices could increase from $60/ton currently to more than $100/ton in 2025 and as high as $200/ton in 2026.

Sustainable Aviation Fuel

Following adoption of RED III in October 2023 (see European Commission 2024), the European Parliament adopted the ReFuelEU Aviation Regulation (European Council 2023). After ratification by the European Council, most of the new aviation rules came into force on 1 January 2024. New rules require aviation fuel suppliers to supply a minimum share of SAF at EU airports, starting from 2% of overall fuel supplied from 2025 (volume-based), then rising to 6% by 2030, 20% by 2035, and 34% by 2040, before reaching 70% by 2050.

Looking at voluntary demand, a number of European airlines have already set more ambitious targets than the ReFuelEU target for 2030 of 6%: Air France/KLM Royal Dutch Airlines (10% by 2030), Ryanair (12.5% by 2030), Iberia (10% by 2030), and International Consolidated Airlines Group (10% by 2030).

Clean Hydrogen

Clean hydrogen is a key rising technology in the path toward net-zero carbon, providing decarbonization solutions in the most challenging parts of the Carbonomics cost curve, including long-haul transport, steel, chemicals, heating, and long-term power storage. Clean hydrogen is a fuel, but as an energy vector it can also be produced by technologies that are increasingly widespread and scaling up, such as renewables and carbon capture. Although the basic scientific principles behind clean hydrogen are well understood, most of these technologies applied in their respective industrial sectors are still at the demonstration or pilot stage.

In the long term, we think hydrogen has a critical role to play in any aspiring path targeting carbon neutrality by 2050. We see a wide range of applications across sectors, including its potential use as an energy storage (seasonal) solution that can extend renewable electricity's reach, an industrial energy source, and an industrial process feedstock. Such uses could include 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. We also see potential applications for hydrogen in long-haul heavy transport.

Hydrogen has had an eventful couple of years, benefiting from strong policy support in the United States from the Inflation Reduction Act (IRA) and in Europe from REPowerEU. The year 2023 was also not without challenges, however: The hydrogen industry experienced pressure from high interest rates, and the US Treasury Department finally released its long-delayed proposed regulations for how hydrogen producers can secure tax incentives in the IRA. The proposed regulations are still being debated by the industry and overall appear burdensome, in our view, especially with requirements for longer-term hourly matching of renewable energy used for hydrogen production. These requirements, together with uncertainty associated with the upcoming presidential elections, continue to hurt backlog and near-term growth in the United States. We believe that this uncertainty is holding back major new US projects, despite the tax credits, while in Europe we continue to see medium-scale projects going ahead—especially for refineries and bio-refineries.

Carbon Capture and Storage

Carbon sequestration efforts can be broadly classified into three main categories, outlined in Goldman Sachs Research (2020):

1. natural sinks, encompassing natural carbon reservoirs that can remove carbon dioxide from the air (efforts include reforestation, afforestation, and agro-forestry practices);
2. carbon capture, utilization, and storage technologies (CCUS) covering the whole spectrum of carbon capture technologies applicable to the concentrated CO_2 stream coming out of industrial plants, carbon utilization, and carbon storage; and

3. direct air carbon capture and storage (DACCS), the pilot carbon capture technology that could recoup CO_2 from the air, unlocking almost infinite decarbonization potential, irrespective of the CO_2 source.

We envisage two complementary paths to enable the world to reach net-zero emissions: conservation and sequestration. The former refers to all technologies enabling the reduction of gross GHGs emitted. The latter refers to natural sinks and carbon capture, usage, and storage technologies that reduce net emissions by subtracting carbon from the atmosphere.

The need for technological breakthroughs to tackle emissions that cannot currently be abated through existing conservation technologies makes sequestration a critical piece of the puzzle in leading the world to net zero at the lowest possible cost. Carbon sequestration efforts are critical for a global carbon neutrality path, as they can (1) unlock emissions abatement across the hardest-to-abate sectors, where technological net-zero alternatives have not yet been developed or remain highly inefficient and expensive—a prominent example is heavy, highly energy-intense industrial processes; (2) avoid the early retirement of young plant fleets and assets, thereby easing concerns around stranded assets in the age of decarbonization; and (3) reduce the total load of GHGs in the atmosphere to the required carbon budget, thus correcting for any overshoot. In this context, direct air carbon capture is the key technology to abate accumulated emissions directly from the atmosphere.

Clean Tech Policy Support

The global ecosystem of clean tech innovators has benefited significantly from policy support and the capex opportunities available for renewables, driving technological innovation throughout our Carbonomics cost curve.

Inflation Reduction Act (IRA)

The IRA became law in August 2022, and its impact has been striking. As of October 2023, we estimate that about $500 billion in large-scale clean tech projects have been announced in new private clean energy investments thanks to the IRA, and we expect more announcements in the coming years. Some of these projects, however, have not yet started construction and are waiting for the US Treasury to issue key clarifications, especially in green hydrogen and carbon capture.

We estimate that CO_2 savings from IRA incentives and induced investments to 2032 will amount to 22 gigatons, implying a $52/ton cost of CO_2 abated to the US government. This abatement CO_2 price varies by technology: For solar and onshore wind, the CO_2 price is less than $25/ton given their 25+-year longevity and the mature nature of the technologies. For hydrogen, EVs, and biofuels, however, the price exceeds $100/ton given the shorter project life (the average car life is 15 years) and the relative immaturity of many of these technologies.

We also consider how the IRA changes the cost curve of decarbonization for the United States. Incorporating US IRA tax credits and other incentives, the Carbonomics cost curve for the United States moves 75% lower.

Carbon Pricing

We believe that carbon pricing will be a critical part of any effort to move to net-zero emissions, while incentivizing technological innovation and progress in decarbonization technologies. The still-steep carbon abatement cost curve highlights a growing need for technological innovation, deployment of sequestration technologies, and effective carbon pricing. At present, 73 carbon pricing initiatives are underway, covering 39 national and 33 regional governments worldwide, mostly through cap-and-trade systems. These initiatives are now gaining momentum beyond developed markets, with Indonesia launching the initial phase of its own national carbon pricing scheme in February 2023. The carbon pricing systems have, however, shown varying degrees of success in reducing carbon emissions so far. According to the World Bank Group, these initiatives together cover 13 gigatons of CO_2 equivalent, representing approximately 24% of the world's total GHG emissions.

European Carbon Market Policy

In Europe, we argue that the carbon market is at a crossroads, growing from a successful but narrow instrument that facilitates the move away from coal power generation to a driver of decarbonization across much of the European economy. We also argue that the lower natural gas prices we expect in the second half of the decade—driven by a 50% increase in the global liquefied natural gas (LNG) market—provide an opportunity for EU policymakers to push the EU Emissions Trading System (ETS) to the price level required for the decarbonization of heavy industry (€100–€130/ton on our Carbonomics cost curve) without energy cost inflation to industry and consumers. The introduction of the Carbon Border Adjustment Mechanism (CBAM) and the potential for a parallel ETS for transport and heating complement this transformation. We envisage three key catalysts for this shift: (1) the introduction of CBAM in 2026, (2) a likely deficit in the permit market after the market stability reserve (MSR) in 2026 and before the MSR in 2030, and (3) auctioned emissions in industry and transport exceeding those in power generation by 2030.

Stress-testing key assumptions on industrial production, coal retirement, and renewable ramp-up in our supply–demand model for credits, we conclude that by 2028 we should see a structural breakthrough in the market toward a CO_2 price of €100–€130/ton—the level we estimate would incentivize CCUS on a large scale. For 2026–27, our negative view on natural gas pricing, driven by an acceleration in LNG supply growth, implies some downside risk to prices in the EU ETS market. But it also suggests an opportunity for EU regulators to tighten the carbon market and achieve their "Fit for 55" commitment, leveraging lower energy prices to accelerate the energy transition. This dynamic should prevent an excessive decline in power prices from potentially derailing the buildup of renewables. We estimate that EU ETS auctions could generate €62 billion annually in tax revenue for the EU member states by the end of the decade.

EU CBAM: Near-Term Beneficiaries

The EU CBAM will impose a direct carbon tariff on the embedded emissions from 2026 of selected imported products—iron and steel, aluminium, cement, fertilizers, electricity, and hydrogen—with potential implications for product prices, margins, and volumes. In our view, the EU CBAM may (1) be a potential catalyst for global carbon pricing; (2) create margin risks for high-carbon products (if charges are absorbed) or declines in sales (if passed through, depending on demand elasticity), with potential "green" premium benefits for low-carbon products; (3) lead to goods being rerouted based on embedded emissions; and (4) accelerate green capex investment.

We believe that explicit carbon schemes (such as the EU ETS) have scope to be a more efficient, technology-agnostic instrument of decarbonization and clean tech innovation. Carbon leakage and unfair competition can, however, be an issue in the absence of a globally coordinated carbon pricing mechanism, prompting a focus on a border adjustment to ensure a level playing field. The CBAM approved by the EU could help remedy the issue of carbon leakage by placing a tariff-like cost on emission-intensive imports and exports to attempt to reconcile the difference in carbon pricing between the EU and its trading partners.

Although the EU CBAM is ultimately an incremental charge, we see a number of potential near-term relative beneficiaries:

- **Producers of low-carbon solutions:** Arguably the most obvious to benefit, companies that have a lower carbon intensity EU CBAM-covered product offering relative to global peers may see increased demand from European customers. An implicit "green premium" could result from this increase, despite any margin implications being driven by lower CBAM-related costs for such products as opposed to an increase in product pricing.
- **European low-carbon-facility operators:** We estimate that European producers with more sustainable products could benefit from a temporary early mover advantage, even in highly carbon-intensive industries, such as cement.
- **Steel value chain—scrap steel and EAF steel production:** The EU CBAM will incentivize a more rapid transition toward electric arc furnace (EAF) use from blast furnace (BF) use. (About 70% of the world's steel is currently produced via BF, which has a carbon intensity 75% higher than an EAF.) Because scrap steel is a key feedstock into an EAF, we see its producers as likely beneficiaries.

- **Audit and assurance:** One of the biggest near-term challenges for companies is meeting the compliance and reporting obligations of their customers. This challenge has multiple layers, including adjusting monitoring and reporting to meet the EU definition of direct versus indirect emissions. Companies we have spoken with have commented that doing so will likely require in-house or outsourced engineers to work alongside sustainability teams. Receiving assurance on EU CBAM disclosures will be a mandatory requirement under the regulation once the Definitive (payment) Period begins in 2026.

European Natural Gas Prices

The European energy crisis started in 2021, with a tight gas market exacerbated by the Russia–Ukraine conflict. Gas and power outlays rose approximately €2 trillion in 2022 (of which €0.8 trillion was imported), creating an affordability crisis and fears of deindustrialization. The LNG supply response—with a customary four to five years' time to market—is now under construction, with LNG supply set to accelerate from the beginning of 2025, we estimate. It will bring a total 204 million tons per annum (mtpa) of LNG onto the market by 2028, according to our estimates, almost 2× the 115 mtpa of curtailed Russian supplies to Europe. The increase will bring the global gas market back into material oversupply, especially in 2026–28. Sectors that benefit the most from lower gas prices are industrials and European cyclicals. The deindustrialization theme has become a growing concern over the past few years, mainly because of a challenging cost environment driven by high energy prices and regulatory hurdles. Lower energy prices could ease such concerns and have material benefits to the European consumer, reducing the average bill for a European household by about €218/month according to our estimates.

European Carbon Market and Carbon Capture Economics

Changes in the EU ETS system will likely mean changes in carbon pricing. Historically, the European carbon price has been correlated with the coal-to-gas pricing ratio, given that power generators have been buying more than 90% of total carbon allowances since 2016, while such sectors as industry and aviation have been receiving more than 90% of carbon allowances as free allocations. We argue that the upcoming changes in the ETS system suggest the European carbon market will no longer be correlated with the economics of coal-to-gas switching (effectively, the decarbonization of power generation) and will converge to the economics of industrial carbon capture (effectively, the decarbonization of industry)—mainly because of the phase-out of free allocations for industry in 2026–34 coupled with the introduction of the CBAM in 2026.

Carbon capture cost varies for different industrial applications. CCUS encompasses a range of technologies and processes that are designed to capture the majority of CO_2 emissions from large industrial point sources and then provide long-term storage solutions or utilization. The CCUS chain consists of processes that can be broadly categorised into three major parts: (1) the separation and capture of CO_2 from gaseous emissions; (2) the subsequent transport of this captured CO_2, typically through pipelines, to suitable geological formations; and (3) the storage of CO_2—primarily in deep geological formations, such as former oil and gas fields, saline formations, or depleting oil fields—or the utilization of captured CO_2 for alternative uses and applications (e.g., to help produce synthetic hydrogen based fuels). The cost of capturing CO_2 is the key contributor to the total cost and can vary significantly between different processes, mainly according to the concentration of CO_2 in the gas stream from which it is being captured, the plant's energy and steam supply, and integration with the original facility. For some processes, such as ethanol production and natural gas processing or after oxy-fuel combustion in power generation, CO_2 can be already highly concentrated, leading to costs below $50/trillion CO_2eq (as in natural gas processing, ethanol, and ammonia). For more diluted CO_2 streams, including the flue gas from power plants (where the CO_2 concentration is typically below 20%) or a blast furnace in a steel plant (20%–30%), the cost of CO_2 capture is much higher. The average industrial carbon sequestration cost used in our European cost curve is approximately $120/ton.

Conclusion

Achieving the goals set by the Paris Agreement is one of the most significant challenges of our time, requiring policy coordination, efficient financing, and technological innovation.

In this chapter, we examine the progress of some key low-carbon technologies and present the Carbonomics cost curve, an important tool for investors and corporates to assess the cost of decarbonization across different sectors. In 2023, we saw significant deflation in technologies dominated by China such as battery and solar panel prices, which moved the cost curve lower despite higher interest rates and clean tech inflation. As a result, we estimate that the initial roughly 50% of global anthropogenic greenhouse gas (GHG) emissions—what we classify as "low-cost decarbonization"—can now be abated at an annual cost of about $1.0 trillion based on our 2023 Carbonomics cost curve. By sector, CO_2 cost for power generation remains the lowest on the Carbonomics cost curve while Transportation mostly sits in the "high cost" area of the decarbonization cost curve. That said, we estimate that the weighted average carbon abatement cost in power generation increased by about 3× year over year—from $20/ton in 2022 to $66/ton in 2023—owing to cost inflation in offshore wind and higher interest rates. In contrast, Transport saw a 30% year-over-year decrease in the weighted average carbon abatement cost in 2023—to $422/ton CO_2 equivalent—thanks to the material deflation in battery costs.

We also believe that carbon pricing will be a critical part of any effort to move to net-zero emissions, while incentivizing technological innovation and progress in decarbonization technologies. The current carbon market is developing worldwide but it still has limited reach in terms of compliance. At present, 73 carbon pricing initiatives are underway, covering 39 national and 33 regional governments worldwide. Carbon pricing initiatives cover only up to 24% of global GHG emissions, however, even with the addition of China in 2021, and the global weighted average carbon price is only $5/ton. In Europe, we argue that the carbon market is at a crossroads, growing from a successful but narrow instrument that facilitates the move away from coal power generation to a driver of decarbonization across much of the European economy. We expect lower natural gas prices in the second half of the decade (driven by a 50% increase in the global LNG market), which should provide an opportunity for EU policymakers to push the EU ETS to the price level required for the decarbonization of heavy industry (€100–€130/ton based on our 2023 Carbonomics cost curve) without energy cost inflation to industry and consumers. Carbon pricing also needs to be fair and prevent carbon leakage. The EU CBAM in 2026 could help address this issue by placing a tariff-like cost on emission-intensive imports and exports to reconcile the difference in carbon pricing between the EU and its trading partners.

Finally, ambitious new regulations are also emerging for clean tech innovations, and government incentives have potential to unlock large-scale clean tech development. We analyze in detail the example of the US IRA, estimating that its incentives have reduced the US Carbonomics cost curve by 75% and already unlocked around $500 billion of clean tech investments.

Bibliography

European Commission. 2024. "Renewable Energy Directive." https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en.

European Council. 2023. "RefuelEU Aviation Initiative: Council Adopts New Law to Decarbonise the Aviation Sector" (9 October). Press release. www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector/.

Goldman Sachs Research. 2020. "Carbonomics: The Green Engine of Economic Recovery" (16 June).

Goldman Sachs Research. 2022. "Carbonomics: The Clean Hydrogen Revolution" (4 February). www.goldmansachs.com/insights/goldman-sachs-research/carbonomics-the-clean-hydrogen-revolution.

Goldman Sachs Research. 2023a. "Carbonomics: The Third American Energy Revolution" (30 August). www.goldmansachs.com/insights/goldman-sachs-research/carbonomics-the-third-american-energy-revolution.

Goldman Sachs Research. 2023b. "Carbonomics: Updated Cost Curve Shows Diverging Trends between Power and Transport" (27 November). www.goldmansachs.com/insights/goldman-sachs-research/carbonomics-updated-cost-curve-shows-diverging-trends.

Intergovernmental Panel on Climate Change (IPCC). 2023. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the IPCC [Core Writing Team, H. Lee, and J. Romero (eds.)]. Geneva, Switzerland, pp. 35–115. doi:10.59327/IPCC/AR6-9789291691647.

World Bank. 2024. “State and Trends of Carbon Pricing 2024.” https://hdl.handle.net/10986/41544.