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CHEMICAL MARKET ANALYTICS

Pathways toward sustainability

A roadmap for the global chemical industry

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Foreword

The report by researchers from Princeton University and Deloitte that you have in front of you is the result of an extraordinarily bold and productive collaboration between industry and academia, one that aims at nothing less than a reset of the global conversation about sustainability.

Placed front and center is the profit-making corporation, an agent of change too often underappreciated. The corporation confronts actual investment options and weighs present and prospective costs and risks. Subordinated here are the policymaker, the consumer, and the activist, all of whom of course can affect the relative attractiveness of the options the corporation considers. The implicit message of this report is that sustainability can only be achieved when the corporation is able to commit to the process.

The report opens the black box within which corporations make decisions, especially those that involve the allocation of financial capital. Its focus, in this instance, is the basic chemical industry, but the strategy of analysis could be applied to many other industrial sectors. The goal is to reduce greatly the greenhouse gas emissions within the production facilities and also those associated with the industry's energy and other inputs. Much of the detail of the analysis concerns the interaction of time frames measured in decades. How fast will the costs of new technologies fall, will demand change, will supportive policies become more generous? No one knows, of course, and nonetheless corporations must make decisions about the allocation of capital for decarbonization in the face of such uncertainties. In this report, three scenarios are provided to promote a pragmatic discussion of alternative answers.

The analysis in this report illuminates many vexing topics, "Net-zero" meets common sense: dramatic reductions in emissions are the main objective, and small remainders ("modest… residual emissions") are left alone. A sensible pace, too, is derived, not enforced, and 2050 shares attention with 2060 and 2080. Progress associated with reductions in upstream scope 3 emissions, such as those associated with methane leakage, is quantified. The key competition between investments by the chemical industry in electrification and in carbon dioxide capture and use or storage (CCUS) is displayed. And careful consideration of the "asset cycle" reveals the trade-offs between new builds and retrofits.

I hope this report will be followed by several others that continue the exploration of a sustainable chemicals sector, because there are several important issues just beyond the systems boundary here. One of the thorniest is the carbon dioxide emissions associated with the final destination of any carbon-containing chemical. These so-called downstream scope 3 emissions are often considerably larger than the emissions associated with producing the chemical in the first place: the carbon dioxide emissions associated with burning gasoline in a vehicle much exceed those associated with the production of gasoline at the refinery, for example. One can anticipate pressure to find non-carbon substitutes for many of today's basic chemicals when sustainability becomes a strong driver—to be sure, alongside pressure to retrieve and either reuse or sequester the carbon, options considered in depth in this report. Future demand for ammonia as a fuel, for example, may be underestimated here.

In this report, the carbon dioxide managed by CCUS has been produced as a by-product of burning a carbonaceous fuel (a fossil fuel or biofuel); it has not been extracted from the Earth's atmosphere, an option (known as direct air capture) wisely excluded here, because its capture costs are far higher. The report does not explore the phased build-out of the overarching carbon dioxide management infrastructure, consisting of large numbers of widely dispersed sites for the geological storage of carbon dioxide as well as carbon dioxide pipelines connecting these storage sites to the factories where the carbon dioxide is captured. The scale of the CCUS effort envisioned would create a new infrastructure on track to rival those now in place for electricity and gas.

Over the past decade or so, political support for this version of CCUS has waned, because some environmental advocacy groups have sought to end the use of fossil fuels entirely. The strategies highlighted in this report arguably require a U-turn on the part of those groups to become viable, and perhaps this report will help build the case that such a U-turn is necessary.

Still another follow-up report could consider the feedstocks for the chemical industry, which today are the low-value components of the hydrocarbon mixtures that come out of the ground as crude oil and natural gas. If, some day, demand for the high-value components (gasoline and diesel in the first case, methane in the second) should fall substantially, the oil and gas sector will need to undergo its own transformation to couple with the chemical industry effectively.

The report restricts itself to investments only in today's four most industrialized regions of the world, which is entirely defensible when the goal is to study industrial transformation. A subsequent report of considerable merit would look at fresh starts in parts of the world where little of the chemical industry has yet emerged.

My final suggestion is that a subsequent report deal with the interplay of public policy and R&D. Such R&D in this instance encompasses, but would not be limited to, materials science, decarbonization technologies, and digital support systems. Recalling again the electric car, we have there an example of an option resulting from extensive R&D that may well soon be superior in performance and lower in cost than today's dominant vehicles. In that case, subsidies that generated the option in the first place will be able to be phased out. As this report reveals, electrification may provide superior, less-expensive options in the same sense for the chemical industry as well as in some regions. But much of the early progress with lower-emission chemicals will require the adoption of options that bring increased cost, such as will be the case wherever carbon dioxide is managed rather than vented to the atmosphere. In such instances, we have the classic case where a subsidy of some kind is required to produce the low-carbon investment, justified principally by less resulting damage from climate change. The underlying damage assessment, we have all learned, is itself contentious; ultimately, public opinion carries great weight in driving both green consumption and green policy.

Public opinion, in turn, will be affected by how nasty our planet turns out to be. Indeed, over the next few decades, the same time interval that is the focus of this report, the Earth will gradually reveal how it responds to the changes we are subjecting it to and how much trouble it will cause us. How quickly humanity will gain the necessary insights to make wise investments depends strongly on how aggressively the global climate science effort to extract the Earth's secrets is pursued. Accordingly, an ambitious global climate science effort serves the self-interest of the chemical industry, and many other industries, as they confront risk and return from their strategic investments on behalf of a sustainable world.

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Rob was not involved in this study. His participation in this foreword is based on his knowledge of the subject, and the views expressed by him are solely his own.

Executive summary

Why do we need this study?

Pathways toward sustainability: A roadmap for the global chemical industry is timely in its publication as many companies seek to lower carbon emissions. As the year 2030 rapidly approaches, corporate commitments on emissions reduction loom larger than ever. To take full advantage of the economic opportunity and to make progress on the corporate commitments, a path is needed toward chemicals and materials that have a smaller, eventually zero, greenhouse gas emissions intensity, while at the same time being produced at scale—profitably. This transformation may require significant capital investment, innovation in the abatement solution space, and cooperation between industry players, governments, and other organizations.

Chemicals supply nearly every end-use product or material, with more than 90% of manufactured goods containing chemicals.[1] Thus, the chemical industry is a critical partner for countless industries to meet their scope 3 emissions goals. The chemical industry produces products in millions of metric tons and the processes to produce those millions of tons are very energy intensive. According to data from Chemical Market Analytics by OPIS,[12] there was 576 million metric tons (Mt) of demand for the 10 building blocks across the four in-scope regions for the 2023 baseline. This equates to 729 $MtCO_2$ for direct scope 1 and indirect scope 2 emissions. The emissions challenge is exacerbated by the expected growth in chemicals and materials demand globally. Based on the Chemical Market Analytics by OPIS data set used in this study, global demand is expected to double by 2080 compared to 2023 values.

To develop an actionable transformation strategy to meet voluntary emissions reduction ambitions, industry players require a forward-looking perspective based on data-backed and asset-level information that projects a tangible timeline for emissions reduction. This paper also explores how the green premium shifts down the value chain, potentially catalyzing a transformation that could unleash huge amounts of economic upside for early movers.

While several studies exist[3] that fix the timeline to eliminate all industry emissions by 2050, this study provides a necessary forward-looking view that pushes beyond 2050 to evaluate scenarios based on technology readiness, capital expenditure appetites, cooperation between industry players and governments, and the willingness to pay for low-emissions products. It offers a perspective on the challenge for meeting corporate emission reduction ambitions including potential pathways to achieve these goals.

This study is motivated by conversations with stakeholders across the value chain (e.g., chemical companies, brand owners, retailers, nongovernmental organizations [NGOs], industry groups, and more) that voiced a need for data-driven information to understand the true state of the industry and potential future states. Ultimately, this study aims to provide stakeholders with the information needed to make strategic decisions informed by data-driven inputs. This study answers these questions:

- What are plausible future scenarios that the industry will face, and what are the likely key drivers for those outcomes?
- What is the capital expenditure required for the industry to achieve emissions reductions?
- What are key abatement technologies that will enable the industry's emissions reductions?
- How do regions differ in projected CapEx spend, abatement application, and other emission reduction approaches?

What did we do?

This study uses a techno-economic model, designed and run by a research team at Princeton University's Andlinger Center for Energy and the Environment. The scope includes 10 building block (BB) chemicals (ammonia, benzene, butadiene, chlorine/caustic, ethylene, hydrogen, methanol, propylene, toluene, and xylene) in four regions: North America,[4] Europe,[5] Middle East,[6] and China.[7]

This model uses inputs based on asset-level data provided by Chemical Market Analytics by OPIS, as well as other public sources, to project emissions abatement trajectories to 2080 taking into consideration economic factors including abatement technology costs and cost-learning curves. This techno-economic model evaluated abatement trajectories under three scenarios that reflect varying strengths of:

- Coordination and governance on decarbonization;
- Demand for sustainable goods and services; and
- How these two dimensions affect the capital investment environment for emissions mitigation projects.

There are, of course, uncertainties around future costs, revenue opportunities, and the regulatory environment, which obscure the path to lower building block emissions. The scenario-planning approach adopted for this study recognizes these significant real-world uncertainties and how these might impact decarbonization investment decision-making by exploring three hypothetical futures among the infinite number of potential scenarios that could play out over the next half-century. Scenarios are used to describe general projections around the globe as a basis to model how key differences could impact hypothetical actions. This paper does not recommend or argue for region-specific actions. Scenario narratives qualitatively describe alternative evolutions of sustainability priorities globally over the next half-century, and these are assumed to impact investment priorities in the chemical sector. Accordingly, the industry's capacity and appetite for allocating abatement capital, vary by scenario:

- The **Sustainable United (SU)** scenario assumes there is strong global cooperation with nations imposing abatement-enabling regulations and incentives. Rapid innovation drives down clean technology costs, and data-driven science facilitates global technology exchange. There is a pervasive bottom-up demand for sustainable products and services among consumers. Quantitatively for the modeling, capital is deployed at rates sufficient to retrofit all facilities existing today (2023) and abate any needed capacity expansions by midcentury: 2050 for North America (NA) and Europe (EU), and 2060 for China (CH) and the Middle East (ME). The first abatement projects are assumed to come online in 2030.
- In **Green Authority (GA)**, there is strong global cooperation with nations imposing abatement-enabling regulations and incentives. Rapid innovation drives down clean technology costs, and data science drives global technology exchange. However, consumer willingness to pay a sustainable premium remains low. For the modeling, capital is assumed to be deployed at a slower rate than in SU.
- In **Grassroots Green (GG)**, there is consumer-led demand and willingness to pay for sustainable products in higher-income groups. Geopolitical tensions limit global cooperation, and this scenario assumes subdued innovation. Nationalistic procurement policies drive domestic investment, but fragmented supply chains and low technology transfer hold back advanced clean technology. In the model, capital is assumed to be deployed at a slower rate than in GA, based on study design.

Within each scenario, four alternative classes of abatement technology options are considered for future emissions reduction: CO_2 capture, utilization, and storage (CCUS); blue or green hydrogen; process electrification and substitute feedstocks (circular or biogenic). No judgment on the relative likelihood of any of these scenarios is made, since scenarios are not intended to predict specific futures but instead represent the range of possibilities.

Drawing on a database provided by Chemical Market Analytics by OPIS of approximately 2,700 BB chemical production facilities across NA, EU, CH, and ME (as of 2023),[8] facility-by-facility abated CO_2 emissions (scopes 1, 2, and upstream 3), abatement capital investment required, and levelized cost of abated emissions (scope 1 and 2) are estimated. The database includes facility-by-facility production capacities, input feedstocks, process types, capacity utilization rates, unit consumption rates of fuel, steam and electricity, and unit rates of process CO_2 emissions (distinct from fuel-combustion emissions). The demand by region to 2050 and associated regional production capacity expansions (or contractions) were extrapolated to develop estimates to 2080.

For each scenario, the following regionally aggregated industrywide values over time are reported for each building block, assuming all facilities for that BB adopt the same abatement technology. For BBs with multiple possible abatement technology options, calculations for industrywide adoption of each option provide the following results:

- CO_2 emissions (scope 1, 2, and upstream 3). Note: Grid electricity carbon intensities (for scope 2 emissions) and upstream scope 3 emissions vary by region and scenario.
- Average regional CO_2 emissions intensity per unit BB produced (scope 1 and 2).
- Annual capital deployments in 2024$ required (to abate existing and future new capacity).
- Cumulative capital deployed in 2024$ to 2080 (to abate existing and future new capacity).
- Average annual capital deployed to abate existing facilities.
- Anonymized facility-by-facility levelized abatement costs.
- Abatement costs are assumed to fall ("learning-by-doing") as the number of deployed projects grows. Cost learning across the initial few deployments is slower than in subsequent deployments. Learning is fastest in SU and slowest in GG.

For the purposes of this study, achieving "net-zero" means deeply decarbonizing systems (to as close to zero emissions as practicable) leaving a modest level of residual emissions that are very difficult and costly to abate. These residual emissions would need to be permanently offset either by nature-based or engineered carbon dioxide removal measures, such that there is no further accumulation of greenhouse gas (GHG) in the atmosphere. Some net-zero standards[9] require organizations to reduce emissions by more than 90%, leaving no more than 10% to be offset by removals. Across our scenarios, capital is deployed at various rates to retrofit existing facilities and to abate new facilities built to meet demand growth such that net-zero is achieved as described above for North America and Europe in 2050 and China and the Middle East in 2060 in Sustainable United. It should be noted that this study has not assessed the implementation feasibility of retrofitting individual existing facilities, which will depend on the availability of land and services, construction access, and permit restrictions, among other criteria.

Additionally, a market assessment was completed that used application data and expert interviews to identify priority end markets that are most likely to support investment for low-carbon chemicals. This assessment includes identifying target downstream sectors most likely to cooperate with chemical industry players to develop needed market mechanisms. Namely, business models and cost-sharing that ensure value capture for lower-emission products. The market assessment also included product vignettes that estimate the increase in cost for lower-emissions intermediates and end products.

What did we find?

The model demonstrates a tremendous opportunity for growth and transformation in the chemical industry's journey toward net-zero in second half of the century. While current investment levels in lower-emissions technologies are below what will ultimately be needed for corporates to achieve their sustainability goals, the path forward is clear: With bold capital commitments and a persistent focus on innovation, the sector can achieve significant emissions reductions and unlock new sources of value.

The routes to significant emissions reductions, however, will require substantial capital investment and a green premium for BB chemicals and resulting downstream products. For example, the Sustainable United scenario for abatement of olefins and aromatics emissions in North America requires an average annual decarbonization CapEx of $3.7B/year (cumulative $99B for net-zero by 2050), compared to $2.7B/year ($106B for net-zero by 2063) for Green Authority and $2.2B/year ($111B for net-zero by 2080) for Grassroots Green. For perspective, the average annual CapEx for all purposes was $2.7B/year during the past 33 years in North America's NAICS sector 325110 (petrochemical manufacturing).

The capital requirements to abate existing facilities across all building blocks in each region for each scenario are shown in figure 1. In some regions, full abatement of existing facilities is not reached before the end of modeling time horizon.

Figure 1. Capital abatement investments

Capital abatement investments		NA	EU	ME	CH	All
Year by which all existing assets are abated	SU	2050	2050	2060	2060	2060
Average emissions abatement CapEx (billion 2024$/yr)	SU	5.1	4.2	1.8	16.0	27.1
Cumulative CapEx to abate existing capacity (billion 2024$)	SU	136	98	66	453	754
Cumulative CapEx for existing + new capacity, 2025–2080 (billion 2024$)	SU	241	148	116	603	1,108
Year by which all existing assets are abated	GA	2063	2065	2080	2080	2080
Average emissions abatement CapEx (billion 2024$/yr)	GA	3.7	3.0	1.3	11.4	19.4
Cumulative CapEx to abate existing capacity (billion 2024$)	GA	145	101	70	499	815
Cumulative CapEx for existing + new capacity, 2025–2080 (billion 2024$)	GA	265	157	128	682	1,231
Year by which all existing assets are abated	GG	2079	2080	> 2080	> 2080	> 2080
Average emissions abatement CapEx (billion 2024$/yr)	GG	3.0	2.5	1.3	8.6	15.4
Cumulative CapEx to abate existing capacity (billion 2024$)	GG	151	99	63	389	702
Cumulative CapEx for existing + new capacity, 2025–2080 (billion 2024$)	GG	281	166	130	627	1,203

These investments, above and beyond "business-as-usual" capital spending levels, underscore the period of capital-intensive transformation that lies ahead for the industry. There is, however, potential to take advantage of existing asset life cycles, and to strategically align investments in decarbonization with opportunities for growth and modernization to improve competitiveness. This is a promising area for future exploration by companies and investors, which was not considered in this study. Likewise, the role of government support was beyond the current scope and could be explored in a future study.

Closing the investment gap will require a combination of supportive government policies and robust customer demand. The early commercial stage of abatement technologies and the current green premium for low-carbon products create a unique window for innovative, forward-thinking enterprises to lead the market and capture outsized value, especially in regions and sectors ready to advance sustainable solutions.

The pace of emissions reduction is directly linked to the industry's willingness to invest in abatement projects. While net-zero by 2050 is an ambitious target, the industry is well-positioned to make substantial progress by setting bold, yet achievable, goals—supported by a suite of proven and emerging technologies such as CCS/CCUS, clean hydrogen, and cracker electrification. Regional differences in carbon intensity and technology costs present further opportunities for tailored solutions and competitive advantage.

Regional insights

The study's global and regional approach reveals important differences in emissions intensity, industry scale, capital requirements, and abatement costs. Each region's unique feedstock and energy mix creates opportunities to leverage local advantages and accelerate decarbonization:

- **Production volume variability:** China leads with the highest projected chemical production capacity in 2050 (734 Mt), while Europe has the lowest (149 MT).
- **Shifting capacity shares:** By 2080, North America, China, and the Middle East are expected to approximately double their chemical capacity, while Europe's capacity increases by about 30%.
- **Regional technology mix:** Feedstock and fuel choices vary by region, impacting emissions intensity. For example, Europe's use of heavy liquid feedstock results in lower emissions than China's coal-based production but higher than North America's largely natural gas liquid inputs.
- **Abatement technology consistency:** The dominant abatement technologies are similar across regions, except for China, where lower CapEx for electrolyzers and renewable electricity make green hydrogen more attractive.
- **Cost learning and deployment:** Abatement costs decline in regions as technology deployment increases, but feasibility is influenced by local factors such as geology for CO_2 storage, renewable energy availability, and infrastructure.

The chemical industry has experienced robust growth that is expected to continue to increase, driven by rising global populations and expanding economies. This growth, coupled with a roadmap for emissions reduction, could position the sector to deliver both economic and environmental value well into the future. While absolute zero emissions by 2050 is likely out of reach, the industry's movement toward deep decarbonization is achievable.

A key insight from the study is the importance of collaboration and cost-sharing across the value chain. The "green premium"—the cost differential for low-carbon products—is highest upstream but diminishes downstream, highlighting the need for coordinated action to unlock demand and accelerate progress. Collaboration across the value chain can best economically distribute green premiums across the largest available volumes to optimize (and increase feasibility) the cost of goods sold (COGS) per piece of abated end products. Establishing credible, comparable product carbon footprint (PCF) methodologies will further empower buyers and drive market activation for sustainable products.

Decarbonizing chemical building blocks is not only a challenge but also a potential opportunity for the industry to lead in sustainability, create new value streams, and strengthen global competitiveness. The study identifies priority end markets—such as packaging, food and beverage, personal care, and automotive—where demand for lower-carbon products is strongest with potential for significant impacts. For example, in the high-density polyethylene (HDPE) bottle market, China stands out with an advantageous green premium.

By working together, industry stakeholders can mobilize capital, drive innovation, and accelerate the industry's transition to a low-emissions future.

What gaps remain?

This study provides a strong foundation for action, highlighting five key areas for consideration with a focus on industrywide collaboration, CEO-level engagement, and collective stakeholder action:

1. **Financing:** Innovative green finance mechanisms and policy support can narrow the sizable investment gap, enabling the industry to scale up decarbonization efforts.
2. **Product carbon footprint (PCF) calculations:** Harmonizing PCF methodologies will enhance transparency, comparability, and market confidence, empowering buyers and sellers alike.
3. **Policy:** Clear, stable, and supportive global policies will reduce investment risk and provide the certainty needed for long-term planning.
4. **Value chain collaboration:** Building robust markets and partnerships for low-carbon chemicals beyond the current state of bespoke bilateral deals and regional initiatives will accelerate adoption and create new growth opportunities.
5. **Engineering and talent shortage:** Investing in workforce development and innovation will ensure the industry has the skills and capabilities needed to commercialize and scale new technologies.

With a spirit of collaboration, innovation, and shared ambition, the chemical industry is well-equipped to lead the way toward a sustainable, low-emissions future—delivering benefits for businesses, consumers, society, and the planet.

Background and overview

A paradigm shift is occurring in the lower-emissions transformation of the chemicals and downstream sectors. Both the size and urgency of this transformation justifies attention and resources from the players within and beyond the industry. This work aims to provide evidence-based insights to the stakeholders of the chemical industry transformation. Chemicals are considered both hard to abate and essential for modern life. The chemical industry is expected to experience significant growth throughout the next half-century as global populations increase and emerging economies mature, driving development and consumption.

Chemicals are part of nearly every end-use product or material. More than 90% of manufactured goods contain chemicals.[10] The chemical industry produces products in millions of metric tons, and current processes are energy and capital intensive and rely heavily on fossil fuels. The diffuse and sometimes large presence of chemicals in diverse end-use products and materials means that reducing emissions from chemicals production will be key to reducing scope 3 emissions across the rest of the value chain.

This study focuses on 10 building block chemicals that play outsized roles in today's chemical industry:

1. Ammonia
2. Benzene
3. Butadiene
4. Chlorine/caustic
5. Ethylene
6. Hydrogen
7. Methanol
8. Propylene
9. Toluene
10. Xylene

Today, these chemicals account for an estimated 70% of all chemical industry emissions[11] (David Yankovitz, 2024; Catherine Huyett, 2025), and based on data from Chemical Market Analytics by OPIS, the four regions covered in this study—North America, Europe, Middle East, and China[12]—collectively accounted for 671 Mt of production of these chemicals and 729 Mt of direct (scope 1) and indirect (scope 2) CO_2 emissions in 2023, the reference year for this study (see appendix B.)

The emissions abatement challenge is exacerbated by the expected growth in chemicals and materials demand globally. For example, production of the aforementioned 10 chemicals in the four study regions is expected to double by 2080.

A paradigm shift is needed to dramatically reduce emissions from chemicals production. This will require abatement pathways that meet two key criteria:

1. **Technical feasibility.** This includes a foundation of abatement technologies that are sufficiently mature to be commercially deployed within the time horizon of climate commitments at a scale commensurate with the industry needs.
2. **Commercial viability.** Returns on abatement capital investment need to justify the significant resources required. Typical arguments for achieving adequate returns include ensuring sufficient market demand for low-emissions chemicals, stimulating end-market willingness to pay a green premium, and offsetting costs via government incentives.

Reducing emissions has become a priority for chemical companies worldwide, in part, from mounting expectations from consumers and shareholders,[13] (King, 2025), resulting in net-zero pledges.[14] Recent geopolitical and economic shifts have further compelled organizations to reassess their sustainability strategies, emphasizing transparency, flexibility, and resilience in response to evolving policy landscapes[15] (The Conference Board, 2025).

Globally, as regulatory scrutiny and public concern continues, demand for sustainable, lower-emissions products has grown. Some consumers are increasingly willing to choose—and sometimes pay a premium for—products that align with their environmental values, as seen in sectors like automotive and agriculture. Brands that demonstrate credible sustainability practices, such as regenerative agriculture, are more likely to earn consumer trust and loyalty[16] (ADM, 2023).

In this dynamic environment, chemical companies should adapt to rapidly changing policies and market expectations. Scenario planning is essential to navigate uncertainty and inform investment in emissions reduction and sustainable innovation. Leaders in the industry aim to balance societal sustainability goals with profitability, but investments in emissions abatement technologies often involve significant cost and risk, especially as many solutions are unproven at scale.

To justify these investments, executives often require robust, evidence-based narratives and quantitative business cases that address why a particular solution is right for their company and how it compares to alternative projects. Factoring in demand for lower-emissions products, potential return on investment (ROI), and the availability of market enablers is critical. Creative approaches—like aligning abatement projects with planned maintenance or capacity expansion—can help optimize costs.

Understanding demand for low-emissions products enables chemical producers to prioritize investments and develop roadmaps that target key end-use sectors, thereby reducing some investment risk. Demonstrating a positive ROI is crucial, especially as executives face pressure for short-term financial returns amid geopolitical uncertainty and changing policy environments[17] (Deloitte Consulting LLC, 2025). Insights into consumers' willingness to pay price premiums for sustainable products can strengthen the business case for abatement investments, particularly for early movers seeking to enhance carbon competitiveness. For these investments to succeed, robust market mechanisms—such as voluntary carbon measurement standards, certifications, and data or credit trading platforms—would help facilitate the marketing and sale of lower-emissions products across the value chain.

Ultimately, this study aims to equip the chemicals value chain with data-driven insights to help them achieve their emission reduction targets. Understanding the feasibility and practical pathways to these goals is important for guiding effective, actionable strategies toward a more sustainable future for the chemical industry.

Study objectives

The objective of this study is to provide insights to the potential future of chemical industry emissions. This will enable chemical industry and value chain leaders to develop informed strategies for emissions reduction that consider their customers, capital availability, and technical knowledge and other factors. Each company's production methods and geographical footprint determine which abatement technologies could offer the best mix of feasibility, affordability, and emissions reduction.

In addition to addressing this critical question, this study also aims to understand the ways in which abatement technologies, end- market demand, and the GHG emissions measurement ecosystem will influence the chemical industry's ability to reduce emissions. For instance, while abatement technology availability and commercial readiness are crucial aspects of the industry's ability to decarbonize, the demand of end markets and the ability for the market to credibly and efficiently quantify the carbon footprint of lower-emissions products will also be important in determining scale of abatement and sales.

This study was completed by Deloitte and Princeton University's Andlinger Center. The Princeton University team that developed the techno-economic model was led by researchers who co-led Princeton's 2021 Net-zero America study[18] that quantified alternative pathways by which the US economy could fully decarbonize by 2050. With the current study, the Princeton team brings its knowledge and expertise on decarbonization modeling to the global chemical industry. Chemical Market Analytics by OPIS provided a large chemical industry database to enable this study's analytical approach.

Several existing studies evaluate the future of emissions reduction in the chemical industry[19] (Catherine Huyett, 2025; ICCA and CarbonMinds, 2024). These studies provide valuable data that industry stakeholders can use to inform decision-making and strategic planning around building block chemicals and value chain decarbonization. This study complements those studies in several important ways.

This analysis includes a global scope with region-specific analyses to capture the global nature of the chemical industry. Maturity of abatement technologies and economic demand are both critical factors for decarbonization and serve as pillars of this analysis, which is unique compared to previous studies. Specifically, the techno-economic model is a bottom-up, asset-by-asset evaluation of abatement options for nearly 4,000 assets at almost 2700 chemical facilities (operating in 2023) across the four largest production regions. The model considers the commercial maturity of abatement technologies. The abatement technology costs to retrofit existing facilities decline according to learning curves that vary by region, technology, and technology deployment rate. For the deployment of abatement at new-build facilities required to meet projected demand growth to 2080, estimates are used consistent with the learning curves. To maintain anonymity, regional results are presented in aggregated form, which provides a global outlook of the industry.

A key distinguishing feature of this study is its forward-looking analysis using a scenario planning approach[20] (Heijden, 2011). The approach recognizes significant real-world uncertainties inherent in any analysis looking half a century into the future and explores how these might impact the chemical sector's decarbonization investments and the resulting emissions reduction.

While the study was conducted without financial support from the chemical industry, the approach and inputs were reviewed with internal (Deloitte and Princeton) and external industry and subject-matter experts throughout the study's development. The engagements included three convening sessions (two at Princeton and one at Deloitte's office in Belgium) to solicit feedback from chemical industry players, supplemented by informal one-on-one interviews and content reviews. Third-party, single-blind interviews were also conducted with GHG emissions measurement ecosystem players and chemicals downstream customers. Input and feedback were carefully and independently considered by the study's core team and implemented where they advanced the study's goals while maintaining alignment with the unbiased and independent nature of the study.

Guiding questions

This study focuses on answering key questions that will enable chemical industry stakeholders to make informed decisions regarding emissions abatement strategy and implementation. The most prominent of these questions is: What are plausible futures of chemical industry emissions? Situated within this question are many contributing factors such as the capital expenditure requirements, abatement technology maturity, industry learning rates, and many others. The original idea for this study emerged because although many companies have published ambitions to reduce emissions, typically by 2050[21] (Net-zero Tracker, n.d.), that goal seemed to warrant evaluation due to the sizable emissions remaining combined with feasibility and scalability challenges.

Figure 2. Guiding questions across study dimensions

	Technology	Markets	Ecosystem
Problem statement	Abatement technology is developed and adopted on a learning curve. It will take time for technology to scale, and there will be variations by region.	There is variation in the feasibility and willingness to pursue decarbonization across different end markets due to factors such as cost of abatement and willingness to pay	While they account for 70% of the chemical industry's emissions, building block producers have challenges implementing abatement technologies without global collaboration and adequate incentives
Hypotheses	**Building block emissions will reach net-zero at different rates based on region; it is unlikely that global emissions will reach net-zero by 2050.**	**Some end-market segments will see a higher adoption of decarbonization solutions. This may be driven by willingness to pay for low-emissions products with a certified label.**	**Building Block producers in certain regions will be able to make significant headway in reducing emissions due to larger investments and advantageous regulatory environments.**
Supporting questions	• What is the size of the emissions reduction opportunity in both volume and dollars? • How will emission reduction efforts vary across geographies and what are the regional implications for those derivatives? • What could a sample global footprint look like for the industry?	• What is the demand for low-emissions chemicals in key end-market segments, and what is their likely willingness to pay? • How will end-market willingness to pay impact ability of the chemical industry to decarbonize? • How will building block emissions reductions impact emissions of key end products?	• What are the key global regulatory developments, and how will this influence the industry's approach to reaching net-zero emissions? • What impact does transparency in carbon value, tracking, and certification have on the industry's ability to decarbonize?

Unlike other studies, this study did not base its results on the assumption of achieving full emissions abatement by 2050. This is due to concerns about economic feasibility and the extensive need for capital, as well as sizable demand required for lower-emissions products to drive a profitable return on the significant investments required.

The study posits that the capital requirements for emissions reduction in the chemical industry are so large that it will not be feasible for the industry to directly cover these costs. However, strength of government coordination can greatly accelerate achieving decarbonization. It hypothesizes that government cooperation within and beyond the industry will be necessary to reduce and share costs. For instance, government policies such as emissions reduction incentives could enable the business case and a flow of investment to benefit the industry. Additionally, if industry players are willing to (appropriately) cooperate and share knowledge gained from their abatement initiatives, the learning rate of abatement adoption will increase and drive a reduction in the cost per ton of CO_2 abated. This was tested by altering the level of cooperation within three scenarios by way of variations in the learning rate assumptions, which, combined with the rate of capital expenditure, impacts the capital expenditure totals needed for the industry to reach net-zero. Expected outcomes regarding changes in demand for low-emissions products were also evaluated within the same three scenarios, which tested whether strong market demand could accelerate abatement timelines.

The study also included a complementary market assessment to investigate how likelihood of investment in lower-emissions chemical products varies across end-use markets. This assessment used three main categories of factors that will drive adoption including:

3. **Value chain complexity,** which includes considerations such as barriers to change, cost of product substitution, environmental attributes, policies, market competition;
4. **Demand,** which includes considerations such as sustainability maturity, cost sensitivity, corporate social responsibility (CSR) requirements, demand ($) and growth; and
5. **Impact** of the the volume of chemicals in that end market's value chain.

The study used a prioritization matrix comparing end markets and relative adoption drivers to reveal the end markets with the highest likelihood for investment in lower-carbon chemicals.

The deployment readiness of abatement technologies is paramount, because if technologies have not been developed or are not mature enough to implement, then they are unable to reduce emissions. As mentioned earlier, the study assumes that the abatement technology cost will follow a learning curve, and these curves will vary by region and technology. The study considered the current level of maturity and/or commercialization at scale of most of the available abatement technologies and examined the factors that influence the development and adoption rates of these technologies across different regions (e.g., access to capital, government regulations and polices, and available infrastructure). These factors are then applied to the study's three scenarios to estimate capital expenditure for technology deployment for each case.

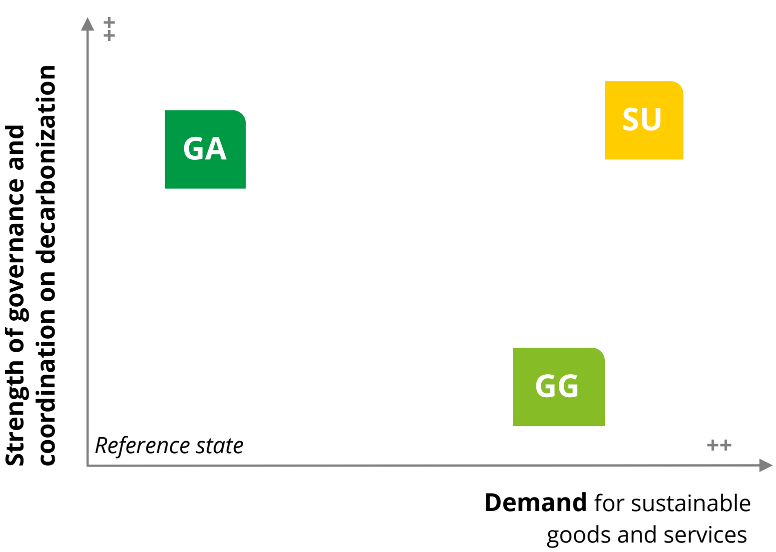
Scenarios overview

This study uses a scenario analysis approach[22] (Heijden, 2011) in the model and market assessment to compare alternative possible future states of emissions reductions in the chemical industry. The scenarios are not predictive future forecasts, but rather narratives to make sense of potential futures that could plausibly evolve. It is important to note the scenarios presented herein are illustrative and are intended solely for the purpose of exploring a range of potential future outcomes. No scenario should be interpreted as a prediction or a preferred or recommended future.

Rather, these scenarios are designed to highlight the inherent future uncertainties and complexities. Given the unpredictable and unresolvable nature of future developments, the scenarios are not exhaustive and do not represent all possible outcomes, but rather a range of possibilities, which might be broadly representative of different futures, even though none, specifically, are likely to play out exactly as described. The method involves building scenarios around two drivers of change that could significantly impact the focal question of interest, "How will the global chemical sector evolve in response to sustainability priorities over the next half-century?" in consultation with industry stakeholders. To frame the scenarios, two high-impact drivers were identified for which the direction and strength of change are highly uncertain over the next half-century (figure 3). All three scenarios are driven by external forces influencing the trajectory of the industry. There is no scenario of the chemical industry driving to net-zero in a vacuum, without important external factors and influences. The drivers of change include:

1. Strength of governance and coordination on decarbonization, and
2. Demand for sustainable goods and services.

Figure 3. A detailed look into the techno-economic model



Sustainable United

This is **strong governance** with nations imposing enabling regulations and incentives, with **strong collaboration** across the sector, and **high willingness to pay** across product value chains.

Green Authority

Although there is **strong governance** with nations imposing enabling regulations and incentives, **collaboration is limited** across the sector and **customer willingness to pay** remains low.

Grassroots Green

There is **consumer-led demand for sustainable products**, especially in higher-income groups. However, geopolitical and economic tensions **limit governance and collaboration**, resulting in lackluster policy support and subdued innovation.

Strength of governance and coordination on decarbonization encompasses many aspects of government involvement and value chain coordination on chemical emissions transformation initiatives. For example, values at the high end reflect more robust emissions policies that support reductions, while industrial policy and strong information-sharing among industry players accelerate cost learning for successive abatement projects. Low values correspond with limited government involvement and more fragmented approaches to abatement.

Demand for sustainable goods and services reflects consumer and customer desire to purchase and pay for goods and services with sustainable attributes, even at premium prices, along the value chain. Values at the high end of the axis correspond to scenarios where consumer support for sustainability is strong, and consumers have a willingness to purchase products with these attributes. Key considerations used for placement along this axis include industry alignment on carbon measurement methodologies, policy alignment with the goal of global decarbonization, and macroeconomic health and stability.

More detailed descriptions of the scenarios are included in Appendix 1 with quantitative assumptions detailed in Appendix 2.

Sustainable United (SU) scenario overview

In the Sustainable United scenario, the world is characterized by strong global governance and widespread demand for sustainable products. This deeply collaborative environment sees governments, businesses, and NGOs united behind the climate agenda and broader sustainability goals, including biodiversity and water resilience. Strong government coordination facilitates deep collaboration across regions and economic sectors, and barriers to corporate collaboration are reduced. Coalitions comprising government, industry, and environmental/social NGOs design policy, regulatory, and incentive measures to drive sustainable change. Cost reductions in technologies for carbon capture, utilization, and storage (CCUS), along with circular and bio-based feedstocks, are achieved, although deployment is partially offset by broader efforts to protect other natural and social capital values. Regulations, to, for example, limit biomass feedstock sourcing to organic municipal waste, native grasses, agricultural residues, and forest residues.

Adoption of waste sorting and collection systems is strong, and innovation in data science and AI helps drive down the cost of clean technologies, facilitating technology exchange and accelerating learning. Consistently strong governance builds trust in governments and businesses that underpins acceptance of technological change, and accelerated clean infrastructure development benefits from authentic engagement and participatory design practices. Furthermore, a pervasive bottom-up demand for sustainable products and services drives widespread adoption of waste reduction, recycling, and product reuse, leading to the near elimination of single-use plastics globally. The chemical industry sees broad alignment on voluntary measurement, tracking, and certification frameworks; substantial cost reductions in clean electricity and heat supply systems, and high levels of willingness to pay for low-emissions energy and products.

Quantitatively, capital is deployed at rates sufficient to retrofit all facilities existing today (2023) and new builds by midcentury: 2050 for North America and Europe, and 2060 for China and the Middle East. The first abatement projects are assumed to come online in 2030. Any capacity expansions are assumed to include abatement but do release residual emissions.

Green Authority (GA) scenario overview

In the Green Authority scenario, strong global governance drives progress through regulation and collaboration, despite skeptical consumers. Global governments unite behind strengthened global institutions to tackle climate change, preserve biodiversity, and address natural capital risks. International agreements across economic sectors are facilitated, with proactive regulators reducing barriers to corporate collaboration. Governments and industry collaborate to design and implement standards, policies, regulations, and incentive measures to drive top-down sustainable change. However, consumers and communities remain resistant to change, limiting the effectiveness of these measures.

Despite this ambivalence, strong regulations and government coordination enable substantial progress in sustainability initiatives. The chemical industry sees broad alignment on measurement, tracking, and certification frameworks, as well as substantial cost reductions in clean electricity and heat supply systems, but low levels of willingness to pay for low-emissions energy and products. Accelerated cost reductions in technologies for CCUS and bio-based feedstocks are achieved, with sourcing limited to sustainable biomass feedstocks. Mechanical and advanced recycling technologies see accelerated cost reductions, and government and industry implementation of waste sorting and collection systems increases consumer awareness and participation, despite their concerns about higher costs. However, societal distrust in governments and corporations continues to hinder the full potential of digital technologies, resulting in grassroots opposition and legal challenges that delay infrastructure projects. Despite these challenges, the chemical industry benefits from broad-based government commitment to sustainability, leading to significant progress in global sustainability commitments on climate mitigation and biodiversity preservation.

Quantitatively, the pace of emissions reductions is limited because capital is assumed to be deployed at a slower rate than in SU, which stretches the timeline for abating building block emissions.

Grassroots Green (GG) scenario overview

The Grassroots Green scenario is marked by consumer-led demand for sustainable products driving localized progress with less governmental regulation, slower rates of innovation, and limited technology transfer. Global tensions and national interests limit cooperation among nations and corporations, with “buy local” procurement policies driving domestic investment in manufacturing and innovation. Low rates of technology transfer and fragmented supply chains result in a significant cost premium for advanced clean technologies.

Competition rather than cooperation underpins corporate practice, leading to distrust among the broader public and hindering collaboration across the value chain. Supply chains lack resilience, and community opposition to development, along with cumbersome permitting processes, hinders infrastructure project delivery. Consumers, particularly in higher income brackets, show a willingness to pay significant premiums, driving some demand for sustainable goods. Clean electricity and heat supply systems see steady but uneven growth at a significant cost premium to carbon-intensive systems. CCUS and bio-based feedstocks expand locally despite high costs, with bio-based feedstocks growing in the tropics and subtropics, despite threats to natural ecosystems. Mechanical and advanced recycling technologies, along with waste sorting and collection systems, expand sporadically, driven by local agendas to reduce conventional feedstock demand and local pollution. However, limited adoption of voluntary measurement, tracking, and certification frameworks, along with high capital costs, continues to slow progress, especially in low- and low-middle-income countries.

Quantitatively, capital is assumed to be deployed at a slower rate than in the GA scenario, which further stretches the timeline for abating building block emissions.

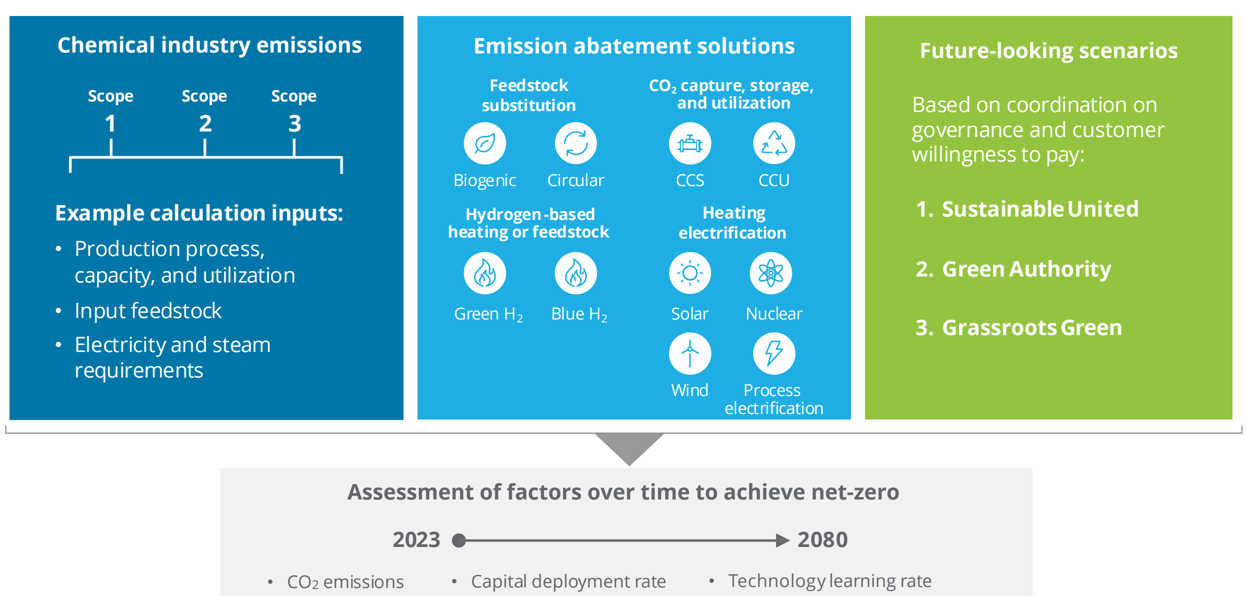
Reference state

All scenarios use 2023 data as the starting point. No business-as-usual future scenario is included, since that does not seem like a plausible option for the future given the pressure hard-to-abate industries are facing from society, governments, and other organizations. The results section will include a view of the reference state that projects current-state scope 1 and 2 emissions intensities scaled by 2080 production volumes, which can be used to visualize what the future would look like with no abatement technologies implemented.

Techno-economic model approach and results

The above scenario narratives qualitatively describe alternative futures of the state of the world that would impact sustainability priorities over the next half-century, including abatement investment priorities. Capital investment levels and unit costs of abatement are estimated via a techno-economic assessment of decarbonization technologies to determine the least-cost abatement options for existing and future building block chemicals production facilities, based on projected regional demand growth. As previously described, this analysis assumes each facility is decarbonized to as low as practicable and excludes the cost of carbon removals required to offset the residual emissions. Figure 4 summarizes the quantitative modeling approach used in this study. The quantitative analysis is anchored in two foundational data sets.

Figure 4. Overview of modeling approach



The first source is a database characterizing building block chemicals production assets operating in 2023 (the most recent full year with available data) provided by Chemical Market Analytics by OPIS. The database includes about 4,000 individual production assets, constituting nearly 2,700 production facilities across the four study regions (table 1). For each asset, the database identifies company owner, geographical location, startup year, chemical production process, production capacity and utilization, input feedstock type; intensity inputs per unit production of feedstock, electricity, steam, fuel (excluding steam-raising fuel), and water consumption; and estimated process CO_2 emissions per unit of production (as distinct from CO_2 emissions from fuel combustion or steam raising). Together with assumed regional and/or subregional emissions intensities of grid electricity and upstream methane leakage, scope 1, 2, and upstream 3 emissions can be estimated for each facility in the database.

Estimates of future production levels and new capacity requirements are also included in the database, derived by Chemical Market Analytics by OPIS from region-level projections of demand, imports, and exports. Chemical Market Analytics by OPIS forecasts annual production to 2050 by estimating regional production volumes required to meet anticipated demand arising from direct domestic consumption and/or exports (if any). Historical production volumes are obtained, where available, from government sources or trade associations, and then Chemical Market Analytics by OPIS product experts utilize industry-based estimates to complement the data for remaining geographies and product markets. Country or region-level production is used to calculate an average operating rate based on total installed capacity within the region. For this study, the average operating rate was applied to each individual facility. This study extrapolates the Chemical Market Analytics by OPIS demand estimates from 2050 out to 2080 assuming trendline growth. A simplifying assumption is made that projected production levels of chemicals do not vary between scenarios.

Table 1. Number of building block chemical production facilities operating in 2023 included in the Chemical Market Analytics by OPIS database for the four study regions.

	North America	Europe	China	Middle East	Total
Ammonia	45	57	177	41	320
Benzene	40	47	160	31	278
Butadiene	9	29	55	8	101
Caustic	53	71	177	40	341
Chlorine	52	77	192	41	362
Ethylene	49	48	101	37	235
Methanol	21	17	199	24	261
Propylene	132	94	225	38	489
Toluene	29	26	78	18	151
Xylene	24	20	79	15	138
Total	**454**	**486**	**1,443**	**293**	**2,676**

The second foundational data set encompasses abatement technology process simulations and cost estimates for four classes of abatement technologies that are plausibly commercially deployable in the chemical industry in the next 15 years and for which cost estimates are available:

- CO_2 capture and storage (CCS) or utilization (CCU)
- Hydrogen as heating fuel or chemical feedstock
- Heating electrification using clean electricity
- Feedstock substitution (circular or biogenic)

Some building block production processes are amenable to more than one abatement approach (table 2). Because olefin production contributes the largest emissions among all building blocks, the largest number of abatement approaches were evaluated for steam crackers, one option for which is shown schematically in figure 5. Similar process-flow diagrams for all abatement options with all building blocks are included in Appendix 2, which also includes documentation of process performance, along with capital and operating cost estimates for abatement technologies. Based on these process technology performance levels and costs, estimates of the cost for abatement retrofits to existing production facilities are made. No assessment is made of the execution feasibility of retrofits (land availability, access, services capacity, etc.). In the case of chlorine production, emissions abatement is assumed to follow projected reductions in carbon-intensity of the grid in the region where the facility is located.

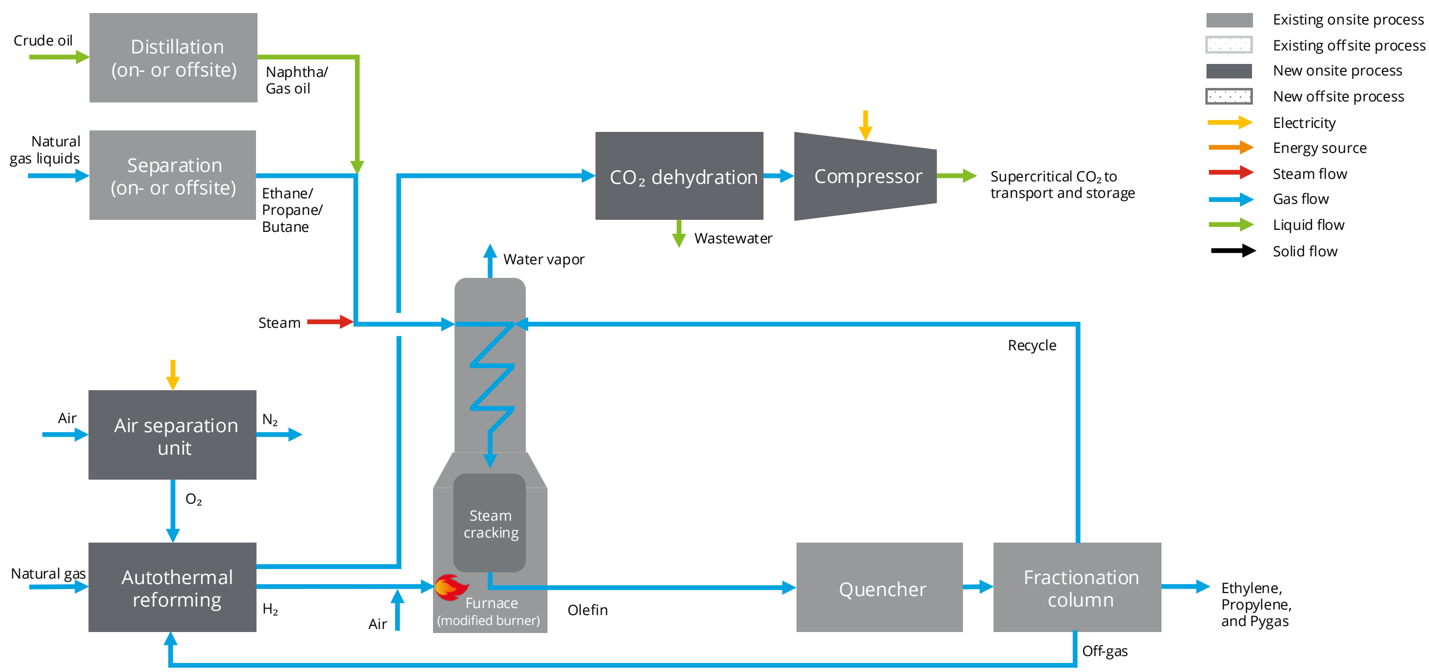
Table 2. Abatement approaches considered for each building block chemical.

			Abatement approach								
			CCS	Hydrogen		Electrification via			Substitute feed		
Building block	Feedstock	Process		Blue	Green	Nuke	Wind	Solar	Circ	Bio	CO_2
Ethylene, Propylene, Butadiene	Ethane, Propane, Butane, and/or Naphtha	Steam cracking	✓	✓	✓	✓	✓	✓	✓		
Ethylene, Propylene, Butadiene	Methanol	Synthesis	✓								
Ethylene	Ethanol	Dehydration								✓✓	
Propylene	Propane	Dehydrogenation	✓								
Propylene	Gas oil	Cat. cracking	✓								
Benzene, Toluene, Xylene	Reformate	Extraction	✓								
Methanol	Natural gas	Synthesis	✓								
Methanol	Coal	Synthesis	✓	✓							
Methanol	H_2 + CCU	Synthesis			✓✓						✓✓
Ammonia	Natural gas	Synthesis	✓								
Ammonia	Coal	Synthesis	✓								
Ammonia	Green H_2	Synthesis	✓		✓✓						
Chlorine/ Caustic	NaCl	Electrochemical	Follows grid carbon intensity								

Note: Double check marks (✓✓) indicate the option is only available for new greenfield capacity, i.e., it is not considered for retrofits at existing facilities. Green hydrogen refers to production by water electrolysis using the least costly clean potential electricity source (nuclear, wind, or solar PV) for the facility under consideration.

Figure 5. Sample process schematic for emissions abatement

C.1.C. Olefin production facility (steam cracker) + blue hydrogen (natural gas feedstock)



Note: Pictured is low-carbon production of olefins by steam cracking with CCS. In this design, hydrogen is produced by autothermal reforming (ATR) for use as steam-cracker fuel in lieu of natural gas. The CO2 by product of the ATR is captured and compressed for pipeline transport to underground storage. Process schematics for other abatement technologies for olefins and other building block chemicals are provided in Appendix 2.

The two foundational data sets were supplemented by informed assumptions around abatement project cost-learning rates, project construction times, and other parameters. Additional regional or subregional assumptions include emissions intensities over time of grid electricity consumed at a facility, upstream methane leakage rate associated with feedstock and fuel supply, wind and solar energy resource qualities, and others.

The foundational data sets and additional assumptions allow estimates of scope 1, 2, and upstream 3 emissions for each facility with and without abatement. **Scope 1** refers to emissions generated at the facility site. Scope 1 includes fuel combustion and additional fuel combusted to raise steam, as well as process emissions reported in the Chemical Market Analytics by OPIS database. **Scope 2** refers to emissions associated with the offsite generation and delivery of electricity used at a production facility. **Scope 3 upstream** refers to emissions associated with the extraction and delivery of fuels and feedstocks used at the production facility. Scope 3 facility emissions are reduced when an alternative fuel or substitute feedstock is part of the abatement approach and when methane leakage is reduced.

In addition to emissions estimates, key facility-level analytical outputs include abatement capital investment requirements and levelized production costs, both of which depend on how much cost learning has occurred for a particular abatement technology by the time a project is deployed. For a given building block chemical, facility-level calculations are carried out for a region assuming each facility adopts the same abatement technology over the entire time frame of the analysis. In turn, the rate of deployment is based on an assumed availability of investment capital, which varies by scenario, as described below. For building blocks with more than one abatement technology option, each option is evaluated to determine which technology offers the lowest cost of abatement in a region over the analysis time frame.

For each abatement technology, total installed capital cost is estimated for each abated facility. The simplifying assumption is made that once capital has been deployed to abate a facility, that facility will not need any additional capital investment to maintain or replace the abatement system throughout the modeling time horizon. This may underestimate replacement capital needs. In the case of abatement approaches involving procurement of clean electricity (nuclear, wind, or solar photovoltaic), the capital costs for electricity generation are assumed to be part of the required abatement capital. Reference capital cost estimates for abatement technologies deployed in North America (detailed in Appendix 2) are adjusted by location factors to estimate costs for other regions (table 3). Capital costs scale with a facility's production capacity using a scaling exponent that varies with the technology.

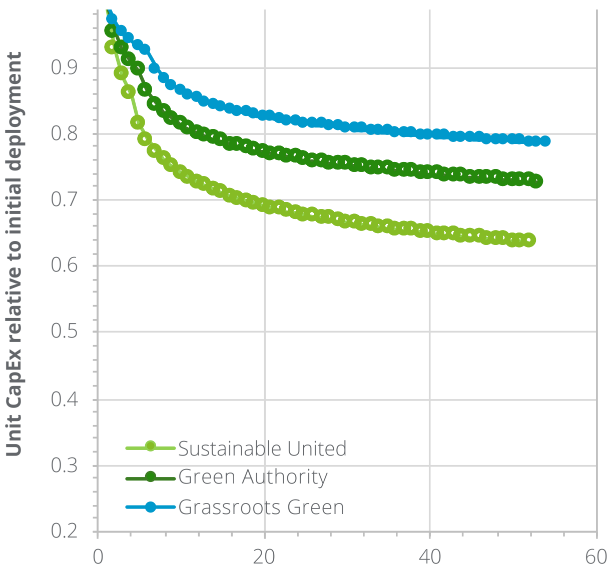
In each scenario, the first abatement project for each building block chemical is assumed to begin operating in 2030 in each region. After the first deployment in a region, cost learning is incorporated into capital cost estimates, with learning rates assumed to vary by technology and by scenario. For a given technology, cost learning is assumed to be slower during an "early mover" phase of deployment and accelerate as commercial experience grows.

Table 3. Installed capital cost assumptions for abatement technologies by region.

		North America	Europe	Middle East	China
Technology	**Reference capacity**	CapEx (2024$)	CapEx as % of North America CapEx		
CO_2 capture	1.7M tCO_2/yr	\$853M / tCO_2/y	100%	46%	46%
NG steam cracker	2.3M tEthy/yr	\$2,585M / tEthy/y	100%	43%	43%
H_2 steam cracker	--	10% of CapEx for natural gas-fueled cracker (for burner replacement)			
Electric steam cracker	--	10% of CapEx for natural gas-fueled cracker (for heating elements)			
Electrolysis	1.1 GWe	\$3,900M / kWe	100%	50%	50%
Recycled plastics	0.05 tPyoil/y	\$2,205M / tPyoil/yr	100%	50%	50%
Wind power	1 GWe	\$3.2M / MWe	100%	38%	38%
Solar power	0.1 GWe	\$1.5M / MWe	100%	93%	93%
Nuclear power	1 GWe	\$10M / MWe	100%	46%	46%

Different levels of assumed information and technology-sharing across scenarios imply the most-rapid learning occurs in Sustainable United and least-rapid in Grassroots Green. Figure 6 presents an illustrative set of cost-learning curves—for steam-cracker abatement via CCS in North America.

Figure 6. Illustrative scenario-based abatement cost learning with increasing technology deployments.



Note: The pictured learning curves are for steam cracker abatement via blue hydrogen fueling in North America.

The Supplementary Information spreadsheet includes learning curves for all other technologies and regions modeled in the study.

In contrast with using a back-casting exercise to model a cost-optimal pathway to reach zero emissions by a target date without consideration of key practical constraints, this study uses forward-looking modeling based on capital availability for abatement projects, arguably the most significant practical constraint. A consistent set of assumptions is adopted across all three scenarios and across all four regions of focus in this study. This introduces the possibility for systematic error bias but preserves the validity of relative differences in results across scenarios and regions. While the absolute value of a specific output may be uncertain for a given year, relative trends should hold.

To quantify the scenarios, annual average levels of capital investment in emissions abatement projects for each building block chemical across the industry are assumed, as discussed further in the results section below. Abatement capital is most abundant in the Sustainable United scenario and least abundant in Grassroots Green.

For each building block chemical, the assumed capital deployment rates and the time-dependent trajectories of facility-level abatement costs are factored in to calculate the year by which emissions from all existing facilities are abated, and the following aggregate regional metrics are reported over time for each scenario:

- Annual scope 1, 2, and 3 greenhouse gas emissions "well to gate"
- Annual capital deployed over time (in constant 2024$)
- Cumulative capital deployed over time (in constant 2024$)
- Time trajectory of (anonymized) facility-specific, levelized costs of abatement

While a full analysis of current regulations was not in scope for this study, the model did include assumptions about potentially significant scenario-dependent, policy-driven impacts. While future policies are not directly factored into the model, future government intervention through policy is captured implicitly. For instance, scope 2 electricity decarbonization rate assumptions were adapted from the literature[23] (Fanran Meng 2023). Assumptions around upstream methane leakage rates considered announced methane reduction pledges and best available methane data[24] (Climate & Clean Air Coalition , n.d.) from the IEA[25] (IEA, 2025).

For additional discussion and documentation of the techno-economic modeling approach, assumptions, and limitations, see appendices 1 and 2.

Key techno-economic model results

Techno-economic modeling provides insights into the impact of capital availability on the pace, scale, and cost of emissions abatement over time and across regions.

Abatement technology options and costs

For each study region, the model identified the emissions abatement technology that would provide the lowest levelized cost of abatement for each facility producing a given building block chemical. Table 4 indicates the primary (least cost) and secondary (next lowest cost) abatement option in a region for each building block chemical.

- For **olefin** production, blue hydrogen provides the lowest-cost abatement in North America across the full modeled time horizon. In the Middle East, blue hydrogen is least costly initially, but the electrified cracker option using renewable electricity has the lowest abatement cost starting in 2040, which is assumed to be the first year cracker electrification is commercially deployable in any region. In China, green hydrogen produced using renewable electricity is the least-cost option initially but gives way to cracker electrification with renewables or nuclear electricity supply from 2040.

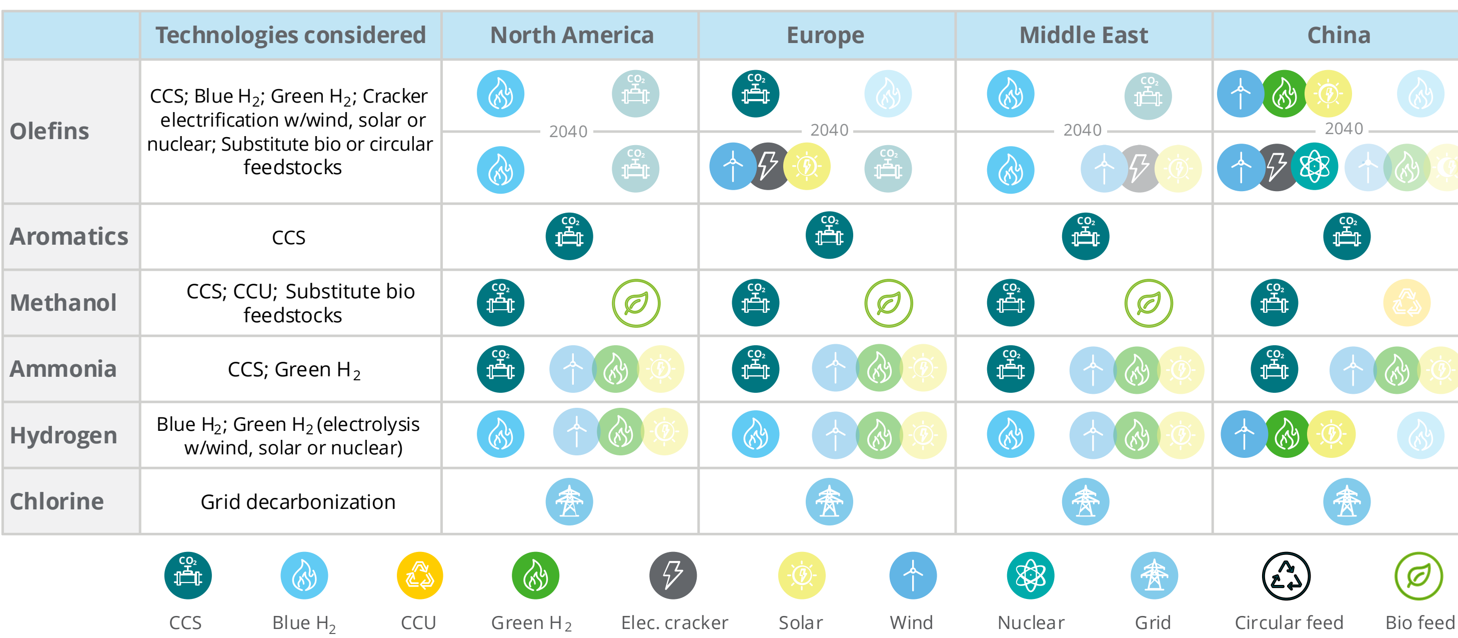
- For **propylene** (not from steam cracking), aromatics, methanol, and ammonia production, CCS is the least-cost option in all regions over the entire time frame of the analysis. In the case of methanol and ammonia, CCS costs are moderated by the ease of capturing high-purity process CO_2, along with lower-purity combustion-derived CO_2.
- For **hydrogen** production, methane reforming with CCS is the lowest-cost technology option in all regions, except China, where electrolytic production using low-cost wind power, combined with relatively high natural gas prices, makes electrolytic production the most competitive option.

The level of abatement achievable with the different technologies in table 4 varies. For example, blue hydrogen, which involves pre-combustion capture of CO_2, enables nearly 100% of CO_2 to be captured, whereas post-combustion capture of CO_2 that characterizes the CCS abatement option in this study captures only 95% of emissions.

For a given chemical, in each region the left-hand icon represents the technology evaluated to have the lowest levelized cost of abatement. The right hand icon represents the abatement technology with the next lowest cost. For olefins production outside of North America, the lowest-cost technologies before and after 2040 are different.

Table 4 includes circular and biogenic feedstocks as abatement options, but they are not least-cost abatement options in any region. Bio-based methanol is the second-lowest-cost option in some regions. Though not promising as abatement options, biogenic and circular feedstock substitution (mechanical and, to a lesser extent, chemical recycling options) tends to be motivated by drivers other than abatement cost reduction, like societal preferences to reduce the reliance on fossil fuels, minimize plastic waste, and for products considered to be recyclable and/or biodegradable. In some cases, consumers are willing to pay a premium for products that meet such criteria. Limitations on feedstock availability and the relatively high cost is likely to limit the capacity for individual facilities.

Table 4. Primary and secondary abatement technology per region by cost.



Note: Broader political and societal factors were not considered for this table.

Substitute feedstocks

Abatement by substitute feedstocks (circular or biogenic) was evaluated, including:

1. Pyrolysis oil from recycled plastics for steam crackers;
2. Synthesis gas from lignocellulosic biomass for methanol synthesis;
3. Corn- and sugarcane-derived ethanol dehydration for ethylene;
4. Pyrolysis oil from lignocellulosic biomass for steam crackers; and
5. Synthesis of hydrocarbons derived from captured CO_2 and low-carbon hydrogen.

Options 1 and 2 were considered deployable for retrofits or new builds. Option 3 was considered technically viable only for new builds. The levelized cost of abatement with these options was far higher (a whole order of magnitude higher with option 5), than with the least-cost abatement approaches enumerated in table 5, but in the case of options 1, 3 and 4, these will likely also be constrained by feedstock availability in some regions. Consider the Sustainable United scenario, for which it was assumed, based on discussions with industry players, that circular and lignocellulosic biomass feedstocks might account for as much as 20% of steam cracker and methanol synthesis feedstocks, respectively, by 2050 in North America and the European Union, and by 2060 in China and the Middle East. Ethanol dehydration was considered as an option for all new-build capacity.

The associated waste plastic and bio feedstock requirements in 2050 and 2080 for the Sustainable United scenario are shown in table 5. To understand waste plastic requirements, in the EU today, about 15 kg per capita of plastic are recycled and about 13 kg per capita are incinerated[26] or, in absolute terms, about 7 million tons per year and 6 million tons per year, respectively. In the US, an estimated 42 Mt per year of plastic waste are generated.[27] This suggests that the waste plastic required to meet 20% of feedstock needs for future steam crackers in Europe and the US may be difficult to source domestically.

Bio-based materials have two very daunting challenges to replace fossil fuels. The first is molecular efficiency. Assuming idealized yield, every metric ton of ethane produces 0.93 tons of ethylene (and the by-product hydrogen is very useful). In contrast, the idealized mass conversion of 1 tonne ethanol to ethylene is only 0.61 metric tons—45% less efficient. This is the well-known “oxygen challenge” of bio-based fuels and chemicals. The second challenge for bio-based materials is simply scale. For perspective on ethanol feedstock requirements for future dehydration units producing ethylene, the annual ethanol production in North America, Europe, and China (in 2024) was 61, 5.5, and 4.5 billion liters, respectively.[28] This also suggests that the required ethanol may be difficult to source domestically. The potential scale is compounded by procurement competition from other hard-to-abate sectors such as aviation and heavy-duty long-haul road transportation, concerns over land-use change, and perceived threats to food security.

The estimates[29] in table 5 assume pyrolysis oils from waste plastics would constitute 20% of input feedstocks for ethylene production, synthesis gas produced by lignocellulosic biomass gasification would constitute 20% of input feedstocks for methanol production, and ethanol would provide 100% of the feedstock for (only) new facilities built to meet future demand growth.

Table 5. Substitute feedstock requirements in the Sustainable United scenario.

	North America		Europe		China		Middle East	
	2050	2080	2050	2080	2050	2080	2050	2080
Waste plastic (million t/yr)	78	88	8	11	239	326	46	141
Biomass (million t/yr)	3	11	1	2	4	8	12	17
Ethanol (billion liters/yr)	—	52	—	0	—	93	—	112

Impact of capital availability on emissions: Example–Steam cracker abatement via CCS in North America

Before introducing broad modeling results, the example of **steam cracker abatement via CCS in North America** is described to illustrate how capital availability impacts emissions reductions trajectories in the model. The modeling finds that an annual average capital investment of $3.2 billion (2024) is required to abate all existing steam crackers in North America by 2050 in the Sustainable United scenario, over and above business-as-usual capital allocation rates. In the Green Authority and Grassroots Green scenarios, when average capital allocation rates are assumed to be constrained to about 30% and 40% (respectively) less than in Sustainable United and technology cost-learning is slower, abatement of existing facilities is delayed until 2063 and 2079, respectively (table 6).

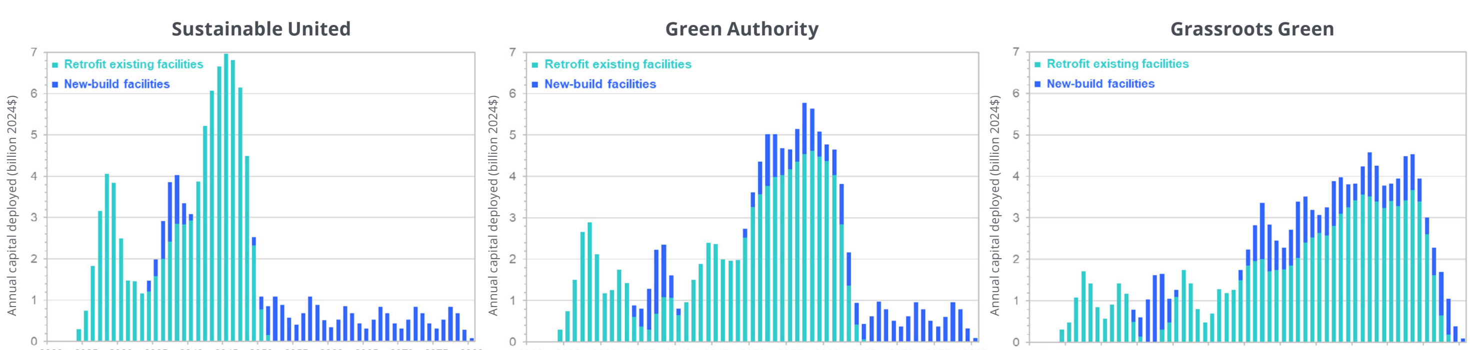
Table 6. Annual average and cumulative total capital invested in abating emissions from existing steam crackers in North America and the corresponding year by which all such facilities are abated.

North America steam crackers	Sustainable United	Green Authority	Grassroots Green
Existing assets abated by:	2050	2063	2079
Avg. decarbonization CapEx (2024$):	3.2B/yr	2.3B/yr	1.9B/yr
Present value of CapEx (2024$):	39B	27B	17B

Figure 8 shows calculated annual capital expenditures across the three abatement scenarios. Expenditure for a given year is the sum of expenditures on multiple projects in various stages of progress through their seven-year development and construction schedules prior to starting commercial operations. Capital for each project is disbursed following a logistics curve during project development.

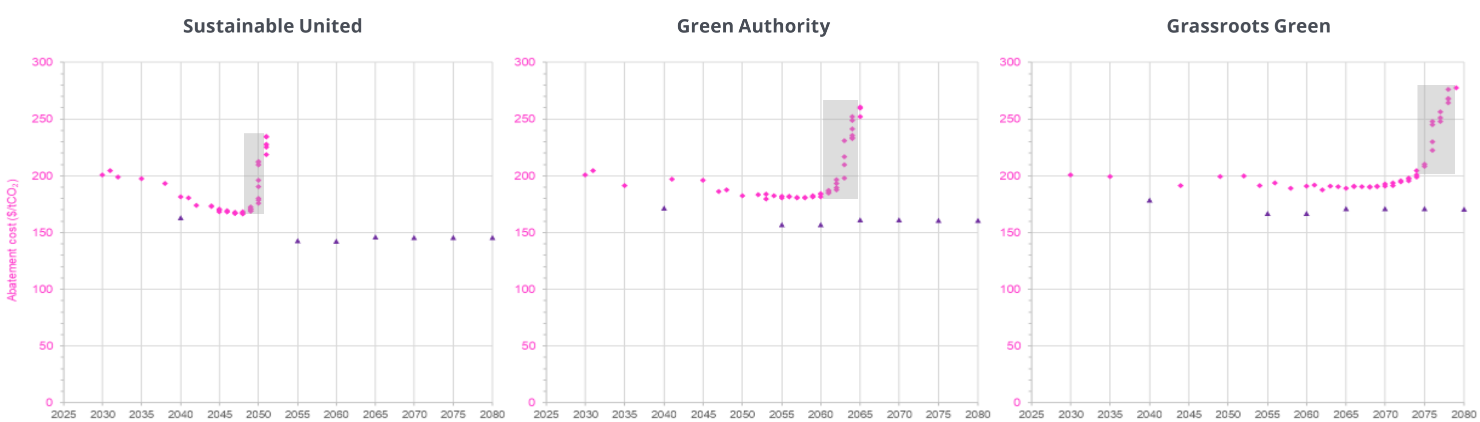
A commonly used metric for comparing cost-effectiveness for different abatement technologies is the levelized cost of abatement, which refers to the average cost over its life span, accounting for all costs (initial investment, cost of capital, operating and maintenance expenses, etc.) and dividing by the total output or benefit (e.g., the amount of CO_2 avoided). Over time, the sequence of existing facilities abated follows by order of increasing levelized cost of abatement, which considers cost learning that is, itself, related to the cumulative number of projects previously deployed. The facility with the lowest levelized cost at any point in time tends to be the largest-capacity facility due to economies of scale, so the order of abatement deployments also tends to follow decreasing capacity.

Figure 8. Annual capital expenditures for abatement of steam crackers in North America via CO2 capture and storage in the Sustainable United, Green Authority, and Grassroots Green scenarios (left to right).



To abate all existing facilities by 2050 in the Sustainable United scenario, three abated facilities are assumed to be operating before 2035, requiring capital spending starting in the mid-2020s and reaching $3B to $4B per year in the late 2020s (figure 8, left panel). Levelized costs of abatement for these initial projects are around $200 per ton (figure 9). Parallel development does not allow for cost learning between projects so costs for all three projects in the Sustainable United scenario are "first-of-its-kind." But projects that come on line after 2035 benefit from cost learning, leading to levelized costs of abatement that decline over time until the mid-2040s, when most remaining unabated facilities are relatively small and/or distant from lower-cost CO_2 storage resources, leading to increasing levelized abatement costs (figure 9, left panel). In practice, these small facilities remaining to be abated in the late 2040s would likely be retired and collectively replaced by larger-capacity facilities that enable scale economy benefits to be captured in abatement costs. Capital spending in the early/mid 2040s is $4B to $7B per year (figure 8, left panel), before declining in the second half of that decade (figure 9) due to the lower absolute capital required for abating smaller-capacity facilities. Post-2050, average annual spending is modest compared with pre-2050 since investments are needed only to abate new-built facilities, which are assumed to be world-scale, built near low-cost CO_2 storage resources, and benefit from cost learning, resulting in levelized costs around $150 per ton (figure 9).

Figure 9. Facility-specific levelized costs of scope 1 emissions abatement (2024$ per tCO_2 abated) using blue hydrogen for steam crackers in North America for Sustainable United, Green Authority, and Grassroots Green scenarios (left to right). Pink diamonds are abatement retrofits to existing facilities and purple triangles are abatement costs for new units as they are built to meet future demand growth. Note: In practice, the small existing facilities with high abatement costs shown with gray overlay, might instead be retired and collectively replaced by larger facilities, potentially in different locations that can capture scale economy benefits, and benefit from access to resources, which results in lower production and abatement costs.

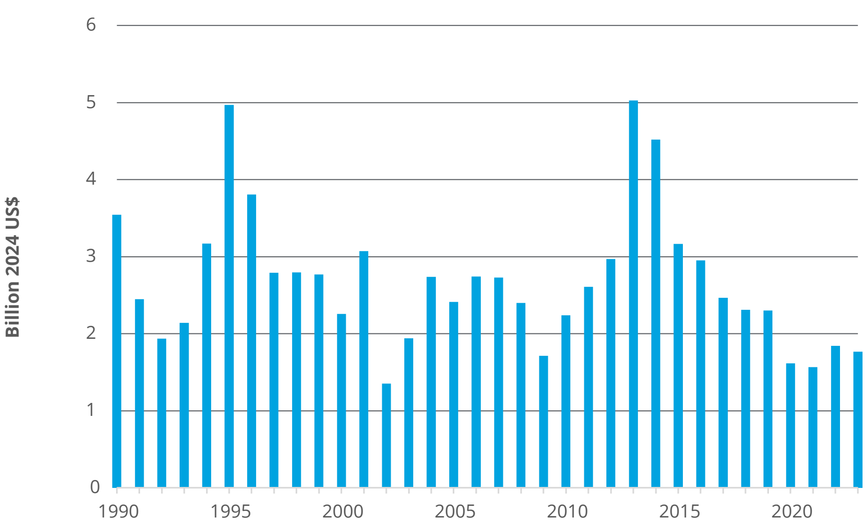


The lower average annual capital deployment levels in the Green Authority and Grassroots Green scenarios push complete abatement of existing steam crackers well beyond 2050 (table 3). The number of facilities abated in the early 2030s is reduced compared with Sustainable United, with attendant lower annual capital requirements (figure 9, center and right panels). Slower cost learning is reflected in increased levelized costs of abatement (figure 9, center and right panels).

The cumulative totals of the capital streams in figure 9 (for retrofit of existing facilities) are shown in table 3. The cumulative emissions abated are the same across all three scenarios due to the same facility scope. The more rapid cost learning that characterizes the Sustainable United scenario results in lower cumulative capital required than in the Green Authority or Grassroots Green scenarios. When capital investments for abatement of new builds are included, the cumulative capital invested over the full modeling time horizon to 2080 would increase 25% to 30% over the levels shown in table 3.

The capital expenditures for steam cracker abatements in the three scenarios can be compared with historical capital spending levels in the North American petrochemical manufacturing industry (NAICS code 325110). From figure 3, annual historical business-as-usual capital expenditures for this industry averaged $2.7 billion per year from 1990 to 2023. The average abatement capital spending for steam crackers alone in the three scenarios range from $3.2 billion per year in Sustainable United to $1.9 billion per year in Grassroots Green (table 3). It is worth noting that capital expenditures for abatement projects would typically be in addition to business-as-usual industry capital investments.

Figure 10. Historical capital investments by publicly traded petrochemical manufacturers in North America (North American Industry Classification System, NAICS) code 325110.[30] NAICS 325110 includes establishments primarily engaged in manufacturing of (1) acyclic hydrocarbons like ethylene and propylene and/or (2) cyclic aromatic hydrocarbons such as benzene, toluene, and xylene, from refined petroleum or liquid hydrocarbons. Aggregate capital invested from 1990 to 2023 was $91 billion (2024$), or an average of $2.7 billion per year.



Capital requirements across all regions and building blocks

The approach described above for steam crackers in North America was applied across all building blocks and all regions. Table 7 tabulates the average annual capital investment needed in the Sustainable United scenario to abate emissions from all existing facilities for all chemicals in this study by 2050 (for North America and Europe) and 2060 (for China and the Middle East). Also shown are the assumed reduced average annual capital investment rates in the Green Authority and Grassroots Green scenarios and the year by which all existing facilities are abated in those scenarios. Notice that in the Grassroots Green scenario for the Middle East and China, the assumed average capital expenditure rate is insufficient to enable all existing facilities to be abated by 2080—the last year included in the model.

In the case of North America, for which historical business-as-usual capital investment data is readily available, the annual investment rate needed to abate olefins and aromatics facilities (NAICS 325110) in the Sustainable United scenario is 1.4 times, and in addition to the historical business-as-usual average annual investment by petrochemical manufacturers ($2.7 billion per year in NAICS 325110). In the Green Authority scenario, it is comparable to the historical average, and about 20% lower in the Grassroots Green scenario. For abatement of methanol and ammonia facilities in North America, the average annual abatement investments are well below historical business-as-usual levels for the corresponding industry sectors, NAICS 325199 (basic organic chemical manufacturing not elsewhere classified, which includes methanol), $1.6 billion per year (1990–2023), and NAICS 325111 (nitrogenous fertilizer production, which includes ammonia), $3.6 billion per year (2005–2023), respectively.[31]. These comparisons with historical capital spending suggest that capital availability for abatement projects may be a bigger challenge for petrochemicals than for methanol or ammonia, at least in North America.

Table 7. Average annual capital deployed to abate all existing facilities in the Sustainable United, Green Authority, and Grassroots Green scenarios.

	North America			Europe			Middle East			China			Total		
Billion $/year (2024$)	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**
Olefins + aromatics	3.7	2.7	2.2	2.7	2.0	1.6	1.2	0.9	0.9	12.1	8.5	6.3	19.8	14.1	11.0
Steam crackers	3.2	2.3	1.9	2.4	1.7	1.4	1.07	0.78	0.84	9.15	6.40	4.49	15.8	11.2	8.63
On-purpose propylene	0.36	0.26	0.20	0.26	0.19	0.15	0.12	0.10	0.07	2.60	1.87	1.56	3.34	2.42	1.98
Aromatics	0.15	0.11	0.09	0.08	0.06	0.05	0.05	0.05	0.03	0.34	0.25	0.21	0.62	0.47	0.38
Methanol	0.38	0.28	0.21	0.40	0.29	0.24	0.25	0.19	0.16	1.86	1.34	1.11	2.89	2.09	1.74
Ammonia	1.0	0.74	0.57	1.04	0.75	0.62	0.30	0.23	0.19	2.08	1.50	1.25	4.46	3.22	2.68
Totals	**5.1**	**3.7**	**3.0**	**4.2**	**3.0**	**2.5**	**1.8**	**1.4**	**1.3**	**16.0**	**11.4**	**8.6**	**27.1**	**19.4**	**15.4**
Existing facilities abated by	**2050**	**2063**	**2079**	**2050**	**2063**	**2080**	**2060**	**2080**	**>2080**	**2060**	**2060**	**>2080**			

Table 7 tabulates the cumulative total capital expenditures needed to abate emissions from all existing facilities in each scenario across the four study regions. The requirements range from $754 billion for the Sustainable United to $815 billion for Green Authority. Cumulative capital is lower in Grassroots Green because not all existing facilities in the Middle East and China can be abated by 2080 at the average annual capital deployment rate stipulated in that scenario. In terms of regional ranking, capital needs are greatest in China (about 60% of the total in Sustainable United and Green Authority), followed by North America, Europe, and the Middle East. By building block, capital for abatement of olefins and aromatics accounts for about 60% of the total in each region. Finally, total cumulative abatement capital deployed to abate existing and new-build facilities from 2025 to 2080 is $1.1 trillion to $1.2 trillion (Table 8). Note the deployment of more costly technologies involving circular and bio-based feedstocks in line with societal preferences discussed earlier would increase these estimates.

The cumulative capital investment requirements estimated here appear consistent with, if not more conservative than, an earlier modeling study that estimated higher abatement capital investment requirements but for a much larger scope of study:[32] full supply chain emissions abatement for 18 large-volume base chemicals plus 14 large-volume plastics and the treatment of corresponding plastic wastes, versus cradle-to-gate abatement for 10 large-volume chemicals in our study (without downstream supply chain abatement). The scope of the earlier study was also global, rather than being limited to the four regions considered here, and it also assumed higher future percentage demand growth than assumed here. Finally, it also assumed complete abatement of emissions instead of the maximum practicable level considered here—abating the last 10% to 20% of emissions is widely understood to be disproportionately more costly than abating the first 80% to 90%.

Table 8. Cumulative capital deployed to abate existing facilities. Note that in the Grassroots Green scenario in the Middle East and in China, there is insufficient capital available to abate all existing facilities by 2080.

	North America			Europe			Middle East			China			Sum		
Billion 2024$	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**
Olefins + aromatics	100	106	111	62	61	61	45	48	47	308	337	257	515	553	476
Steam crackers	86	92	97	53	52	52	40	42	44	199	221	161	378	407	353
On-purpose propylene	10	10	10	7	7	7	4	5	3	96	103	84	117	125	104
Aromatics	4	4	4	2	2	3	1	1	1	12	13	12	20	21	19
Methanol	10	10	10	10	10	7	9	10	7	69	76	63	97	106	87
Ammonia	27	29	31	27	29	31	11	12	9	77	85	69	142	156	139
Totals	**136**	**145**	**151**	**98**	**101**	**99**	**66**	**70**	**63**	**453**	**499**	**389**	**754**	**815**	**702**

Table 9. Cumulative total abatement capital deployed from 2025 to 2080. Note that in the Grassroots Green scenario for the Middle East and in China, the deployed capital is not sufficient to abate all existing facilities by 2080.

	North America			Europe			Middle East			China			Sum		
Billion 2024$	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**	**SU**	**GA**	**GG**
Olefins + aromatics	129	140	147	79	81	89	79	87	89	402	456	419	689	764	745
Steam crackers	109	119	125	68	70	77	69	76	81	289	335	319	536	600	602
On-purpose propylene	15	15	16	9	9	10	7	7	6	96	103	84	127	135	115
Aromatics	5	6	6	2	2	3	3	3	3	16	18	17	26	29	28
Methanol	27	30	32	17	18	16	15	16	15	82	91	82	141	156	144
Ammonia	84	95	102	51	57	61	23	26	25	120	135	126	279	312	314
Totals	**241**	**265**	**281**	**148**	**157**	**166**	**116**	**128**	**130**	**603**	**682**	**627**	**1,108**	**1,231**	**1,203**

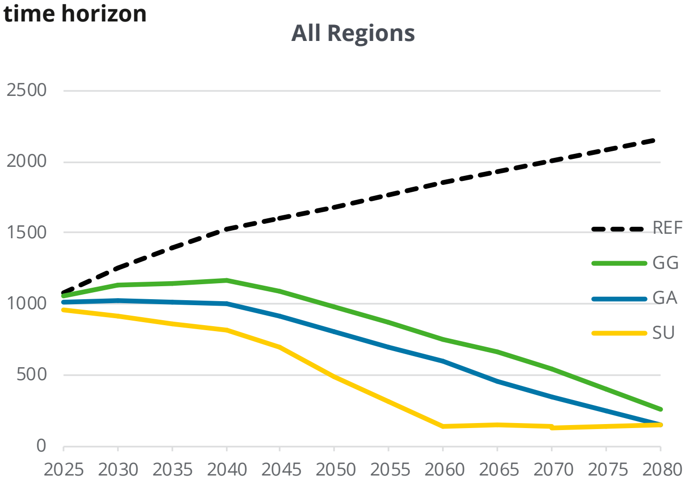
Future of industry emissions

As discussed earlier, the scenarios presented in this study are intended solely to represent an illustrative range of potential future outcomes. No scenario should be interpreted as a prediction or a preferred or recommended future. Rather, these scenarios are designed to highlight the inherent uncertainties and complexities that will drive emissions of the chemical industry.

Annual emissions resulting from the abatement technology deployments described above for all in-scope building block chemicals across all regions for each scenario are shown in Figure 11. For perspective, a reference case is also shown, with emissions intensities (scopes 1, 2, and upstream 3) "frozen" at the estimated 2023 levels, but with BB demand growth the same as in the abatement scenarios. (It is unlikely that future emissions intensities will remain unchanged, so the frozen intensities case is referred to here as a reference case rather than "business-as-usual".)

Table 9 shows estimated regional-average emissions intensities (scope 1 and 2) in 2023 for the chemicals evaluated in this study. Across most chemicals, intensities are highest for China, where coal-based production disproportionately increases regional average intensities. In the frozen-intensities reference case emissions grow by 70% from 2025, to 1.7 Gt/y by 2050, in line with projected annual production growth. Emissions exceed 2 Gt/y by 2080, when production is 2.5 times the 2025 level. Chinese facilities contribute 55% to 60% of the annual totals and olefins contribute 40% to 50%. Cumulative emissions from 2025 to 2080 are 95 Gt in the frozen-intensities case, compared to 27 Gt, 39 Gt, and 48 Gt in the SU, GA, and GG scenarios, respectively.

Figure 11. Total annual emissions (scopes 1, 2, and upstream 3) for all in-scope building blocks and regions for each of the three abatement scenarios (SU, GA, and GG) over the study time horizon



Shown in figure 11 for for comparison is the emissions trajectory for a reference case with emissions intensities frozen at 2023 average region-specific levels.

Table 10. Region-average emissions intensities (scopes 1 and 2) of building block chemicals production, as estimated for 2023.

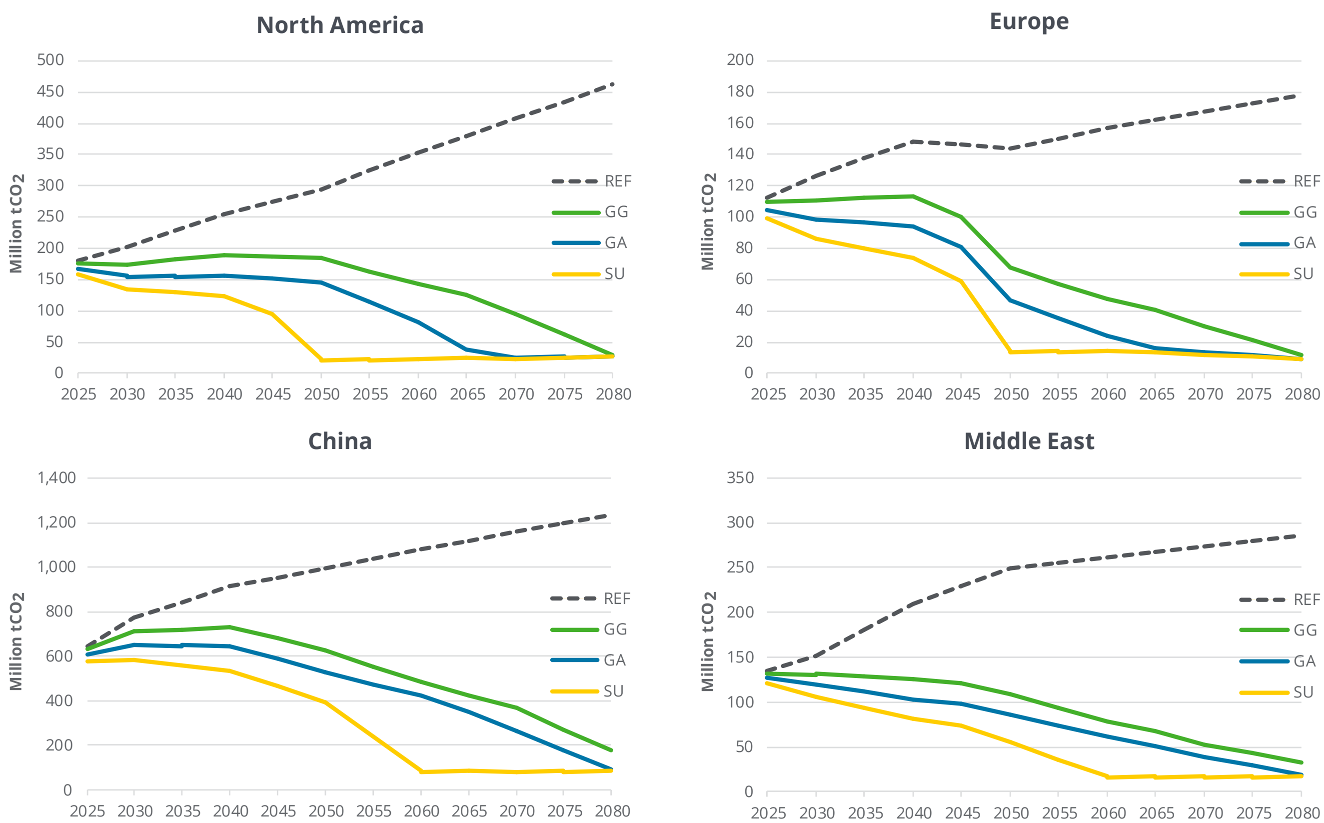
Building block chemicals	Emissions intensity (tCO2e / ton product)			
	North America	Europe	Middle East	China
Methanol	0.63	0.92	0.63	2
Ethylene	1.17	1.45	1.2	2
Propylene	1.11	1.32	1.1	1.6
Butadiene	0.04	0.03	0.09	0.1
Benzene	0.12	0.1	0.17	0.16
Toluene	0.06	0.06	0.06	0.07
Xylene	0.14	0.11	0.14	0.13
Ammonia	1.6	1.82	1.5	1.72
Hydrogen	9.35	9.34	9.4	9.4
Chlorine/Caustic	0.36	0.41	1.35	1.3

Here, propylene is a weighted average of steam-cracker and catalytic-cracker production. See the supplemental Information (SI) spreadsheet for region-average estimates of intensities disaggregated by scope (including 1, 2, and 3).

Figure 12 shows emissions estimates by region for each scenario and the frozen-intensities reference case. (Note the variations in y-axis scales across the regions. Notice that regional emissions diverge slightly between scenarios in 2025 because of scenario-based assumptions regarding reductions of regional grid carbon intensities and upstream methane leakage rates relative to 2020 anchor values).

- In **North America**, the rates of capital deployment for abatement are sufficient across all three scenarios to ensure monotonic decline in total emissions, even in the face of industry growth.
- In **Europe**, emission declines are similarly monotonic, but with less variation across scenarios than in North America due to more limited production growth in this region.
- In the **Middle East**, emissions decline more slowly than in North America or Europe despite a higher production growth rate, because the target date for abating all existing facilities in the Sustainable United scenario is a decade later in the Middle East. The situation is similar for the Green Authority scenario. In the Grassroots Green scenario, the low capital deployment rate combined with production growth causes emissions to increase through the end of the 2030s before beginning to decline. The industry does not reach full abatement by 2080 in this scenario.
- In **China**, the rapid growth in production drives an emissions increase initially in both the Green Authority and Grassroots Green scenarios. The capital deployment rate in the Green Authority scenario is sufficient to abate all facilities by 2080, but it is insufficient in the Grassroots Green scenario to achieve this.

Figure 12. Annual emissions by region for the three abatement scenarios and the reference case.



Emissions are shown disaggregated by region for each scenario in Figure 12. Modeled global emissions in 2025 are about 960 $MtCO_2$, with China accounting for 58% of the total, followed by North America (18%), the Middle East (14%), and Europe (11%). In the Sustainable United scenario, global emissions decline 53% by 2050, when all existing facilities in North America and Europe have been abated. Global emissions decline to 14% of 2025 emissions (140 $MtCO_2$) by 2060, when all existing facilities in China and the Middle East have also been abated. Emissions rise slightly beyond 2060 due to added production units. These units are built with emissions abatement but nevertheless have residual emissions that are technically difficult (and/or extremely costly) to abate.

In the Green Authority scenario, with its slower abatement deployment rate, emissions due to production growth roughly balance abatements in Europe, North America, and the Middle East until about 2040, while emissions rise in China during this period. Emissions then begin declining in all regions and reach full abatement by 2080. In the Grassroots Green scenario, rising emissions are also observed until about 2040, and emissions decline more slowly after that than in the Green Authority scenario. Emissions are not fully abated in China or the Middle East by 2080 in the Grassroots Green scenario due to the slower pace of capital deployment.

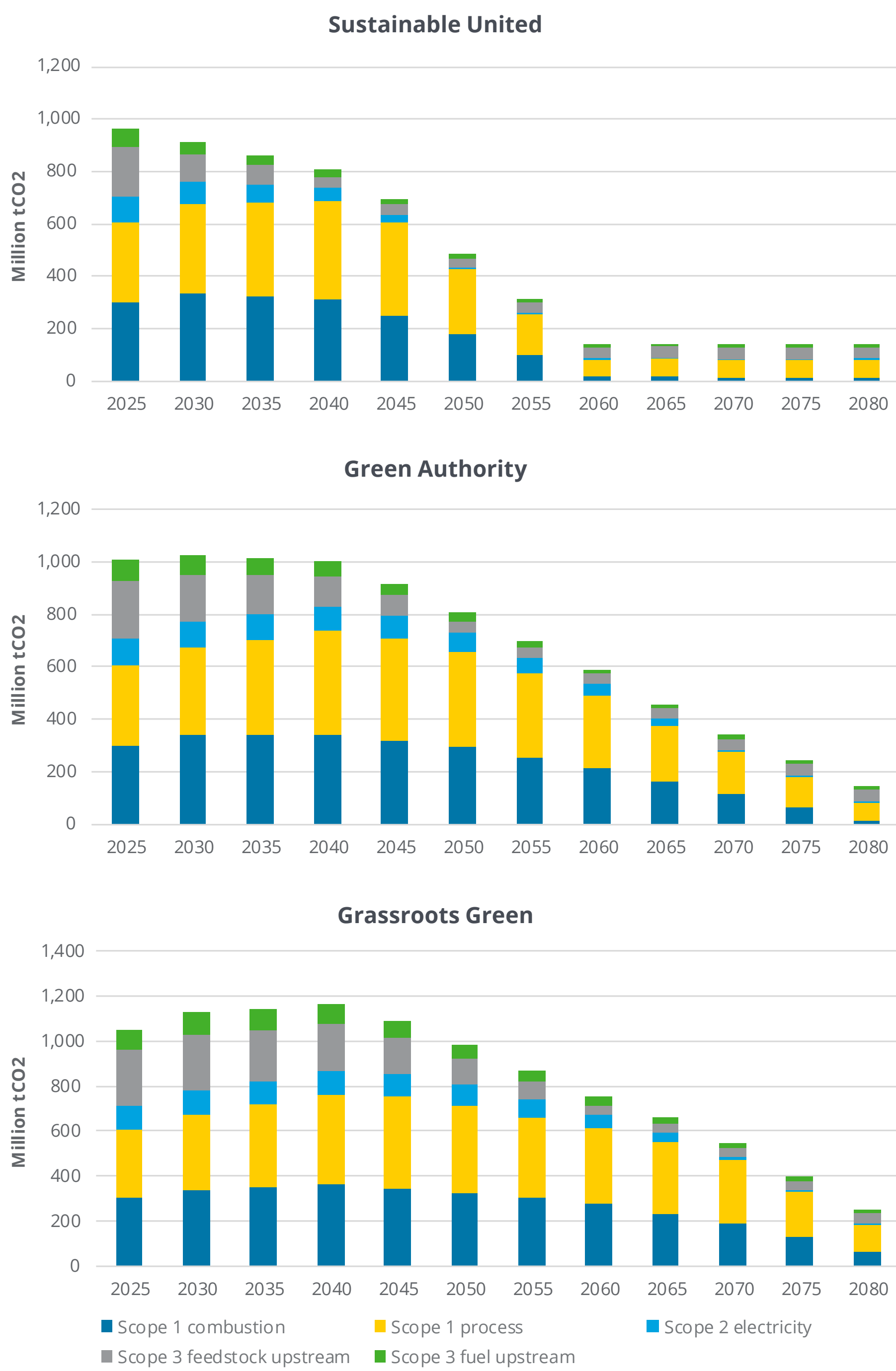
Figure 13. Sustainable United emissions by region for production of building block chemicals considered in this study, including scope 1, 2, and upstream 3 emissions.

Figure 13 shows emissions across the four study regions disaggregated by emissions scope. Scope 1 combustion and process emissions, which have been modeled facility-by-facility as discussed earlier, are an estimated 608 $MtCO_2$ today, or about two-thirds of total emissions. In the Sustainable United scenario, by 2060 scope 1 emissions are reduced by over 85% but still account for about two-thirds of the total. Scope 2 emissions are nearly eliminated by 2060, with the assumption that the grid has been largely decarbonized in all regions. (For assumptions behind scope 2 and 3 emissions reduction rates, see appendix.) Scope 1 and 2 emissions together are 83 $MtCO_2$ in 2060. Upstream scope 3 emissions from methane leakage during fuel and feedstock production and delivery decline over time in line with oil and gas industry commitments to achieve "near-zero" upstream emissions as soon as 2030, but this considers that upstream emissions associated with coal in China are more challenging to abate. On a global basis, scope 3 upstream emissions are assumed to be reduced by 95% from today's level by 2060 in the Sustainable United scenario, and these account for about one-third of the residual emissions of the industry in 2060.

In the Green Authority and Grassroots Green scenarios assumed scope 2 and scope 3 upstream emissions reduction rates are less aggressive than in the Sustainable United scenario and compound the slower rate of emissions reductions associated with reduced capital spending on abatement of scope 1 emissions.

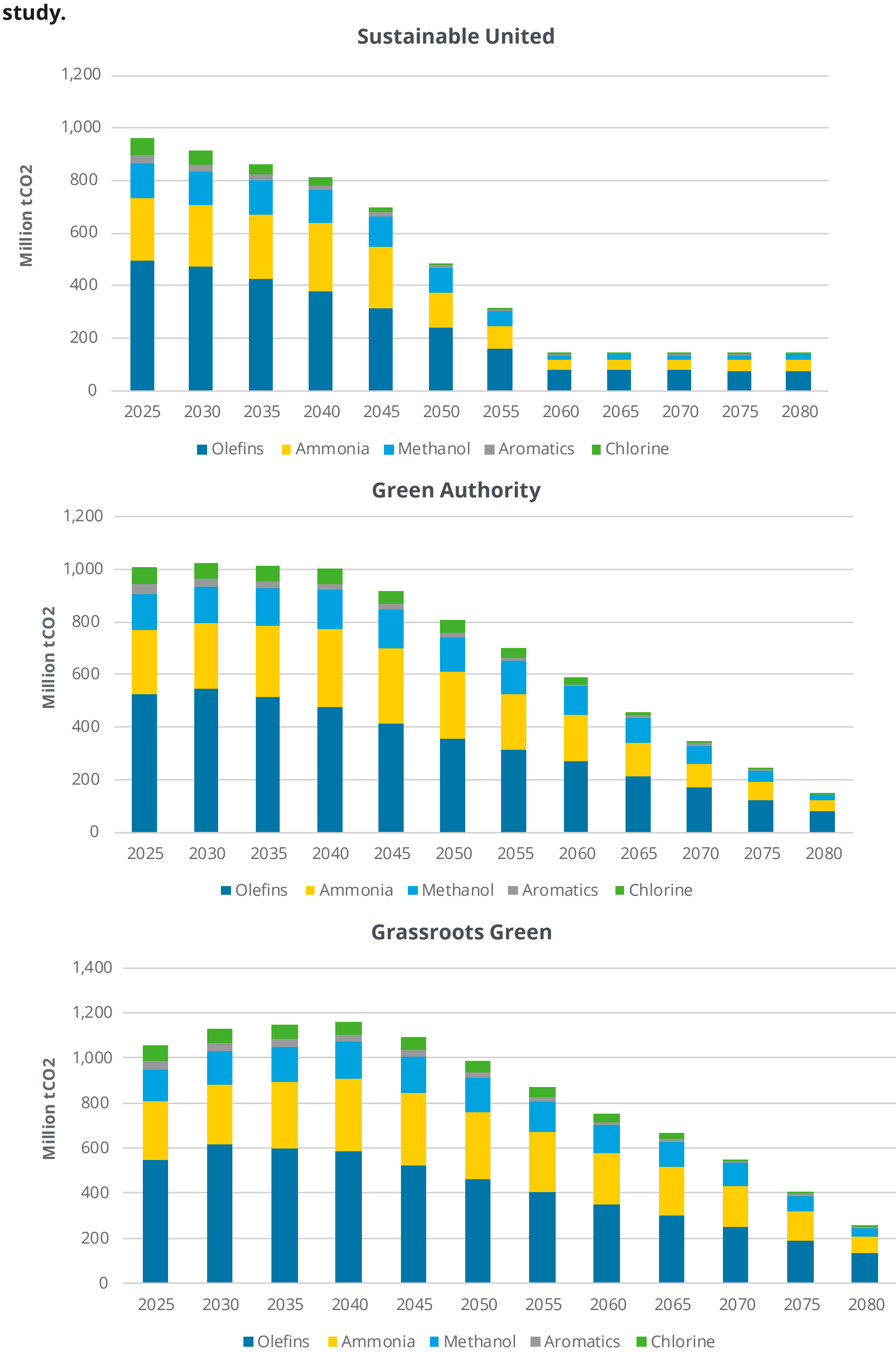
Finally, global emissions for each scenario are shown disaggregated by building block chemical in Figure 14. Olefins production accounts for the largest fraction of emissions across the time horizon analyzed, followed by ammonia, methanol, chlorine, and aromatics. Notably, emissions for ammonia and methanol production decline modestly in the Sustainable United scenario through the mid-2040s,

Figure 14. Sustainable United scenario emissions by scope for production of building block chemicals across all regions considered in this study.



while increasing initially in the Green Authority and Grassroots Green scenarios. These trends are related in large part to emissions contributions from China, where there is especially high-demand growth. China accounts for 40% to 60% of global production of both ammonia and methanol over the study's time horizon, and production globally nearly doubles for methanol and more than doubles for ammonia from 2025 to 2060. Additional contributing factors include the use of coal as feedstock in China, which results in higher emissions per unit of production from not-yet-abated facilities compared with natural gas-based production, and the target date for full abatement of existing facilities being 2060 rather than 2050. The slower pace of abatement of existing higher carbon-intensity facilities and the added residual emissions from abated new facilities combine to keep emissions from methanol and ammonia production globally relatively flat until the late 2040s. In the Green Authority and Grassroots Green scenarios, the decline in emissions from the 2040s is slower relative to the pace in Sustainable United.

Figure 15. Sustainable United scenario emissions (scope 1, 2, and upstream 3) by building block chemical across all regions considered in this study.



Regional parsing of emissions trajectories by individual building block chemical for the three abatement scenarios is provided in Figure 16 (olefins and aromatics), Figure 17 (ammonia and methanol), and Figure 18 (chlorine).

- For **olefins**, in the Sustainable United scenario, emissions decline more rapidly in North America and Europe than in the other regions due to having 10 fewer years to abate all existing facilities. In China, emissions decline only modestly from 2025 through the 2040s due to additional new capacity built to meet demand growth. In this period, despite building abatement into each new facility, the residual emissions from those facilities roughly offset the reductions achieved by abating existing facilities. In the Green Authority and Grassroots Green scenarios, similar patterns are observed as in the Sustainable United scenario, albeit with less emissions reductions achieved at any given point in time until near the end of the modeled time horizon. In the Grassroots Green scenario, complete emissions abatement is not reached by 2080.
- For **aromatics**, which account for only a relatively small share of total emissions across the building blocks, emissions decline monotonically in all regions in each scenario.
- For **ammonia** and for **methanol**, emissions remain roughly flat in all regions until the mid-2040s in the Sustainable United scenario, because residual emissions from new facilities built to meet growing demand roughly offset the emissions reductions achieved through abatement of existing facilities. Emissions remain roughly flat for longer durations in the Green Authority and Grassroots Green scenarios. Full abatement of these chemicals is not reached by 2080 in the Grassroots Green scenario.
- For **chlorine**, emissions reductions mirror regional grid carbon-intensity reductions.

Figure 16. Emissions by region for olefins and aromatics production for three abatement scenarios

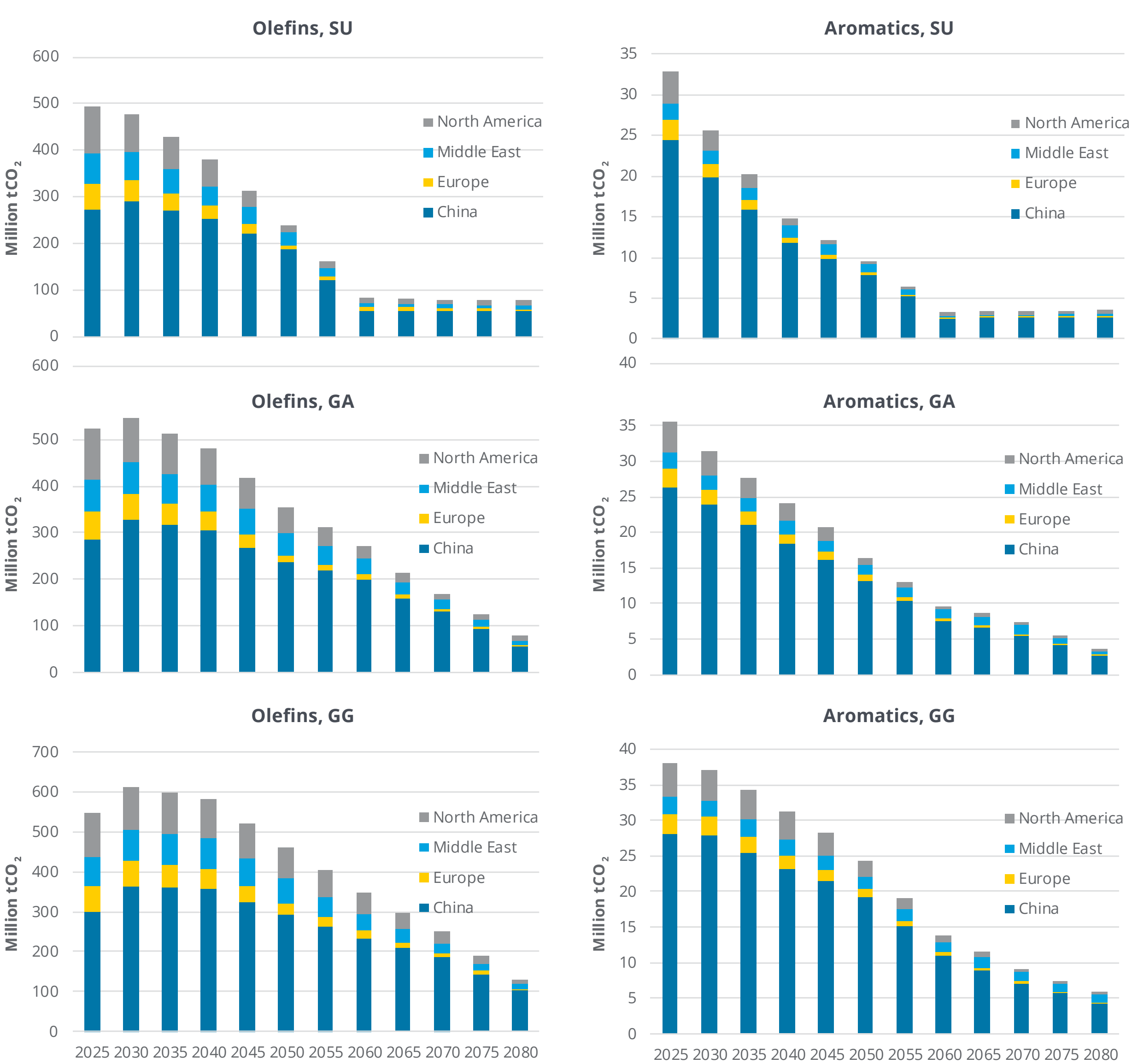


Figure 17. Emissions by region for methanol and ammonia production for three abatement scenarios

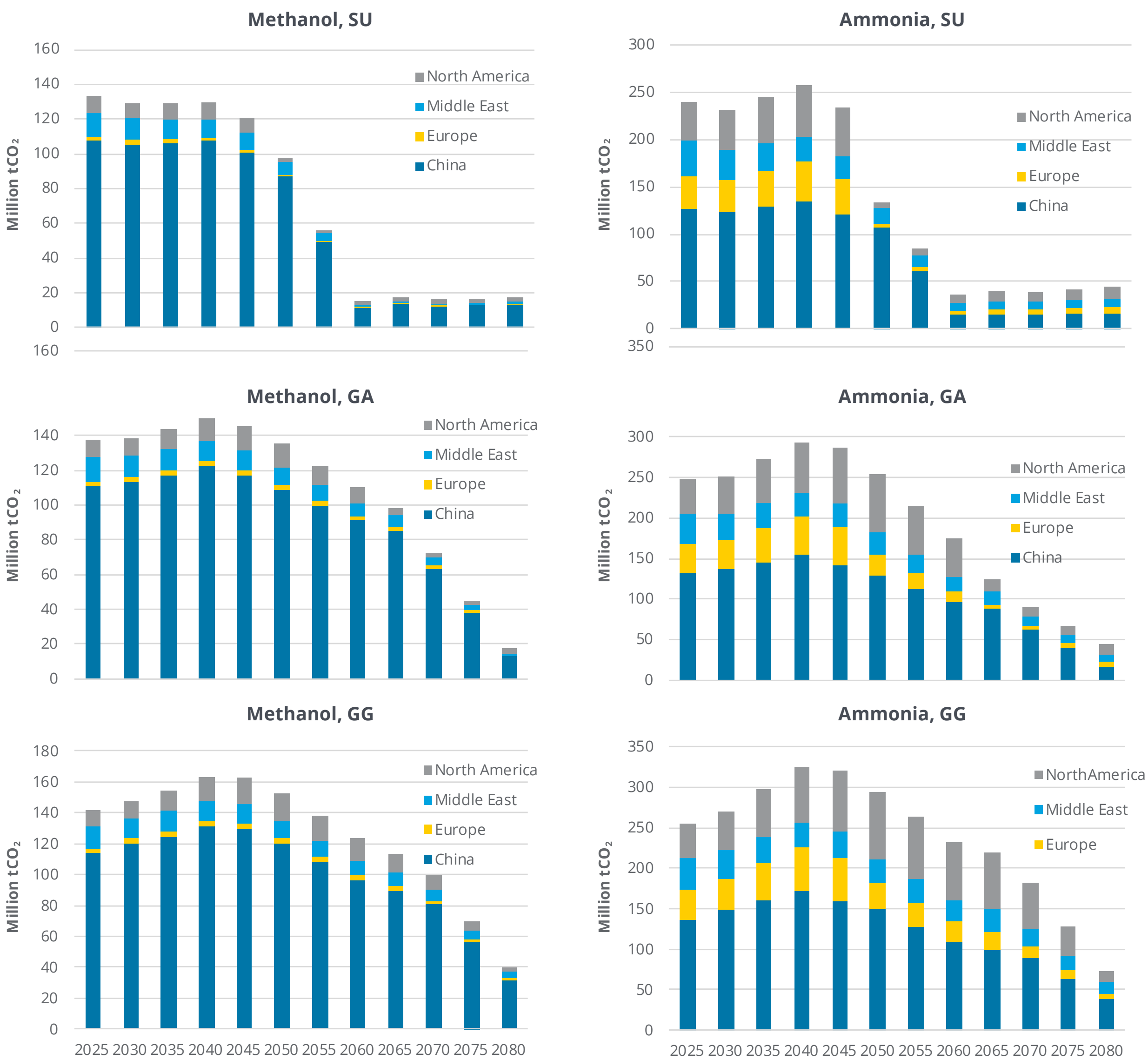
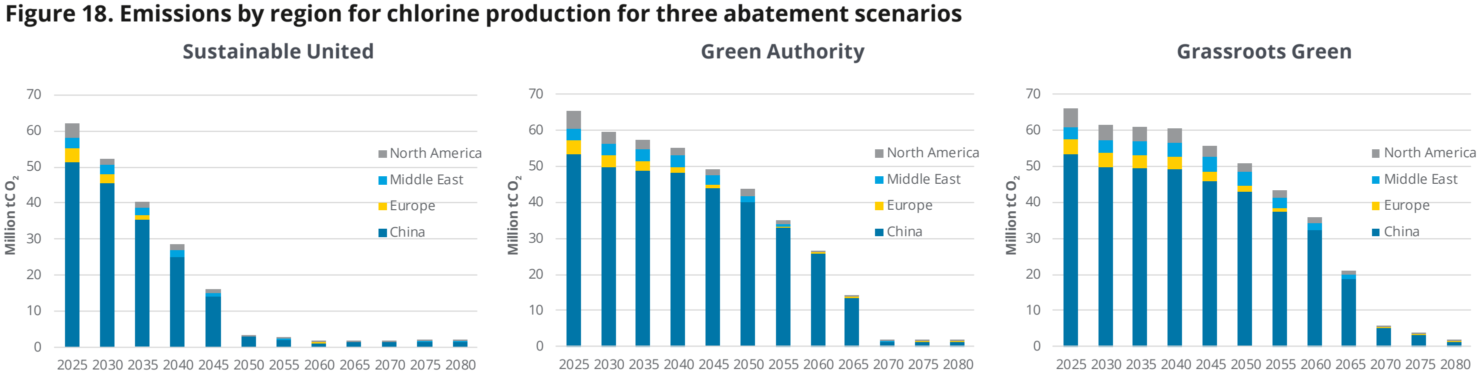


Figure 18. Emissions by region for chlorine production for three abatement scenarios



Market study approach and results

Given the potential futures of the chemical industry, the market study was intended to give stakeholders an idea of where to start, specifically what end markets and what geographies could be prioritized for favorable investment in sustainable chemicals. The main results of the market study demonstrated that collaboration across the value chain (from building block producers through to end-market users) can best economically distribute green premiums across the largest available volumes to optimize (and potentially make feasible) a COGS per piece of abated end products. This conclusion therefore also signifies that a product portfolio-level approach can be a productive approach to abated end products for end markets. Finally, manufacturing considerations, especially for certain end markets that favor customization, or to a lesser extent configuration, should consider a "net whole change" to the entire manufacturing portfolio at certain plants in order to maximize economic and abated impact.

Market study prioritization approach

The market assessment is designed in two parts. First, a set of prioritization criteria were evaluated for 22 end-market sectors ranging from construction to consumer goods, automotive, and medical. The second part of this assessment evaluates the impact of emissions reduction on a sample prioritized product to understand the green premium costs passed along the value chain and to understand regional variation.

The market assessment utilized market report data and expert interviews to examine which end markets and their value chains demonstrate favorability for investment in low-emissions products. The end markets considered were consumer goods, packaging, transportation, textiles and apparel, electronics and appliances, construction, and medical. Chemical Market Analytics by OPIS provided breakdown of building block chemical demand into ultimate downstream end-use markets aligning with the three to four submarkets for each of these end markets that were identified based on Deloitte's industry taxonomy.

The assessment developed a set of prioritized criteria by which end-market value chains were evaluated and scored for prioritization. A higher score indicated that the associated end market had stronger favorability for investment in low-emissions products. Full prioritization assumed the Sustainable United (best case) scenario. The three high-level dimensions of prioritization criteria include:

1. **Value chain complexity,** which includes considerations such as barriers to change, cost of product substitution, environmental attribute, policies, and market competition. For this criterion, a lower value chain complexity is correlated with a high opportunity for investment.
2. **Demand,** which includes considerations such as sustainability maturity, cost sensitivity, corporate social responsibility (CSR) requirements, demand ($), and growth. High demand is correlated with a high opportunity for investment.
3. **Impact** of the volume of chemicals in that end market's value chain. High impact is correlated with a high opportunity for investment.

The impact category quantifies the chemicals inputs, emissions, and potential abatement solutions for each end market to determine the impact that lower-carbon chemicals may have. For example, if an end market has a larger amount of building block chemicals that are used to produce their final product, this would be a positive incentive for this value chain to invest in lower-carbon solutions and would receive a higher score. Alternatively, if an end market has stringent regulations and strict requirements for the qualification of new feedstocks, this would receive a lower score associated with a negative adoption incentive. Each submarket was given a score for each dimension, then consolidated and normalized with high/medium/low ratings to compare across markets to identify highest-priority submarkets. Internal and external interviews were used to validate preliminary findings assessing each industry's favorability for investment in lower-carbon chemicals.

Market prioritization results

While all end markets have drivers and barriers that influence the investment opportunity in sustainable chemicals, a few markets emerged as a top priority based on the assessment's criteria. While prioritization may differ slightly across scenarios (e.g., if demand or regulation dominates), the prioritization matrix presented here assumes the best case, Sustainable United scenario. As seen in figure 19, the results of market prioritization revealed five top-priority end markets: rigid/hard packaging, soft packaging, automotive, food and beverage, and personal care. These five priority markets comprise approximately 43% of building block volume. Therefore, making progress on sustainable chemicals in these markets could cover a substantial portion of industry emissions.

Figure 19. Outputs of end-market prioritization assuming the Sustainable United scenario

	Consumer goods			Packaging			Transportation				Textiles and apparel				Electronics and appliances		Construction			Medical		
	Food and Bev	Household goods (excl. furniture)	Personal care	Paper	Soft	Rigid hard	Aviation	Marine	Rail	Auto	Sporting goods	Textiles and yarn	Luxury	Non-luxury	Consumer products	Tech hardware	Industrial	Building	Infrastructure	Medical device and diagnostic	Pharma	Single-use disposable
Value chain complexity	M	M	M	H	M	H	M	L	M	M	M	H	M	H	M	M	L	M	L	L	M	L
Demand	H	M	H	M	M	H	M	M	M	H	H	M	H	H	M	H	M	M	M	M	M	H
Impact	H*	M	M	L	H	H	M	L	L	H	L	L	L	L	L	L	H	H	H	L	L	L
Total	P1	P2	P1	P2	P1	P1	P2			P1			P2	P2		P2	P2	P2	P2			

Criteria

- High (H)
- Medium (M)
- Low (L)

Priority 1 (P1) markets

- Rigid/hard packaging
- Soft packaging
- Food and beverage (NOT including packaging)
- Personal care
- Automotive

Product vignette: Sunscreen

The market assessment also developed a product vignette to visualize the value chain from building block chemicals to the end-product formulation for sunscreen. Two supplemental exercises were also completed: (1) an exploration of regional cost differences for packaging and (2) an estimation of how cost premiums change across the value chain.

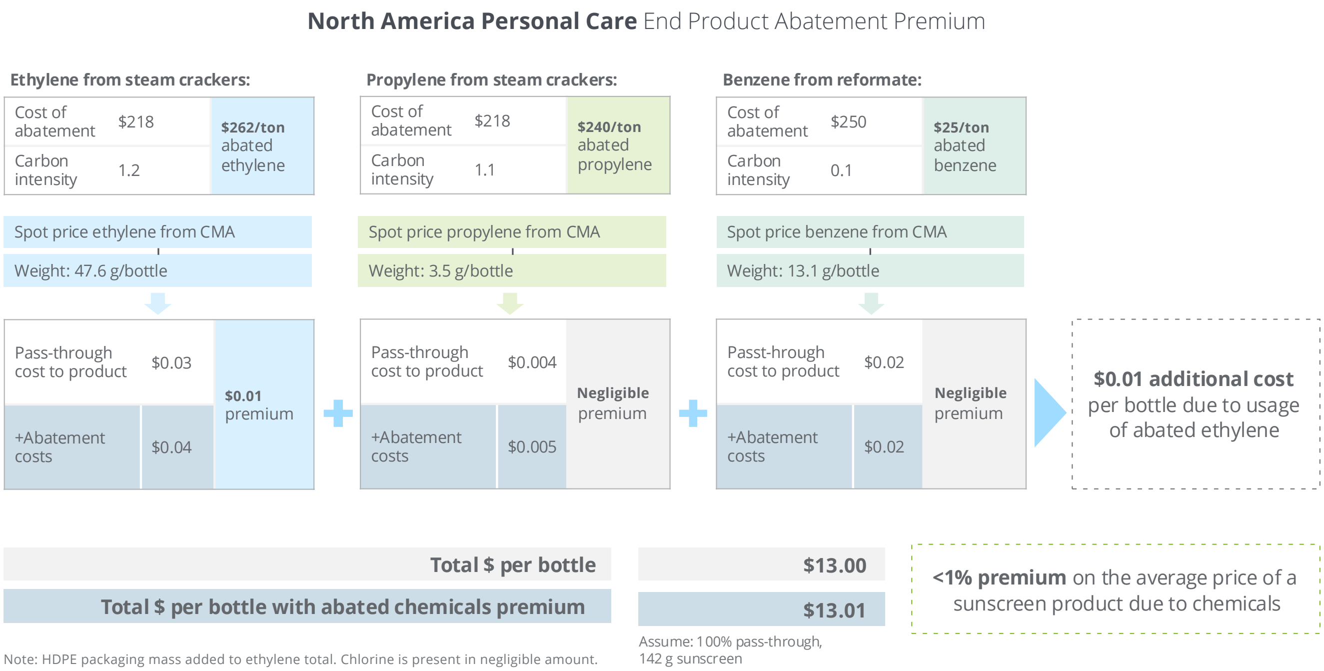
The vignette provides an example calculation of the product cost increase associated with lowering chemical building block emissions utilizing abatement technologies. This cost increase can be interpreted as the "minimum required green premium" for emissions reduction (i.e., the breakeven price for emissions reduction investments per item).

The product vignette used detailed bill of materials (BOM) information combined with abatement technology information from the techno-economic model to evaluate the difference in emissions and the associated "abatement premium" resulting from investing in lower-carbon chemical solutions. Sunscreen was chosen as an example from one of the prioritized submarkets (personal care). For simplicity, these calculations used North America price assumptions and North America regional modeling outputs, assuming the Sustainable United scenario. First, the bill of materials was used to identify component chemicals and then calculate what percentage of input chemicals are based in building blocks. Spot pricing (market prices updated daily for raw materials and building blocks) was provided by Chemical Market Analytics by OPIS and was scaled based on item volume and composition and used to calculate the pre-abatement base building block price. Emissions and abatement costs were calculated using the model and scaled to calculate the premium associated with the lower-emissions product. This is essentially the "additional cost" for a building block to recover the abatement investment.

For sunscreen, decomposing the BOM revealed that, except for water, about 55% of the chemicals in the product formulation could be addressed with a lower-carbon building block by weight.

When factoring in the premiums associated with packaging, scaling the formulation premiums to one bottle (assuming 142 grams), and calculating the price impact in USD, this results in just $0.01 premium per bottle due to abated building block chemicals.

Figure 20. Outputs of end-market prioritization assuming the Sustainable United scenario



This demonstrates that while chemical producers face significant cost increases when opting for sustainable alternatives, when passed on to end products, cost increases are much smaller, accounting for a small fraction of total costs, vis-à-vis labor, R&D, and marketing cost.

In practice, there are market and manufacturing complexities that come into play and are explored in a second example below for packaging.

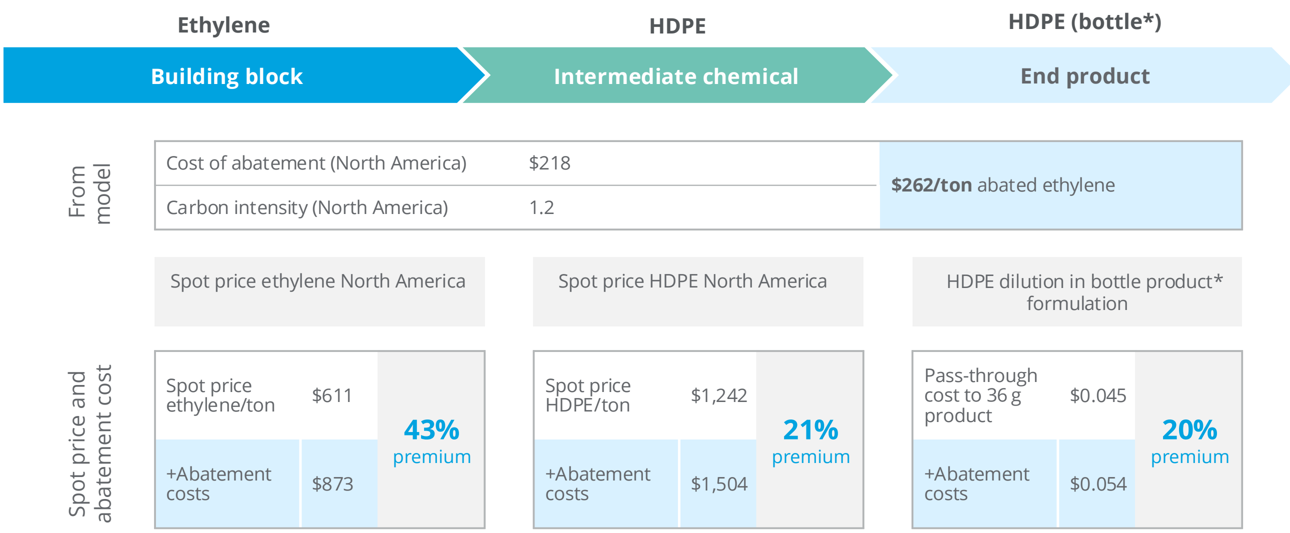
Green premiums down the value chain: packaging

Another angle to consider when it comes to green premiums is how these costs are distributed down the value chain. Here, shampoo packaging is considered as an example.

Calculating the green premium on ethylene using the spot pricing value and cost of abatement in the model (using the North America Sustainable United scenario), ethylene by itself would involve a **43% green premium** to justify investment.

Thinking about how this pass-through cost scales for blow-molded high-density polyethylene (HDPE) [make sure "HDPE"—not HPDE], the green premium on ethylene itself would be 43%. When transforming HPDE packaging into a singular 36 g bottle, comparing the green premium price to a standard bottle with no abated chemicals reveals a **20% premium**. While this price increase is noticeable for the HDPE "bottle," green premiums are significantly less in absolute dollars for companies farther down the value chain (in this example, only $0.01 for a 36 g HDPE "bottle"). For there to be progress toward a lower-emissions future, stakeholders along the value chain must collaborate to share the green premium from the consumer all the way to the building block producers. Based on continuous manufacturing required for building block production, there are notable nuances on the green premium per bottle.

Figure 21. Green premiums down the value chain



High-density polyethylene (HDPE)
* Assume 36 g HDPE/bottle.
Source: CMA; Plastic News

The increase in unit costs of green products reduces as you move down the value chain toward the consumer. This highlights the need for collaboration to ensure the green price premium is appropriately shared up the value chain.

Impact on COGS by utilization

While a penny increase per bottle seems like a trivial price to pay for low-emissions products, there are additional, often overlooked complexities in heavy industry production that add further challenges.

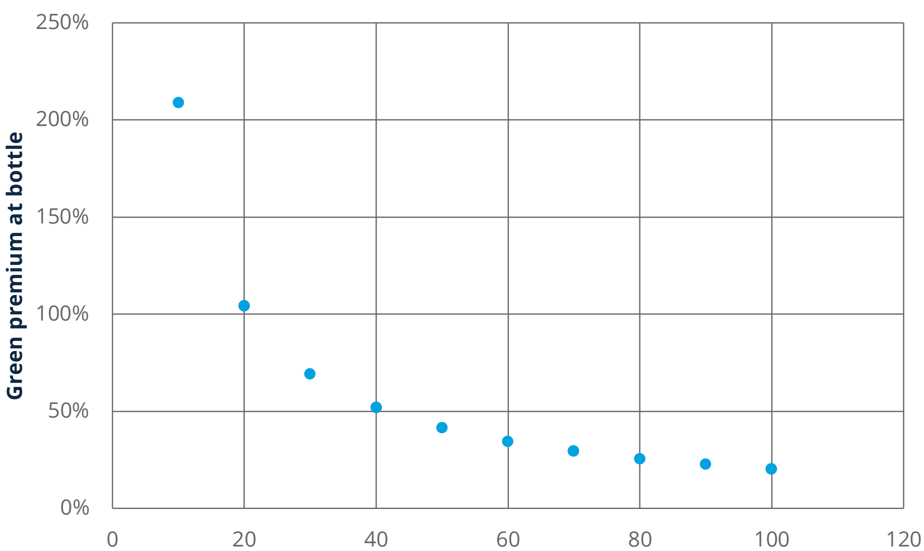
For discrete-based manufacturing, which lends itself to configuration or customization, this customization can limit material sharing and economies of scale required for premium sharing. For example, in the automotive industry, the lowest-cost version of any vehicle model is manufactured on the same line as the highest-priced (often highest-margin) version. The total number of these "specialty" units can continuously vary, based on real-time customer preferences. It's important to note that due to the cost-prohibitive nature of manufacturing change-outs and to achieve raw material economies of scale, to optimize abated products in these manufacturing scenarios would favor abating ALL products and not just certain higher-margin/higher-priced product. In contrast, much of the process industry and all chemical building blocks are manufactured in continuous processes. These continuous manufacturing processes will need to be "abated" to achieve a net-zero future sometime in the middle of this century.

The consequence is that lower-emissions building blocks will come in units measured in millions of metric tons. An ethane-based steam cracker will either be abated or not abated. It will not run for, say, 10% of the time in "abated" mode and 90% in unabated mode. This leads directly to a COGS implication. Since the COGS of all the production capacity will be same, anything less than 100% of that capacity sold as "low-emissions product" will have an impact on needed selling price. More succinctly, the amount of product sold as low emissions will need to bear all additional costs (figure 21). Alternatively, building block producers and end-market sellers could collaborate to commit to utilize the entire capacity of the low-abated building block thus distributing the costs over a larger volume and shifting the abated "low-emissions" product COGS toward the end market.

The significance of this can be seen by considering the impact of selling less than 100% of capacity. In the analysis of figure 22, the percentage of production volume sold as "low-carbon" correlates with green premiums required to support additional price, and the economic impact at the end-product level. As the share of low-carbon production increases, the associated costs and premiums required to support the transition become evident, reflecting their effect on individual unit pricing. Therefore, a noticeable green premium of 20% quickly becomes a (likely prohibitive) green premium of more than 50%.

The impact is especially jarring at the level of dollars per ton HDPE. While $1,500 per ton is perhaps still in the range of high volume, more commodity-type plastics greater than $2,000 per ton is decidedly a specialty material.

Figure 22. Green premium per bottle based on percentage of production volume sold as "low emissions"



Production volume sold as low carbon (%)	Green premium required ($/t)	Required NASP ($/t)	Impact at level of HDPE bottle ($/36 g)	Green premium at bottle
10	2,620	3,862	0.14	209%
20	1,310	2,552	0.09	104%
30	873	2,115	0.08	69%
40	655	1,897	0.07	52%
50	524	1,766	0.06	41%
60	437	1,679	0.06	34%
70	374	1,616	0.06	29%
80	328	1,570	0.06	26%
90	291	1,533	0.06	23%
100	262	1,504	0.05	20%

Note: If low volumes of low-emissions products are sold, green premiums rise dramatically.
HDPE = high-density polyethylene; NASP =

Green premiums by region: Packaging

While only the North American perspective was used in the example above, a cross-regional analysis of the sunscreen packaging premiums was completed to provide insight into the most advantageous areas for production (figure 23). Both the raw building block material price and abatement cost (from the model) vary by region, so the output took both factors into account.

Packaging premiums have significant regional variation due to spot price differences and variations on costs to abate, which led to ranges from a 21% premium in North America to 41% in China.

Figure 23. Sunscreen packaging premiums by region

		North America	Europe	China
Form model	Cost of abatement	$218	$289	$237
	Carbon intensity	1.2	1.45	2
		$262/ton abated ethylene	**$419/ton** abated ethylene	**$474/ton** abated ethylene

Spot price ethylene differs by region

Spot price HDPE differs by region

		North America	Europe	China
Spot price and abatement cost	Pass-through cost to product	$0.045	$0.047 (Passthrough cost to product)	$0.042
	+Abatement costs	$0.054	$0.062	$0.059
		21% premium	**32%** premium	**41%** premium

HDPE = high-density polyethylene
Note: Middle East was not included as part of this study due to data limitations.
Source: CMA; Market Research

Lower carbon ethylene-based packaging (HDPE) produced in Europe, and China is more costly to downstream buyers. Europe is impacted more strongly by its higher abatement costs while China is more impacted by its carbon intensity due to coal usage.

The market assessment did not factor into regional regulation. These variables could be included in a future phase of analysis.

While illustrative examples were provided here, calculations like these can help chemicals companies prioritize end markets of interest and products with the greatest abatement potential to inform their deployment strategy. Understanding market pull will help inform opportunities for engaging broader value chain players and strengthen ecosystem collaboration, helping to show potential demand supporting large-scale investments.

Gaps impacting the future state of the chemical industry

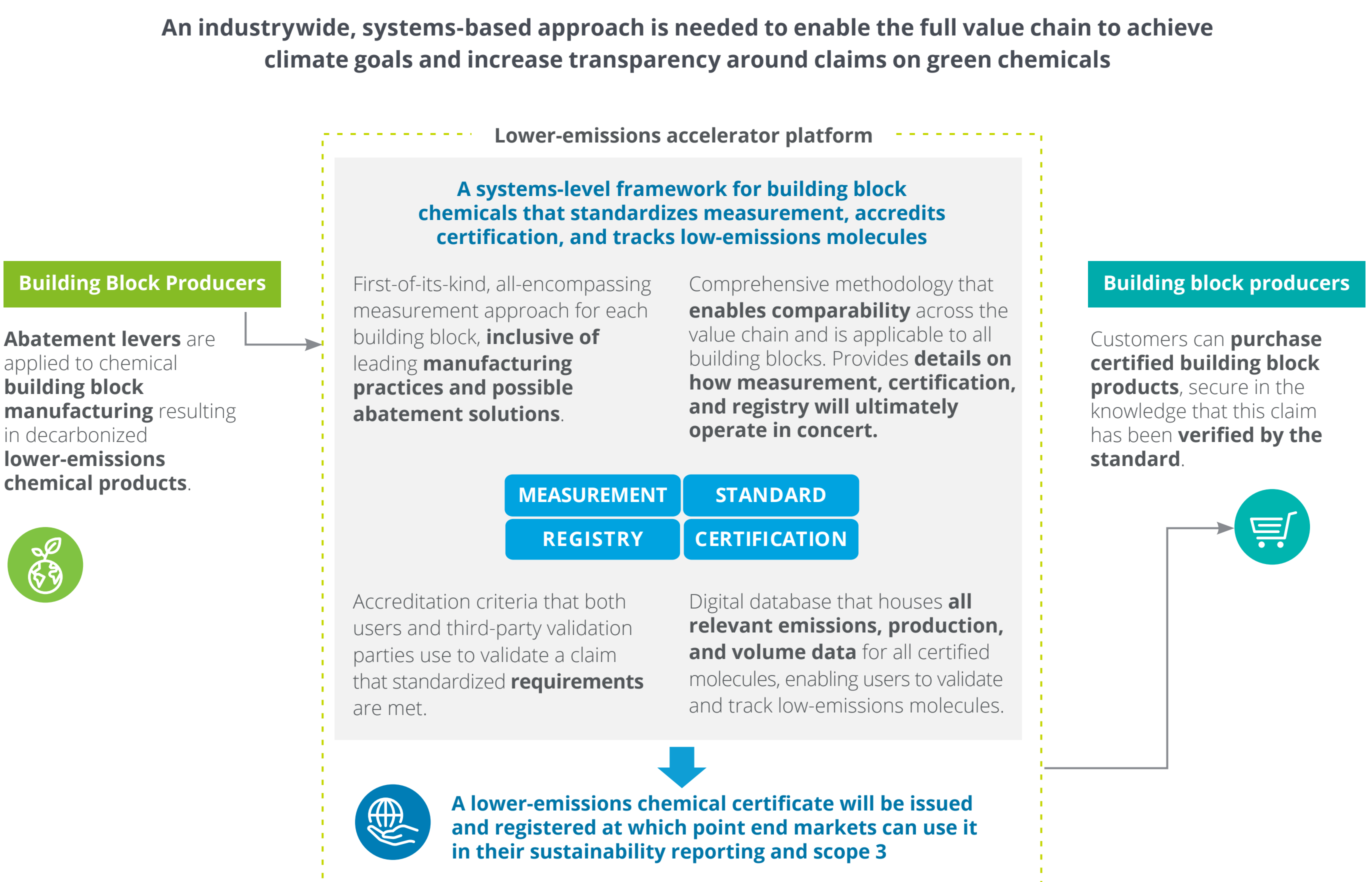
1. Financing

Innovative green finance mechanisms and supportive policies are a crucial driver to bridging the significant investment gap needed for the chemical industry to achieve net-zero. Substantial capital, especially for upstream chemical building blocks that drive most industry emissions, is required to scale decarbonization and create an equitable economic model. Distributing the value of lower-carbon intensity across the value chain will help secure investment and drive change. Focusing on optimizing production and emissions reduction in the 10 key chemical building blocks—responsible for most of the industry output and emissions—is a strategic starting point. Efficiency improvements, such as advances in cracker electrification and thermal control, can further lower costs and accelerate adoption. A comprehensive cradle-to-grave analysis of these building blocks can help identify optimal pathways, prioritize investments, unlock new capital, foster innovation, create jobs, and increase demand for economically and environmentally optimized products.

2. Product carbon footprint accounting methods

Harmonizing product carbon footprint (PCF) methodologies is important to enhance transparency, comparability, and market confidence, enabling buyers and sellers to make informed decisions. Currently, there is no comprehensive, universally accepted, transparent, and consistent method to measure product carbon intensity, which is beneficial for demonstrating credible progress in reducing CO_2 emissions. Establishing a validated and standardized approach would not only support credible emissions reporting but also help create an economic system that rewards low-carbon products by assigning them tangible value (figure 24). This is particularly important in complex supply chains, where upstream investments in emissions reduction need to be communicated downstream to consumers. To facilitate certified low-carbon product purchasing and enable businesses to objectively compare suppliers, the industry should advance a clear, consistent, and transparent system for measuring, tracking, and verifying product carbon intensity. Addressing gaps in current methodologies and advancing standardization will be key to aligning market incentives and supporting the economics necessary for widespread adoption of lower-carbon products.

Figure 24. System-level framework for building block chemicals



3. Policy

While the purpose of this study is not to recommend specific policies, stable and long-term policy frameworks across the globe—such as tax credits and incentives—can help create market certainty and encourage investment in decarbonization technologies.

Implementing carbon pricing regimes (such as carbon taxes or cap-and-trade systems) helps internalize the environmental costs of greenhouse gas (GHG) emissions, making lower-emissions options more competitive. Complementary policies may include direct subsidies, fiscal incentives, and carbon contracts to bridge the cost gap between conventional and low-carbon technologies.[33]

Globally, government funding and incentives for research and development can lower costs and increase efficiencies across new technologies (e.g., electrolysis, storage, transportation of green hydrogen, carbon capture, and alternative feedstocks). Collaboration between industry, startups, and academia for pilot programs can also help.

Policies that require companies to disclose climate-related risks and GHG emissions (including scopes 1, 2, and 3) can drive transparency and accountability.

4. Value chain collaboration

Building robust markets and partnerships for low-carbon chemicals beyond the current state of bespoke bilateral deals and regional initiatives will accelerate adoption and create new growth opportunities. Coordination and collaboration across the value chain can accelerate global progress toward lower emissions. The market study revealed the green premium for building blocks is high at the front end of the value chain (more than 43% for ethylene production), but it is small at the back end of the value chain, with—in the case of full utilization—the green premium dropping by 2x to about 20% for a consumer product like a shampoo bottle. Figuring out how to distribute costs and increase transparency around low carbon will be important to mobilize a market for green chemicals and downstream consumer products.

5. Engineering capacity (talent and innovation)

Investing in workforce development and innovation will help to ensure the industry has the skills and capabilities needed to commercialize and scale new technologies. The chemical and broader energy, resources, and industrials (ER&I) sectors are experiencing skills gaps in digital, engineering, and technical roles needed for decarbonization and digital transformation. Many organizations do not feel ready to address gaps at scale, and there is a lack of confidence in accessing the required talent from the marketplace. As a result, companies are increasingly turning to internal solutions, such as optimizing organizational structures and upskilling current employees, to meet decarbonization needs. Furthermore, there will need to be advances in chemical and material sciences that lower costs and increase efficiencies across the entire ecosystem.

Conclusion

Lowering chemical industry emissions over the next 50 years is not only technically feasible and strategically viable but also presents a tremendous opportunity for strategic growth and leadership.

By embracing collaboration, bold capital investment, policy and market innovations across the world, the sector is well-positioned to play a pivotal role in advancing global decarbonization goals.

Producing low-carbon chemicals is an exciting frontier—one that offers both significant challenges and remarkable opportunities. Chemical companies have a unique chance to differentiate themselves by adopting innovative, viable low-carbon strategies. Those who lead the way will capture new markets, unlock value from the growing scarcity of low-carbon products, and set the pace for industry transformation.

The intersection of prioritized end markets, emissions impact, and a willingness to innovate will help shape the evolution of the carbon market and open doors to the realization of future growth.

This study provides a clear, data-driven foundation, highlighting both the progress made and the exciting possibilities ahead. By motivating industry leaders, it can pave the way for greater collaboration across the value chain. Together, the chemical industry can make a lower-emissions future not only achievable but also more accessible and beneficial for all stakeholders.

Acknowledgments

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Glossary of key terms and definition

Abatement technologies: Technologies or methods used to reduce or eliminate greenhouse gas emissions from industrial processes.

Absolute (net) zero: The state where a company or entity reduces its total greenhouse gas emissions to zero, with no reliance on offsetting emissions through carbon credits or other external measures.

Amortization: Spreading the cost of an investment over its useful life, often used in financial analysis for capital projects.

Annual capital outlays: The amount of money spent each year on investments such as new facilities or equipment.

Asset-level information: Data specific to an individual piece of equipment (or groupings of interconnected unit operations) within a facility.

Bill of materials (BOM): A detailed list of raw materials, components, and parts needed to manufacture a product.

Bio-based feedstocks: Raw materials derived from biological sources (e.g., plants, agricultural waste) used to produce chemicals as alternatives to fossil-based inputs such as coal, oil, or natural gas.

Building block (BB) chemicals: The 10 key chemicals (e.g., methanol, ethylene, ammonia) that serve as the foundation for most chemical products and account for the majority of industry emissions.

Capacity factor: A measure of how often a facility or piece of equipment operates at its maximum output over a specific period.

Capital expenditure (CapEx): Funds invested by companies to acquire or upgrade physical assets such as facilities, equipment, or technologies.

Carbon capture, utilization, and storage (CCUS): A group of technologies that capture carbon dioxide emissions from industrial processes, use them in other processes, or store them underground to prevent release into the atmosphere.

Carbon intensity: The amount of greenhouse gas emissions produced per unit of product or energy.

Certification ecosystem: The network of organizations, standards, and processes that verify and certify the carbon footprint or sustainability of products.

Circular feedstocks: Materials that are recycled or reused in the production process, reducing the need for new raw materials and minimizing waste.

CO_2 abatement potential: The estimated amount of carbon dioxide emissions that can be reduced or eliminated by a specific technology or approach.

Decarbonization: The process of reducing carbon dioxide and other greenhouse gas emissions from industrial activities.

Downstream: Later stages in the value chain where products are processed, marketed, and sold to end users.

Ecosystem assessment: An evaluation of the organizations, standards, and processes that support measurement, certification, and market functioning for low-emissions products.

Electrification: Replacing fossil fuel-based energy sources with electricity (preferably from renewable sources) in industrial processes.

End market: The final industry or sector that uses chemical products as part of its value chain (e.g., packaging, automotive, construction).

Feedstock: The raw material used to produce chemicals or fuels.

Greenhouse gas (GHG) emissions: Gases such as carbon dioxide and methane that trap heat in the atmosphere and contribute to global warming.

Green premium: The additional cost associated with producing a product using lower emissions or more sustainable methods compared to conventional methods.

Hard/soft Packaging: Types of packaging materials: "Hard" refers to rigid containers (e.g., bottles); "soft" refers to flexible materials (e.g., bags, wraps).

High/low-purity streams: Refers to the concentration of a specific chemical in a process stream, which can affect the cost and feasibility of emissions abatement.

Hydrogen (Blue/Green): Hydrogen used as a fuel or feedstock. "Blue" hydrogen is produced from natural gas with carbon capture; "green" hydrogen is produced using renewable energy.

Intermediate feedstocks: Materials produced in one stage of chemical processing that are used as inputs in subsequent stages.

Levelized abatement cost: The average cost of reducing one ton of carbon dioxide emissions over the lifetime of costs of an abatement technology.

Market prioritization matrix: A tool used to rank and compare end markets or submarkets based on criteria such as demand, impact, and value chain complexity.

Market study: An analysis of market trends, drivers, barriers, and opportunities to assess demand and prioritize investments in lower-emissions products.

Methane leakage: Unintentional release of methane (a potent greenhouse gas) during extraction, processing, or transport of fossil fuels.

Net present value (NPV): A financial metric that calculates the present value of future cash flows or investments, accounting for the time value of money.

Net-zero: Deeply decarbonizing systems (to as close to zero emissions as practicable) leaving a modest level of residual emissions that are very difficult and costly to abate.

NPV cost of abatement (NPVCOA): The net present value of all costs associated with implementing emissions abatement technologies over a specified period.

Operating expenditure (OpEx): Ongoing costs for running a facility or process, such as maintenance, labor, and utilities.

Platform (data/value platform): A digital or organizational system that enables data management, tracking, and value transfer for low-emissions products across the value chain.

Policy incentives: Government measures (e.g., subsidies, tax credits) designed to encourage investment in emissions reduction technologies.

Process emissions: Greenhouse gases released directly from chemical reactions during production, separate from emissions from fuel combustion.

Product vignette: A detailed example tracing the journey of a product (e.g., sunscreen) from raw materials to the final consumer item, highlighting considerations around emissions and costs.

Region-level analysis: Assessment of data and trends specific to geographic regions (e.g., North America, Europe, China, Middle East) within the global chemical industry.

Regional capital cost factor: A multiplier used to adjust capital expenditure estimates based on regional differences in costs.

Registry: A system or database for recording and tracking emissions, certifications, or other relevant data for products or facilities.

Scope 1, 2, and 3 emissions:

Scope 1: Direct emissions from owned or controlled sources (e.g., factory emissions).

Scope 2: Indirect emissions from the generation of purchased electricity, steam, heating, and cooling.

Scope 3: All other indirect emissions in a company's value chain (e.g., raw material extraction, product use).

Submarket: A smaller, more specific segment within a larger end market (e.g., personal care within consumer goods).

Supply chain resilience: The ability of a supply chain to withstand and recover from disruptions; important for ensuring consistent delivery of sustainable products.

Scenario analysis: A method of exploring and comparing different plausible future outcomes based on varying assumptions about key drivers (e.g., policy, demand).

Techno-economic analysis/model: A comprehensive evaluation that combines technical and economic factors to assess the feasibility and impact of projects or technologies.

Total installed capital costs: The full amount spent to purchase and install new equipment or facilities, including all associated expenses.

Upstream: The earlier stages in the value chain, such as raw material extraction and initial processing.

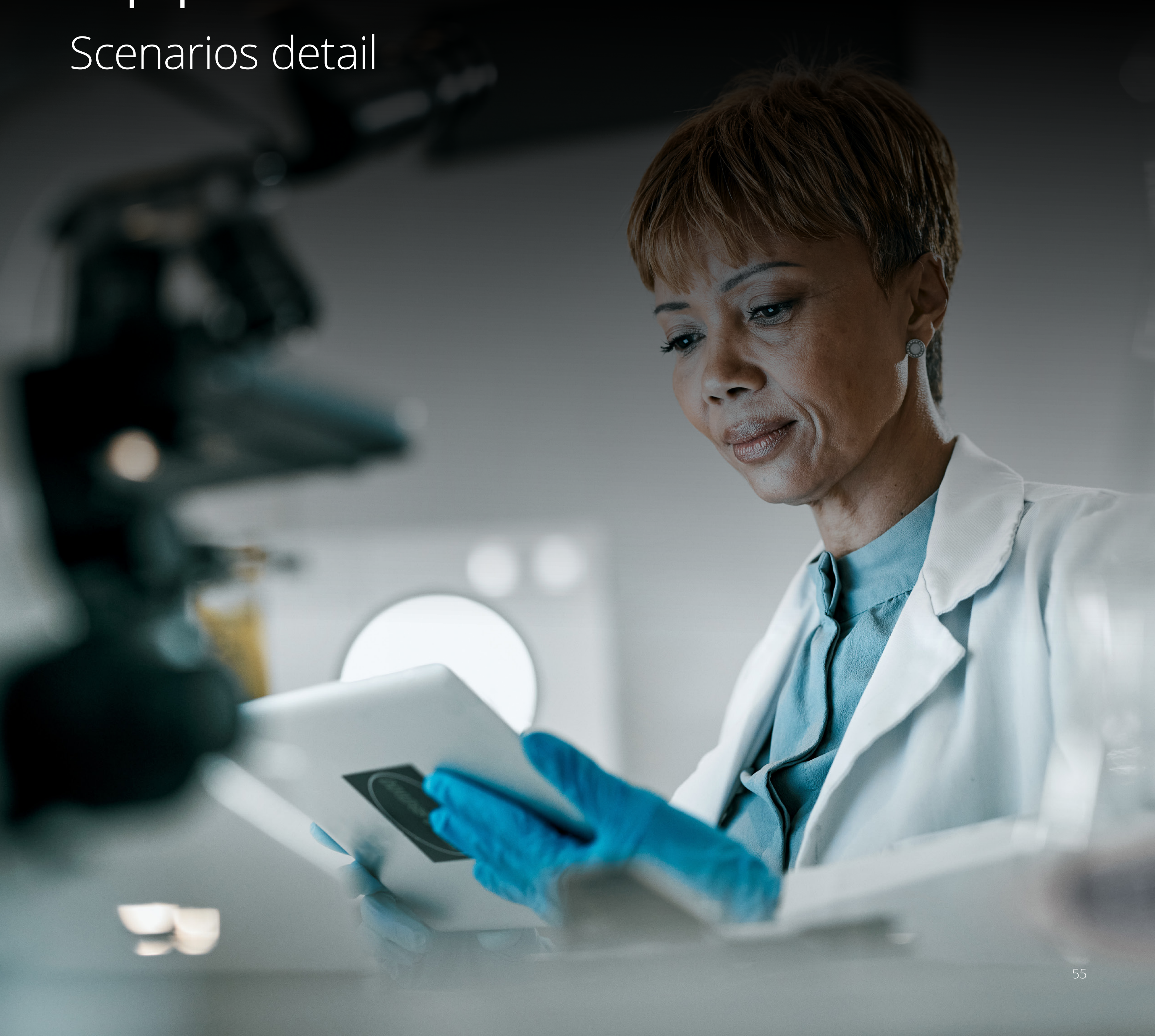
Value capture: The process of securing financial or strategic benefits from investments or innovations, such as producing low-emissions products.

Value chain: The full range of activities and stakeholders involved in producing, processing, and delivering a product from raw materials to end users.

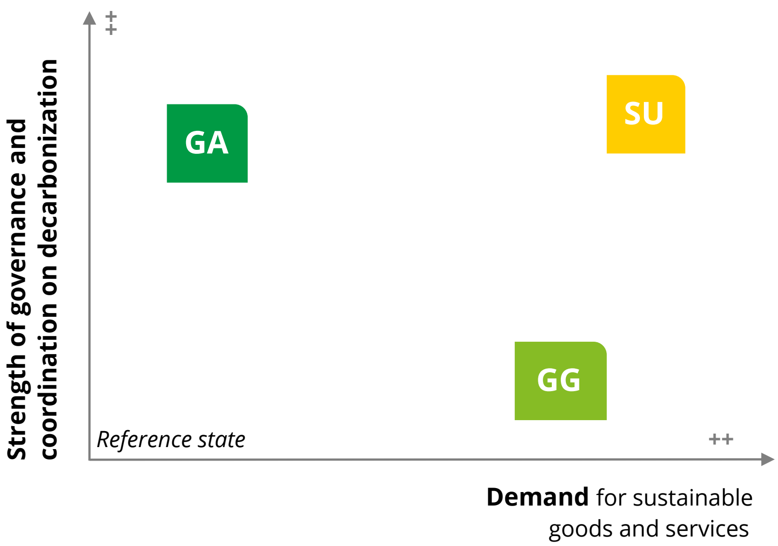
Willingness to pay: The amount consumers are prepared to spend on products with sustainable attributes, such as lower emissions.

Appendix 1

Scenarios detail



Note: This appendix provides detailed qualitative narratives around each scenario. The Methodology Appendix details scenario-specific assumptions around the distribution of capital expenditures and changes in the rate of learning curves as applied to abatement technology implementation. Distribution of capital expenditures for implementation of emissions abatement solutions is the forcing function for the results of each specific scenario. These differences in the learning curves affect the number and timing associated with deployment of assets in this scenario.



Sustainable United

This is **strong governance** with nations imposing enabling regulations and incentives, with **strong collaboration** across the sector and **high willingness to pay** across product value chains.

Green Authority

Although there is **strong governance** with nations imposing enabling regulations and incentives, **collaboration is limited** across the sector and **customer willingness to pay** remains low.

Grassroots Green

There is **consumer-led demand for sustainable products** especially in higher-income groups. However, geopolitical and economic tensions **limit governance and collaboration**, resulting in lackluster policy support and subdued innovation.

Sustainable United

Strong global governance with widespread demand for sustainable products

A deeply collaborative world is committed to tackling global challenges related to climate change and has embraced sustainability and social well-being as fundamental to enduring business value. Governments, businesses, and NGOs unite behind the climate agenda and broader sustainability goals, including biodiversity and water resilience.

Strong government coordination facilitates deep collaboration between regions and across economic sectors, and proactive regulators seek to appropriately reduce barriers to collaboration among corporations. Coalitions comprising government, industry, and environmental/social NGOs collaborate to design policy, regulatory, and incentive measures to drive sustainable change.

Such coalitions play a pivotal role in developing and harmonizing the formation of carbon markets, standards, and regulations. Widespread and durable uptake is ensured by robust and transparent monitoring, verification, and reporting standards.

Rapid innovation drives down the cost of all clean technologies, while the responsible use of data science, including AI, allows unprecedented technology exchange between nations and companies, helping to accelerate learning and drive down costs.

Widespread use of digital twins facilitates greater transparency and trust across the stakeholder ecosystem, resulting in durable public acceptance and streamlined permitting processes, resulting in accelerated delivery of infrastructure projects.

The above trends complement a pervasive bottom-up demand for sustainable products and services throughout the value chain and among consumers. Companies, communities, and households more broadly embrace a war on waste, resulting in the widespread adoption of waste reduction and recycling, and product reuse globally. Single-use plastics are virtually eliminated from the global economy.

These trends combine to see accelerated progress on all global sustainability commitments on climate mitigation and preservation of natural capital values like biodiversity and water resources.

In this scenario, in the 2030s, the chemical industry sees:

- Most clean (renewable and nuclear) electricity and heat supply systems approach cost parity with carbon-intensive systems.
- Broad alignment and systemic adoption of regulation, measurement, tracking, and certification frameworks to realize the value of low-emissions energy and products.
- Accelerated cost reductions in technologies for CCUS, along with synthetic and bio-based feedstocks.
- The broad-based commitment to sustainability limits sourcing of biomass feedstocks to organic municipal waste, native grasses, agricultural residues like bagasse, crop stubble, and native and plantation forest residues.
- Accelerated cost reductions in mechanical and advanced recycling technologies.
- Systemic adoption of waste sorting and collection systems. Increased consumer/end user awareness and adoption allows high levels of high-quality, cost-competitive circular feedstocks.
- High levels of willingness to pay among customers along the full value chain, which justifies any significant additional cost of low clean-energy procurement, CCUS, and sustainable feedstocks, in all regions.
- Chemicals producers operating in most nations have access to competitively priced capital markets.

Key details

Sustainable United stands out from the other two scenarios in that it is considered the ideal outcome, and it represents the best-case scenario for emissions reduction in this timeline. This scenario was built around the assumption that chemical building block emissions can reach net-zero by 2050 for North America and Europe, and 2060 for the Middle East and China.

Grassroots Green

Consumer-led demand for sustainable products drives localized progress despite weak global governance, subdued innovation, and limited technology transfer

Global tensions and national interests continue to limit the level of cooperation among nations and corporations. "Buy local" procurement policies drive domestic investment in both manufacturing and innovation. However, low rates of technology transfer and fragmented supply chains hold back innovation, resulting in a significant cost premium for most advanced clean technologies.

Competition, rather than cooperation, continues to underpin corporate practice, and as a result, governments and companies fail to address distrust among the broader public. Such limitations hinder collaboration across the ecosystem of stakeholders in the value chain. Supply chains lack resilience, while community and public opposition to development and cumbersome permitting processes hinder delivery of infrastructure projects.

Isolationist policies drive domestic efforts toward energy and feedstock independence throughout rapidly growing low- and low-middle-income countries in Asia, Latin America, and Africa. This results in steady adoption of renewable and bio-based energy carriers and feedstocks, despite higher costs, but with immature regulations around sustainable development.

Bilateral trade agreements combined with sustainability-linked tariffs like Europe's Carbon Border Adjustment Mechanism (CBAM) facilitate demand, supply, and trade for sustainable products between, for example, North America and Europe, and the supply of clean (green and blue) energy carriers and feedstocks from the Middle East to Europe, and resource-constrained East Asian nations like Japan and South Korea.

Progress is bolstered by a growing bottom-up demand for sustainable products and services among consumers, particularly among higher-income countries. Higher-income consumers and households in Europe, in parts of North America, and in Japan and South Korea embrace waste reduction and recycling and product reuse. Single-use plastics are significantly reduced in these markets.

Lower-middle-income countries also make significant progress on waste reduction and circularity driven by a combination of grassroots movements to reduce local pollution and local regulations around recycled content.

NGOs play a leadership role developing localized carbon emissions standards tailored to regional needs, working directly with early-mover industry players, local governments, businesses, and communities to ensure relevance and effectiveness. Carbon markets evolve in a fragmented yet resilient manner, driven by localized efforts and consumer-led demand for sustainability.

This localized approach builds momentum through the leadership of early movers in various product/sector/geographic markets setting the example for international companies and markets.

In this scenario, in the 2030s, the chemical industry sees:

- Consumers, especially in higher-income brackets, show a willingness to pay significant premiums, which helps drive demand for sustainable goods.
- Clean (renewable and nuclear) electricity and heat supply systems see steady, but uneven growth at a significant cost premium to carbon-intensive systems.

- CCUS, along with synthetic and bio-based feedstocks, see localized expansion despite significant cost premiums to conventional systems and fossil-based feedstocks.
- Bio-based feedstocks see growth in the tropics and subtropic, but not without growing threats to natural ecosystems.
- The adoption of mechanical and advanced recycling technologies, along with waste sorting and collection systems, expanded sporadically, driven by local agendas to reduce demand for conventional feedstocks and local pollution, and to create jobs.
- Limited company, sector, and regional-specific adoption of measurement, tracking, and certification frameworks to realize the value of low-emissions energy and products.
- Limited and high cost of capital continues to thwart progress in low- and low-middle-income countries.

Key details

In Grassroots Green, emissions reduction ambition is driven primarily by consumer demand for sustainable products. This assumes a lower annual capital deployment rate as compared to Sustainable United, but the total CapEx deployment over time is higher in Grassroots Green due to slower and more fragmented adoption of technologies.

At its core, the Grassroots Green scenario represents a high amount of demand for sustainable goods (x-axis), and a low level of cooperation and government involvement (y-axis). However, the scenario is intended to reflect a plausible future, therefore the positioning of this scenario against the drivers on our two axes should reflect an improvement from the origin position of business as usual. The level of cooperation will be driven by companies to attempt to meet this demand and therefore will be higher than the reference state even if they are inefficient at doing so.

This scenario is really about the demand for sustainable goods, which is reflected by a position on the right-hand side of the x-axis. While this demand is strong in Grassroots Green, it is still less than the demand recognized in Sustainable United. This limitation is due in part to an inability to drive demand in lower-income countries without cooperation and government support.

Green Authority

Strong global governance drives progress through regulation and collaboration, despite skeptical consumers

Governments around the world have come together behind strengthened global institutions to tackle climate change, preserve biodiversity, and other natural capital risks. However, consumers and communities remain resistant to change.

Governments facilitate international agreements across economic sectors, and proactive regulators seek to reduce barriers to collaboration among corporations. Governments and industry collaborate to design and implement standards, policy, regulatory, and incentive measures to drive top-down sustainable change.

Regional carbon markets evolve under the strong influence of global governance and regulatory frameworks but remain vulnerable to politicization, which threatens their durability. Furthermore, consumer skepticism and resistance to change limits the overall effectiveness of these markets.

NGOs focus their efforts on education and outreach to improve public support for sustainable products and practices.

Innovation, including the use of data science and AI, drives down the cost of all clean technologies and technology exchange between nations and companies, which helps to accelerate learning and drive down costs. However societal distrust in governments and business underpins grassroots movements that hold back the full potential of digital technologies.

Efforts to accelerate clean infrastructure development have failed to achieve authentic engagement, participatory design practices, and benefits sharing. Such failures hinder public acceptance and fortify grassroots opposition and legal challenges, resulting in no acceleration and increased delays in delivery of infrastructure projects.

Top-down approaches fail to arrest a growing trust deficit in governments and corporations, causing low willingness to adopt new “sustainable” products and/or pay green premium. Consumers see the sustainability challenge as a problem for governments and businesses to solve. Adoption rates for household waste reduction, recycling, and product reuse remain low. Elimination of single-use plastics is resisted by consumers but reduced significantly in many regions via regulatory measures.

In this scenario, in the 2030s, the chemical industry sees:

- Broad alignment on a measurement, tracking, and certification framework to generate confidence in the low-emissions attributes of products.
- Clean (renewable and nuclear) electricity and heat supply systems see substantial cost reductions but remain at a premium to carbon-intensive systems, mostly due to lengthening delivery times.
- Cost reductions in technologies for CCUS, along with synthetic and bio-based feedstocks, are achieved, but these are partially offset by legal challenges and delays.

- Strong regulations to protect natural capital values limits sourcing of biomass feedstocks to organic municipal waste, native grasses, agricultural residues like bagasse, crop stubble, and native and plantation forest residues.
- Accelerated cost reductions in mechanical and advanced recycling technologies.
- Low rates of adoption of waste sorting and systems, which limit the availability and quality of circular feedstocks.
- Consumers and communities remain resistant to change, which slows the adoption of clean technologies and products in most regions, except China and some European countries for example.

Key details

The Green Authority scenario is driven primarily by cooperation and governance, despite a weak demand. Therefore, this scenario sits on the upper end of the y-axis. Nevertheless, it remains lower than the position of Sustainable United, reflecting limitations in the level of governance and cooperation anticipated without limited consumer support for sustainable goods.

While Green Authority lacks consumer demand, the x-axis position is nevertheless farther to the right than the reference state. It is reasonable to anticipate that even if consumer demand wanes, continued weather events driven by climate change, greenfield construction development driven by population growth, and other factors will result in an observable rise in consumer demand for sustainable goods.

Appendix 2

Techno-economic modeling methodology

Modeling scope

Feedstocks included in the scope of this study are both traditional and emerging sustainable feedstocks, including fossil fuels, biogenic feedstocks from fermentation or gasification, and circular feedstocks from advanced chemical recycling.

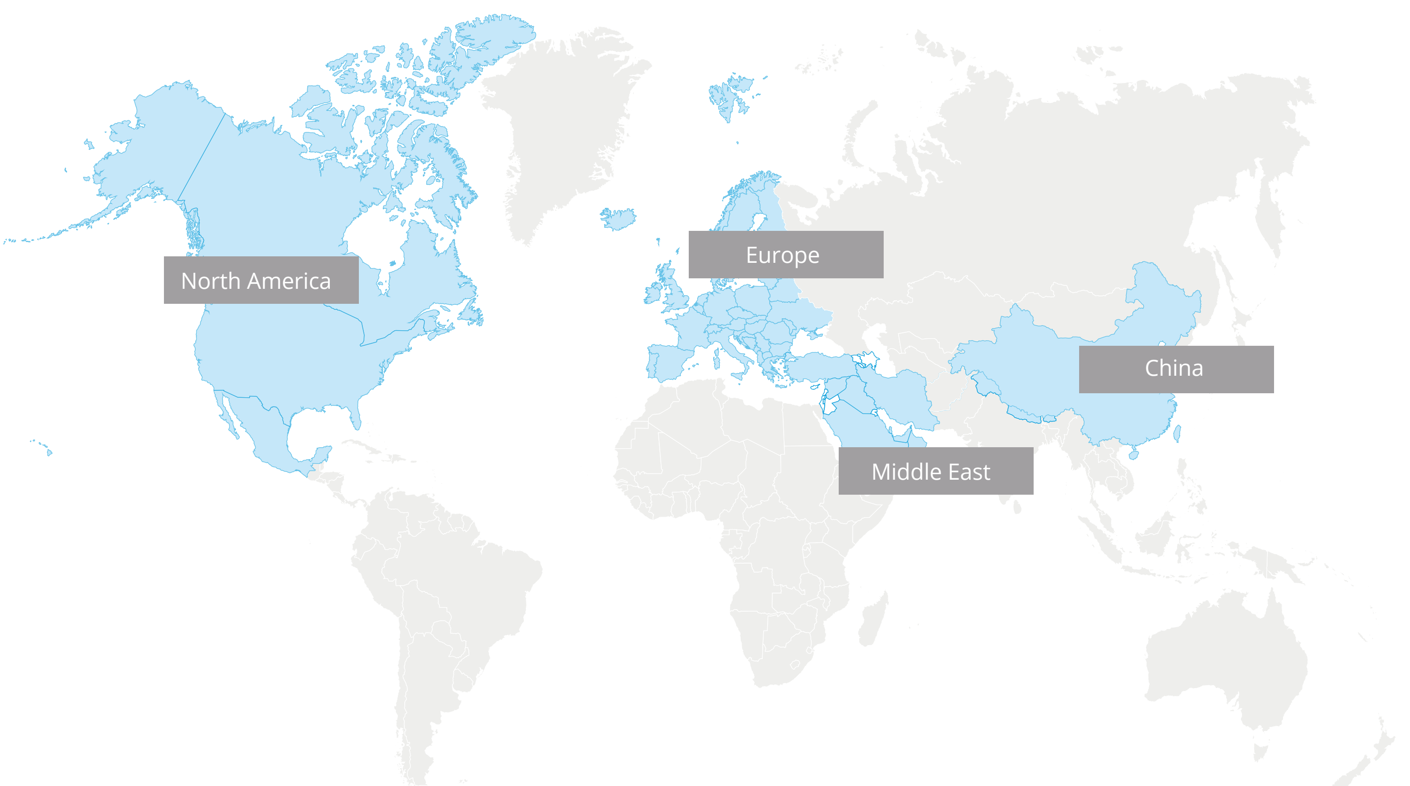
Ten building block chemicals (BBs) were in scope for this study:

1. Ammonia
2. Benzene
3. Butadiene
4. Chlorine/caustic
5. Ethylene
6. Hydrogen
7. Methanol
8. Propylene
9. Toluene
10. Xylene

Abatement technologies considered in the scope of this study include CCS, CCU, clean hydrogen, clean electrification, and feedstock substitution.

The regions considered in the study are North America, Europe, the Middle East, and China. Each of these regions included the countries shown in figure 25.

Figure 25. Geographic scope of the study



Emissions included in scope for this study are scope 1 and 2 CO_2 emissions from combustion, power generation, and chemical conversion processes. Scope 3 emissions associated with upstream feedstock and fuel production and delivery are also included. Upstream methane emissions, detailed below, were assumed to reduce in line with oil and gas industry commitments to achieve "near zero" upstream emissions by 2030. This study did not consider end-of-life emissions, except in the case of circular feedstocks, where avoided emissions associated with a significant alternative fate of such feedstocks in Europe (incineration) were considered.

This is a forward-looking study that evaluated the timing of the industry's ability to reduce emissions over the next half-century. 2023 was the baseline year for projections.

Overview

Two distinct levels of techno-economic modeling were undertaken:

1. Modeling to estimate CO_2 abatement potentials and costs on an asset-by-asset basis across the 10 building block chemicals (BBs) that are the focus of the work.
2. Regional scenario-based modeling of alternative trajectories for industrywide deployment of abatement options over time in each of the four study regions.

Facility-level techno-economic modeling

Key input data set

The modeling built on key inputs provided by Chemical Market Analytics by OPIS, including projections of BB production by region and a comprehensive database of existing (2023) individual chemical production assets.

For each BB, the Chemical Market Analytics by OPIS database includes region-level estimates of BB demands, imports, and exports in the base year (2023) and with market projections to 2050. Annual production is estimated from asset-level production capacities and an estimated region-average capacity utilization rate determined by the balance of region-level demand, exports, and imports. The Chemical Market Analytics by OPIS inputs include estimates of projected new capacity (in aggregate for each region) that would be needed to meet future demands. For a given BB, the capacity of any individual new facility needed to meet projected regional production growth is assumed to be twice the regional average facility capacity observed in 2023, with utilization rates capped at 98%. The Chemical Market Analytics by OPIS projections of demand and corresponding capacities and production levels are extrapolated to 2080 assuming the trend observed from 2025 to 2050 persists. Table 5 shows four region summaries. (Region-specific values are provided in the supplemental spreadsheet, herein after referred to as the Supplemental Information [SI] spreadsheet.) For Europe, aggregate production capacity is projected to decline for most BBs. We assume facilities listed in decommissioning plans reported by Independent Commodity Intelligence Services[34] will be the ones decommissioned through 2050. Further decommissioning beyond 2050 is assumed to go in order of smallest and oldest facilities first.

Demand projections here exclude consideration of hydrogen or methanol as transportation fuels, due to the association with the transport sector, not the chemical industry. For hydrogen outside of production integral to methanol and ammonia production, only hydrogen used in aromatics production is considered. This hydrogen production in the database is not reported at the asset level because the source of the hydrogen is variable (e.g., internal sources or merchant providers). However, the hydrogen demand at aromatics production facilities is estimated. For these facilities, when estimating abatement of emissions associated with this hydrogen, the assumption is hydrogen generated by steam methane reforming would be substituted by green hydrogen.

Table 11. 2023 estimates and decadal projections of demand, production capacities, and annual production by building block. Region-specific data is included in the SI spreadsheet.

	2023	2030	2040	2050	2060	2070	2080
BB demand across all four study regions (Mt products per year)							
Ammonia	89	102	128	145	168	189	210
Benzene	39	46	54	61	69	76	83
Butadiene	7	8	10	11	12	13	14
Caustic	55	61	68	74	80	86	93
Chlorine	56	62	69	74	80	87	93
Ethylene	115	142	167	186	209	231	253
Methanol	72	86	110	123	143	162	181
Propylene	80	99	118	128	143	158	172
Toluene	18	21	24	25	28	30	32
Xylene	46	59	69	79	89	99	109
SUM	**576**	**686**	**815**	**905**	**1,021**	**1,130**	**1,239**
BB production capacity across all four study regions (Mt products per year)							
Ammonia	150	171	221	262	307	351	396
Benzene	53	64	73	82	88	93	99
Butadiene	13	15	16	16	17	19	20
Caustic	81	87	92	98	98	98	98
Chlorine	78	83	88	93	101	107	114
Ethylene	171	210	240	263	281	296	311
Methanol	114	132	150	167	189	208	228
Propylene	150	186	206	228	245	260	343
Toluene	39	46	50	55	58	61	64
Xylene	78	94	104	117	130	143	156
BB production across all four regions (Mt of BB per year)							
Ammonia	107	129	173	204	240	275	311
Benzene	37	43	48	52	55	58	61
Butadiene	8	10	11	12	14	15	16
Caustic	64	71	79	85	92	99	106
Chlorine	61	68	75	81	86	91	96
Ethylene	137	177	214	236	253	267	281
Methanol	74	88	110	125	142	158	174
Propylene	110	134	159	172	188	203	285
Toluene	21	24	27	29	31	32	34
Xylene	50	64	75	87	98	108	118
Hydrogen	2	2	3	3	3	3	3

The Chemical Market Analytics by OPIS asset database includes 4,012 assets encompassing 2,676 facilities with process technologies (table 9) and input feedstocks (table 10) that vary by region. (A production facility consists of one or more assets at the same geographical location. The SI reports the number of facilities by BB in each study region.) For each individual asset, the database includes owner company name, geographical location, startup year, key defining BB production process, production and production capacity (t/y), input feedstock type, and input intensities (t/tproduct) of feedstock, electricity, fuel (excluding steam-raising fuel), steam, and water. While the qualitative method for calculating input intensities for each BB production process is included in this report, these values are not included for data confidentiality. The database also includes estimates of process CO_2 emissions per unit of BB production (as distinct from CO_2 emissions associated with fuel combustion supplying heat or steam to a process).

Table 12 . BB production technologies by region.

	AMMONIA			
Product technology	**Europe**	**Middle East**	**North America**	**China**
Coal			X	X
Hydrogen	X	X	X	
Natural gas	X	X	X	X
Natural gas with CCU		X	X	
Renewable hydrogen	X	X	X	X
To be announced			X	
Unknown/other	X	X	X	X
Coal and anthracite				
	METHANOL			
Product technology	**Europe**	**Middle East**	**North America**	**China**
Bio-feedstock	X			X
Coal to methanol			X	X
Coking gas				X
E-feedstock	X			X
Heavy liq. feedstock	X			
Nat. gas/lt. gases	X	X	X	X
Waste	X			X
	HYDROGEN			
Product technology	**Europe**	**Middle East**	**North America**	**China**
C3 dehydro-poly. grade	X	X	X	X
Coal to olefins				X
Coal to propylene				X
HS FCC		X		X
Metathesis	X	X	X	X
Methanol to olefins				X
Methanol to propylene				X
Steam cracker-chem. grade	X	X	X	X
Steam cracker-poly. grade	X	X	X	X

	ETHYLENE			
Product technology	**Europe**	**Middle East**	**North America**	**China**
Coal to olefins				X
EPB (ethane, propane, butane)	X	X	X	X
EPB/naphtha	X	X	X	X
EPB/naphtha/gas oil/residues	X		X	X
Ethane	X	X	X	X
Ethane/propane	X	X	X	X
Ethanol dehydration			X	X
Higher olefins cracking				X
Methanol to olefins				X
Naphtha	X	X		X
Naphtha/gas oil/residues	X			X
Recovery from FCC/DCC unit	X	X	X	X

	PROPYLENE			
Product technology	**Europe**	**Middle East**	**North America**	**China**
FCC	X	X	X	X
Steam cracker			X	X

	BENZENE			
Product technology	**Europe**	**Middle East**	**North America**	**China**
Coke oven	X	X	X	X
HDA	X	X	X	X
Pygas	X	X	X	X
Pygas/HDA	X	X		
Reformate	X	X	X	X
Reformate/HDA		X		
Reformate/pygas	X	X	X	X
STDP	X		X	
TDP		X	X	X
Transalkylation	X	X	X	X

	TOLUENE			
Product technology	**Europe**	**Middle East**	**North America**	**China**
Pygas	X	X	X	X
Reformate/pygas	X	X	X	X
Reform-distilled	X	X	X	X
Reform-extract	X	X	X	X

	XYLENE			
Product technology	**Europe**	**Middle East**	**North America**	**China**
Pygas	X			X
Reformate/pygas	X	X		
Reform-distilled	X	X	X	X
Reform-extract	X	X	X	X
STDP	X	X	X	
TDP			X	X
Transalkylation	X	X	X	X

Product technology	BUTADIENE Europe	Middle East	North America	China
Bio-butadiene	X			
By-product extraction	X	X	X	X
Extraction - CTO/MTO - ODH				X
ODH (dehydro) process	X			X

Product technology	CHLORINE Europe	Middle East	North America	China
Brine to bleach	X		X	
Diaphragm cell	X	X	X	X
Flexible brine to bleach			X	
From HCL	X	X		X
From KCL+diaphragm cell				X
From KCL+membrane Cell	X	X	X	X
Membrane cell	X	X	X	X
Mercury cell+alkoxide	X			
Others		X		

Product technology	CAUSTIC Europe	Middle East	North America	China
Brine to bleach	X		X	
Diaphragm cell	X	X	X	X
Flexible brine to bleach			X	
Membrane cell	X	X	X	X
Membrane ODC	X			
Mercury cell		X	X	
Others		X	X	

Table 13. BB Feedstocks by region.

Feedstocks Mt/Mt	AMMONIA Europe	Middle East	North America	China
Natural gas	X	X	X	X
Light oil NGLs				
Naphtha NGLs				
Ethane NGLs				
Propane NGLs				
Butane NGLs				
Coking gas				
Coal and anthracite			X	X

Feedstocks Mt/Mt	METHANOL Europe	Middle East	North America	China
Natural gas	X	X	X	X
Light oil NGLs				
Naphtha NGLs				
Ethane NGLs				
Propane NGLs				
Butane NGLs				
Coking gas				X
Coal and anthracite			X	X

Feedstocks	HYDROGEN			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Natural gas				
Light oil NGLs		X		X
Naphtha NGLs				
Ethane NGLs				
Propane NGLs	X	X	X	X
Butane NGLs				
Coking gas				
Coal and anthracite				X

Feedstocks	ETHYLENE			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Natural gas				
Light oil NGLs	X	X	X	X
Naphtha NGLs	X	X	X	X
Ethane NGLs	X	X	X	X
Propane NGLs	X	X	X	X
Butane NGLs	X	X	X	X
Coking gas				
Coal and anthracite				X

Feedstocks	PROPYLENE			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Light oil NGLs	X	X	X	X
Naphtha NGLs				
Ethane NGLs				
Propane NGLs				
Butane NGLs				
Coking gas				
Coal and anthracite				

Feedstocks	BENZENE			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Natural gas				
Light Oil NGLs	X	X	X	X
Naphtha NGLs	X	X	X	X
Ethane NGLs				
Propane NGLs				
Butane NGLs				
Coking gas				
Coal and anthracite				

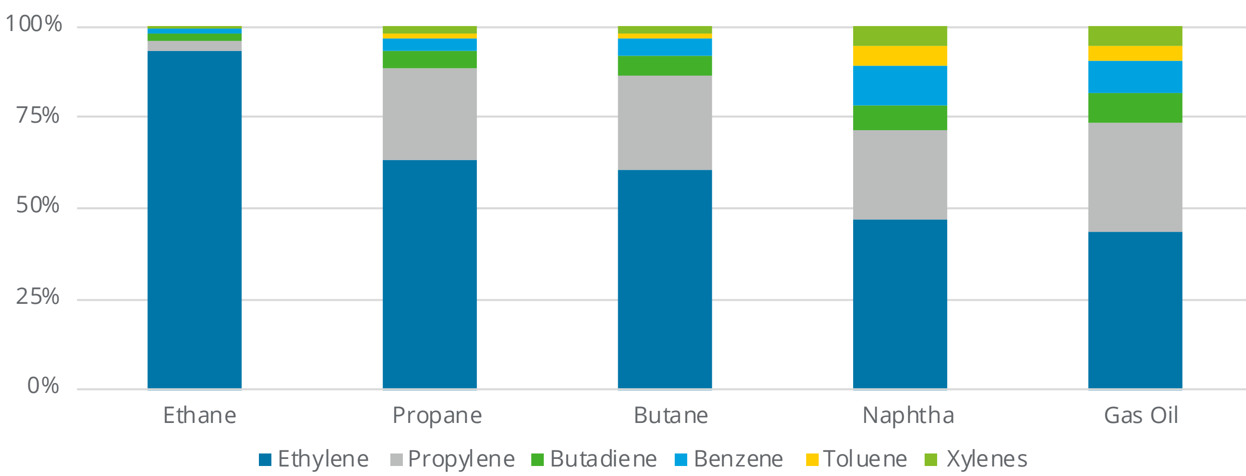
Feedstocks	TOLUENE			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Natural gas				
Light oil NGLs				
Naphtha NGLs				
Ethane NGLs				
Propane NGLs				
Butane NGLs				
Coking gas				
Coal and anthracite				

Feedstocks	**XYLENE**			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Natural gas				
Light oil NGLs				
Naphtha NGLs				
Ethane NGLs				
Propane NGLs				
Butane NGLs				
Coking gas				
Coal and anthracite				
Feedstocks	**BUTADIENE**			
Mt/Mt	**Europe**	**Middle East**	**North America**	**China**
Natural gas				
Light oil NGLs				
Naphtha NGLs				
Ethane NGLs				
Propane NGLs				
Butane NGLs	X			X
Coking gas				
Coal and anthracite				

Steam crackers play the most significant role of any BB production technology across the set of facilities inventoried in the Chemical Market Analytics by OPIS database. Accordingly, key inputs to the abatement modeling in this study were the estimated co-product yields from steam crackers operating with different feedstocks. These were provided by Chemical Market Analytics by OPIS for this study (figure 26).

Figure 26. Relative steam cracker yields by feedstock

Mt/Mt ethylene produced



Source: Chemical Market Analytics by OPIS

Mass and energy balance estimates

Individual CO_2 emissions are calculated at the facility level. For each facility, current (unabated) annual CO_2 emissions are estimated as follows:

- **Scope 1.** The assumed fuel input to a process is natural gas, which is fully combusted. To meet process steam demand, additional natural gas is assumed to be combusted in a boiler with efficiency of 85.7%. To these two combustion emission sources, process emissions, as reported by Chemical Market Analytics by OPIS, are added.
- **Scope 2.** Scope 2 emissions are those associated with generation and delivery of electricity used by a BB production process. Projected grid-average estimates of the carbon intensity of electricity in each region are used. The trajectories of these vary by scenario, as detailed later in this appendix.
- **Scope 3.** Scope 3 upstream emissions refer to those associated with the extraction and delivery of fuels and feedstocks used at a BB production facility. The most significant scope 3 emissions are associated with leakage of methane associated with natural gas extraction and delivery and, in China, coal mining. Assumed scope 3 upstream emissions trajectories vary by scenario, as detailed later in this appendix.

For each asset, the CO_2 abatement potential is estimated for four different technological approaches that are plausibly commercially deployable in the near term (table 8), including the use of CCS CCU hydrogen as heating fuel or chemical feedstock, heating electrification using clean electricity, and substitution by circular or biogenic feedstocks. Some BB production processes are amenable to more than one abatement approach. Because olefin production contributes the largest emissions among all BBs, the largest number of abatement approaches are evaluated for steam crackers.

Table 14. Abatement approaches considered for each building block chemical.

			Abatement approach								
			CCS	Hydrogen		Electrification via			Substitute feed		
Building block	**Feedstock**	**Process**		**Blue**	**Green**	**Nuke**	**Wind**	**Solar**	**Circ**	**Bio**	**Co_2**
Ethylene, Propylene, Butadiene	Ethane, Propane, Butane, and/or Naphtha	Steam cracking	✓	✓	✓	✓	✓	✓	✓		
Ethylene, Propylene, Butadiene	Methanol	Synthesis	✓								
Ethylene	Ethanol	Dehydration								✓✓	
Propylene	Propane	Dehydrogenation	✓								
Propylene	Gas Oil	Cat. cracking	✓								
Benzene, Toluene, Xylene	Reformate	Extraction	✓								
Methanol	Natural gas	Synthesis	✓								
Methanol	Coal	Synthesis	✓	✓							
Methanol	H_2 + CCU	Synthesis			✓✓						✓✓
Ammonia	Natural gas	Synthesis	✓								
Ammonia	Coal	Synthesis	✓								
Ammonia	Green H_2	Synthesis	✓		✓✓						
Chlorine/ Caustic	NaCl	Electrochemical	Follows grid carbon intensity								

Note: Double check marks (✓✓) indicate the option is only available for new greenfield capacity, i.e., it is not considered for retrofits at existing facilities. Green hydrogen refers to production by water electrolysis using the least costly clean potential electricity source (nuclear, wind, or solar PV) in the region where the facility under consideration is located.

Schematic process flow diagrams for all abatement technology options are provided at the end of this subsection, and quantitative techno-economic characterizations used as modeling inputs for each process technology option and each clean electricity supply option are provided in the SI. The four abatement approaches are briefly summarized here.

For abatement involving post-combustion CO_2 capture, amine-based systems are used, with heat needed for solvent regeneration assumed to be provided by natural gas cogeneration, the CO_2 emissions from which are also captured. We assume a 95% capture rate for low-purity CO_2 streams. Process-derived CO_2 streams associated with ammonia and methanol production (as distinct from combustion emissions associated with heat supply to a process) are assumed to be 100% captured by simple dehydration due to their high CO_2 purity. These streams then require only compression for further handling downstream. For underground storage, captured CO_2 is assumed to be compressed and moved by pipeline to suitable storage sites.

For methanol production, one abatement option is considered that would use captured CO_2 as an input feedstock alongside green hydrogen (produced by water electrolysis using electricity from a carbon-free source). The CO_2 is assumed to be captured at a nearby industrial site that may or may not be in the chemical sector. This option is considered only for methanol production and only for future new-build units.

For hydrogen as an abatement option, blue H_2 (from autothermal methane reforming of natural gas with CO_2 capture) and green H_2 are considered. When considered as a steam cracker heating fuel replacing fossil fuel, hydrogen can fully eliminate the combustion emissions associated with cracking. However, the combustion of cracker off-gas (which typically provides heat for other processes outside the cracker) generates some emissions that are included in the CO_2 accounting. When green hydrogen is considered as a feedstock for ammonia production, this is considered only for future new-build ammonia capacity.

Electrification is considered as an abatement option for steam crackers, but it is not considered for commercial deployment until 2040, given its current early stage of technological development.

For any abatement option that uses clean electricity (for example, green hydrogen or steam cracker electrification), the assumption is the BB production facility procures non-carbon electricity from a nuclear power station, wind farm, or solar farm located relatively nearby (e.g., in the same state or province). The assumption is the facility would enter into a power purchase agreement (PPA) with the clean electricity provider for the volume of its annual electricity need. For solar and wind electricity supply, this means there would not be hourly matching of electricity need with renewable generation. However, in estimating capital requirements for the electricity supply (discussed in the next subsection), the capacity of the solar or wind plant is set such that its annual generation matches the annual electricity demand of the facility.

The final abatement option considered is alternative feedstocks substituting incumbent feedstocks. Circular feedstock (oil from pyrolysis of plastic waste) is assumed for ethylene production, and biogenic feedstocks are considered for two BBs: dehydration of corn ethanol for ethylene production and thermochemical gasification of lignocellulosic feedstock (e.g., crop residues) to produce a synthesis gas feedstock for methanol production. The bio-ethylene option is considered only for future new-build facilities. For the bio-syngas option, retrofits are assumed to be feasible at existing facilities (and at new builds), where 20% of syngas from incumbent feedstocks is assumed to be replaced by bio-syngas in all scenarios. The assumed level of circular feedstock use varies by scenario. In the Sustainable United, Green Authority, and Grassroots Green scenarios, these grow to reach 20%, 15%, and 10%, respectively, of total feedstock inputs for the relevant BB in a region by 2050.

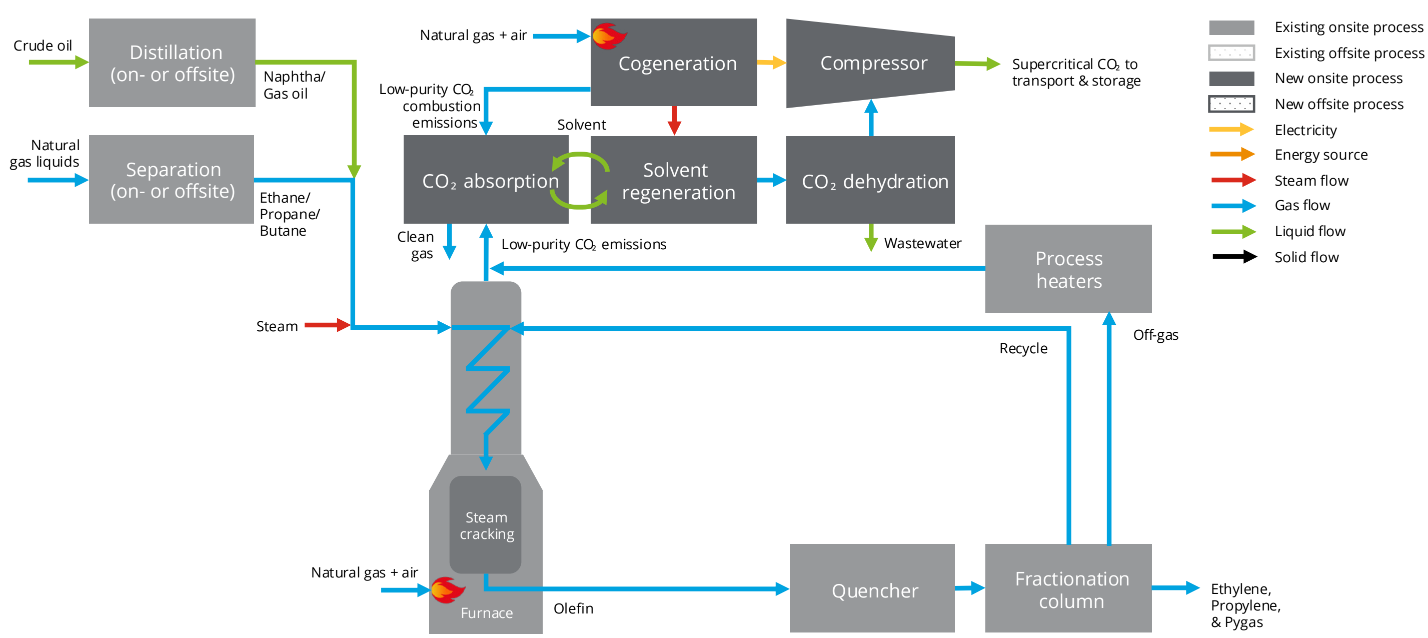
Emissions reductions for chlorine/caustic production result from assumed decarbonization of the grid electricity supply.

START HERE

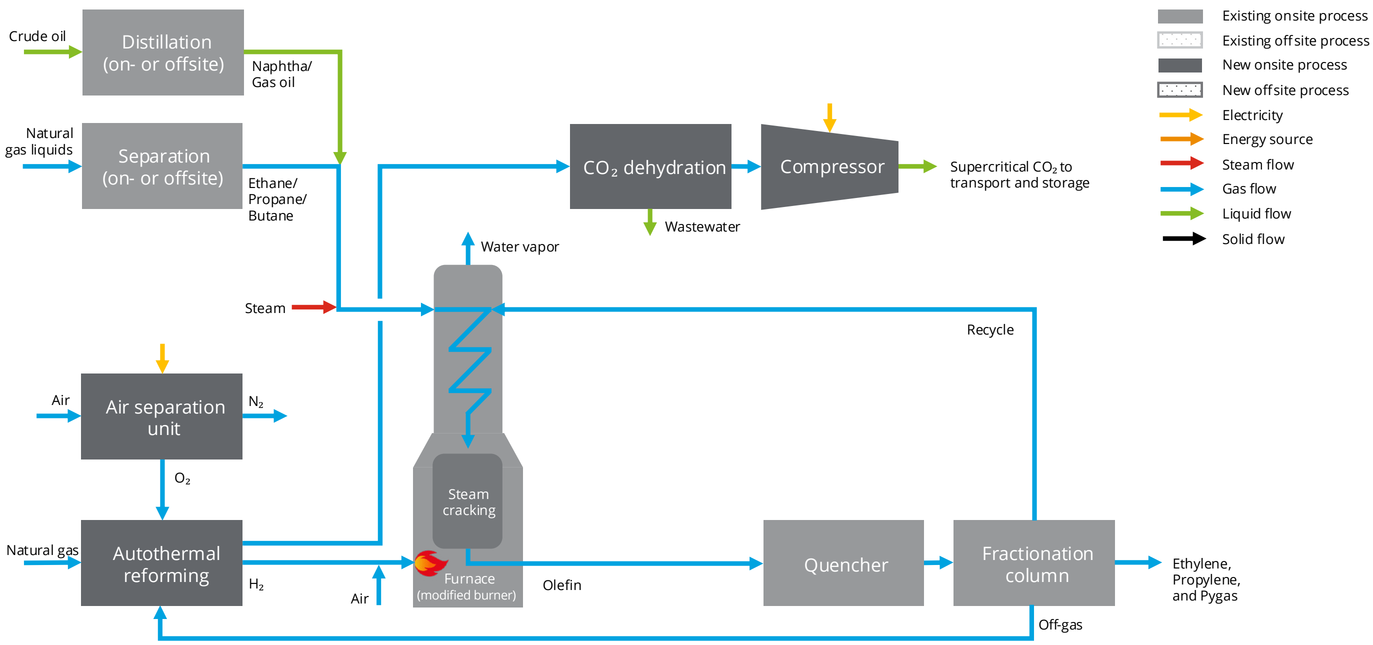
Abatement technology process flow diagrams

No.	Building block	Feedstock	Process production	Abatement approaches								
				CO_2 capture		Hydrogen		Electrification			Feedstock	
				& storage (CCS)	& utilization (CCU)	Blue	Green	Nuclear	Wind	Solar	Circular	Bio-based
				A	B	C	D	E	F	G	H	I
Hydrocarbon group												
1	Ethylene, Propylene, & Butadiene	Ethane, Propane, Butane, and/or Naphtha	Steam cracking	✓		✓	✓	✓	✓	✓	✓	
2	Ethylene	Ethanol	Dehydration									✓
3	Ethylene, Propylene, & Butadiene	Methanol	Synthesis	✓								
4	Propylene	Propane	Dehydrogenation	✓								
5	Propylene	Naphtha	Catalytic cracking	✓								
6	Benzene, Toluene, Xylene	Reformate	Extraction	✓								
7	Methanol	Natural gas	Synthesis	✓								✓
8	Methanol	Coal	Synthesis	✓								
9	Methanol	H_2 & CO_2	Synthesis		✓							
Non-hydrocarbon group												
10	Ammonia	Natural gas	Synthesis	✓								
11	Ammonia	Coal	Synthesis	✓								
12	Ammonia	H_2	Synthesis				✓					
13	Hydrogen	Natural gas	Steam reforming	Hydrogen production facilities in the database are dedicated to supplying aromatic production. We do not model the abatement for these facilities and assume that these grey hydrogen capacities will be replaced by green hydrogen.								
14	Chlorine & Caustic	Salt	Electrochemical	The “well-to-gate” emissions from chlorine and caustic production facilities primarily stem from indirect grid emissions. We do not model the abatement technologies for power generators. However, we estimate varying rates of grid emissions reduction over time for each scenario and each region.								

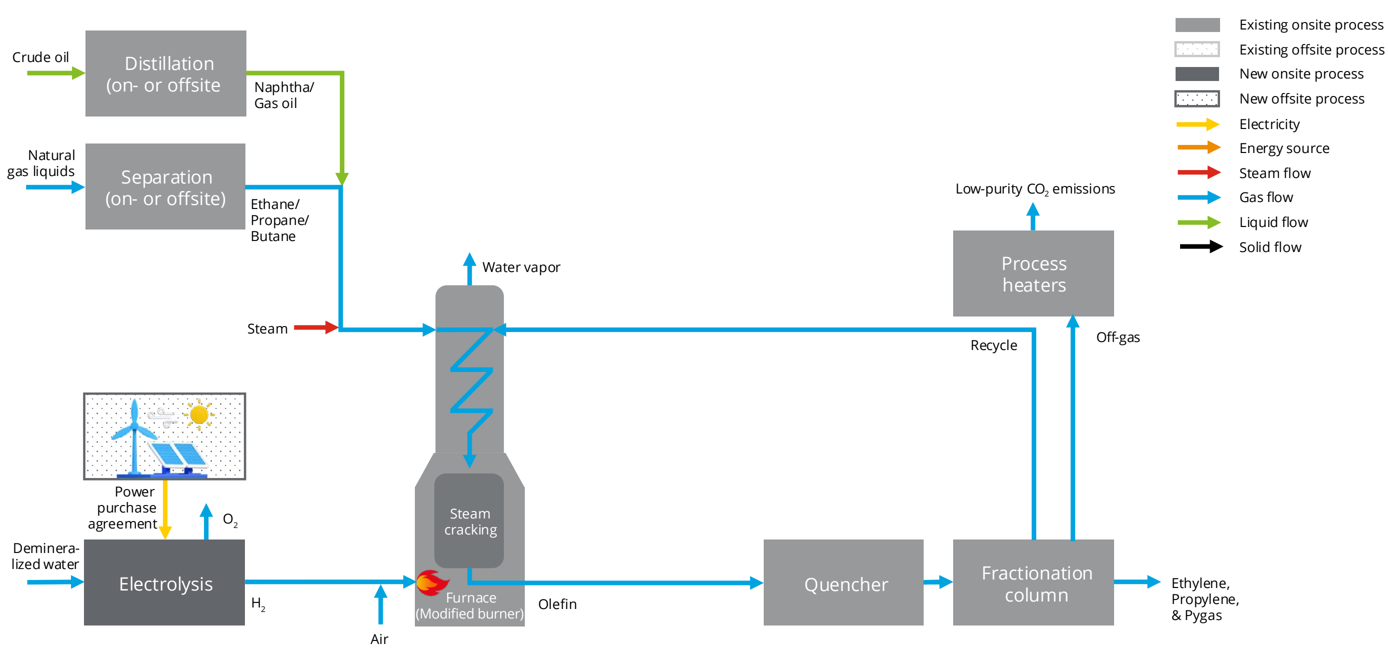
C.1.A. Olefin production facility (steam cracker) + CCS



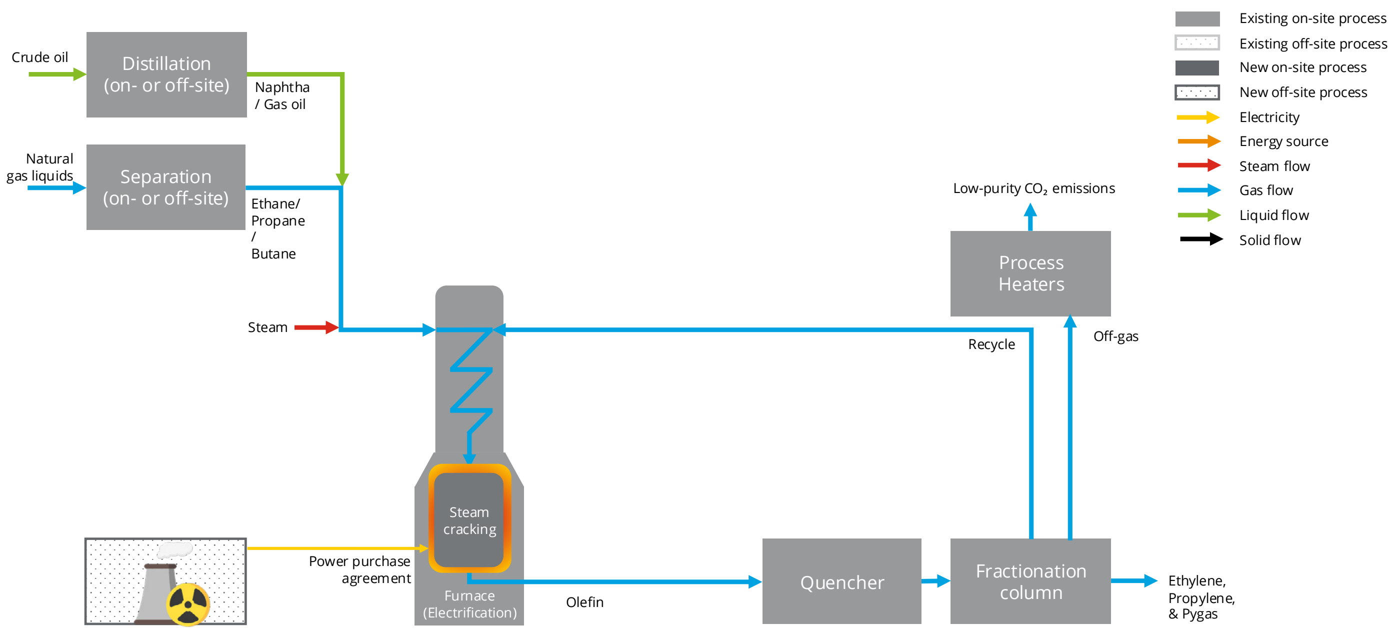
C.1.C. Olefin production facility (steam cracker) + blue hydrogen (natural gas feedstock)



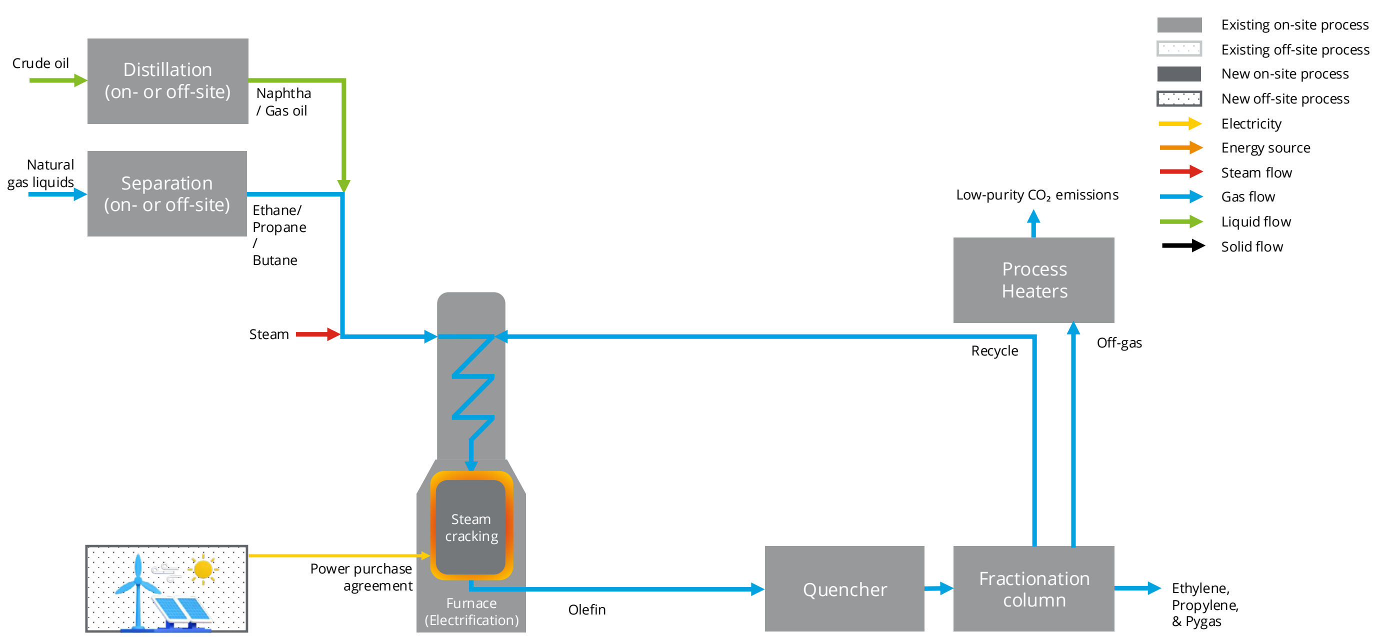
C.1.D. Olefin production facility (steam cracker) + green hydrogen (renewables)



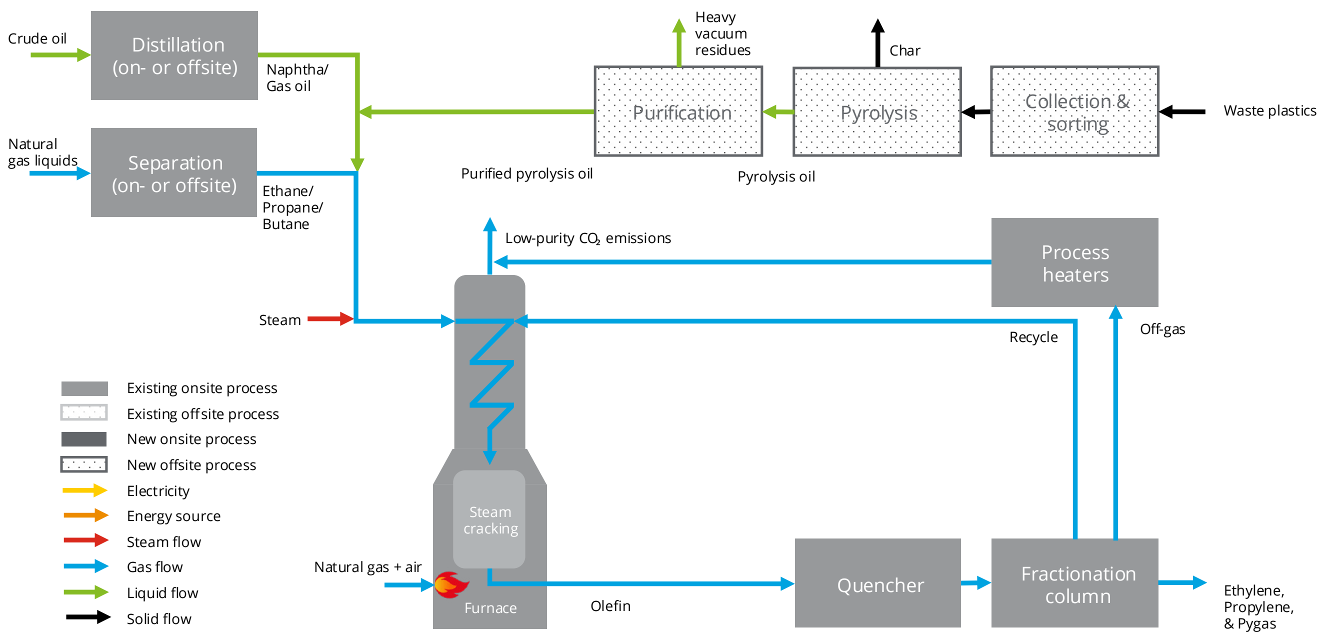
C.1.E. Olefin production facility (steam cracker) + electrification (nuclear)



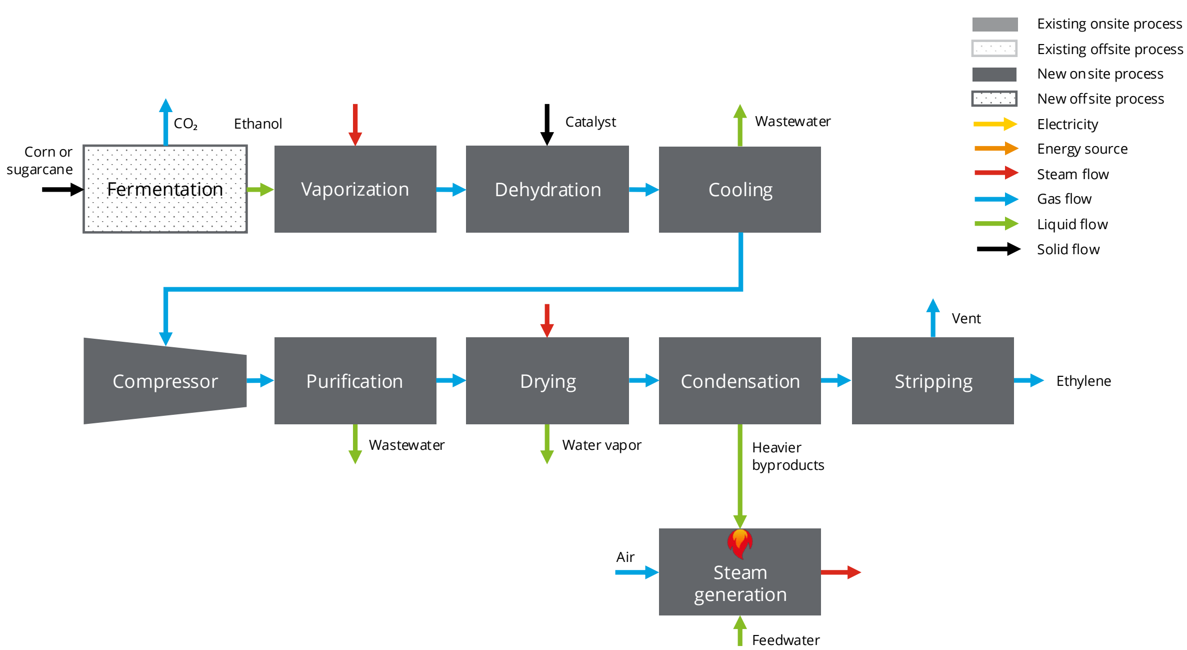
C.1.F/G. Olefin production facility (steam cracker) + electrification (wind/solar)



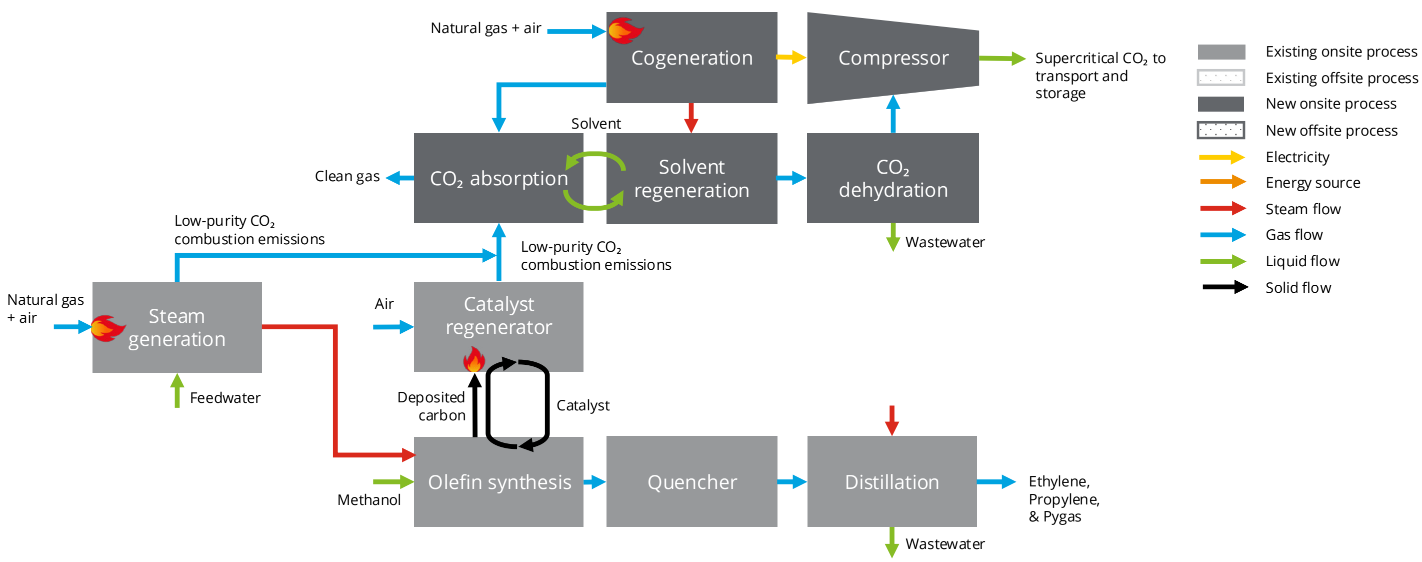
C.1.H. Olefin production facility (steam cracker) + circular feedstock (pyrolysis oil)



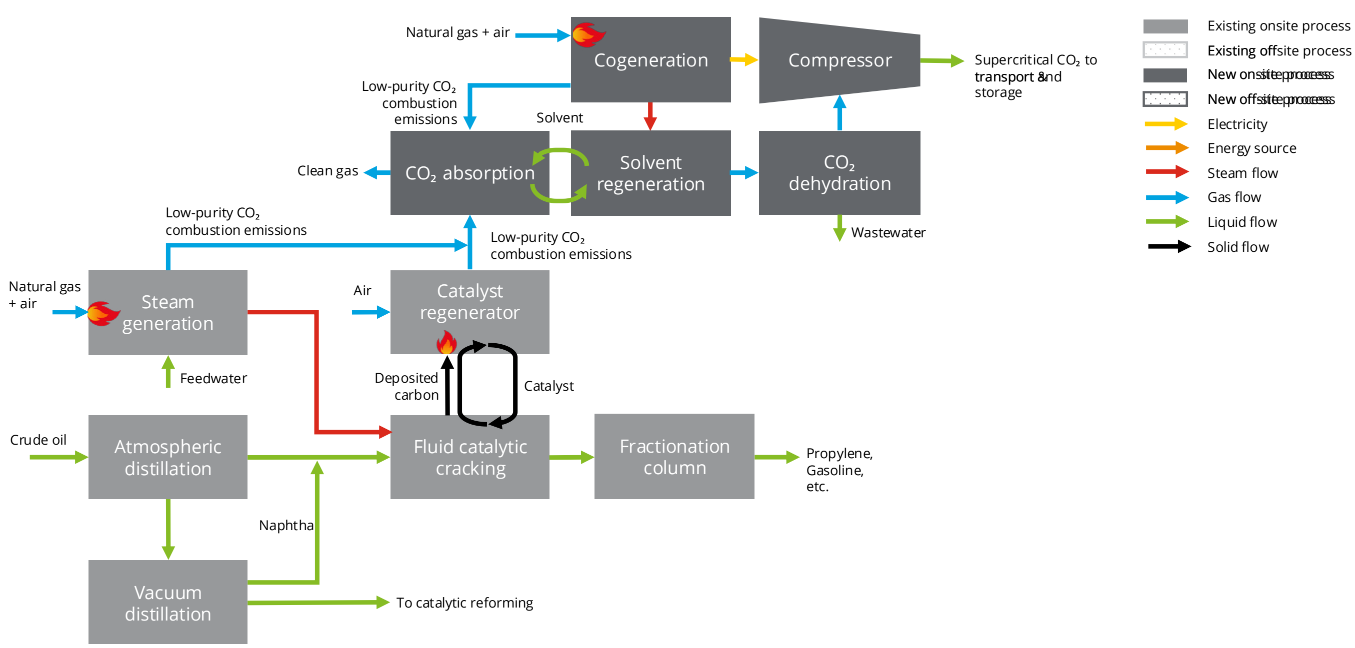
C.2.I. Ethanol-to-ethylene production facility (bio-feedstock) for future new capacities



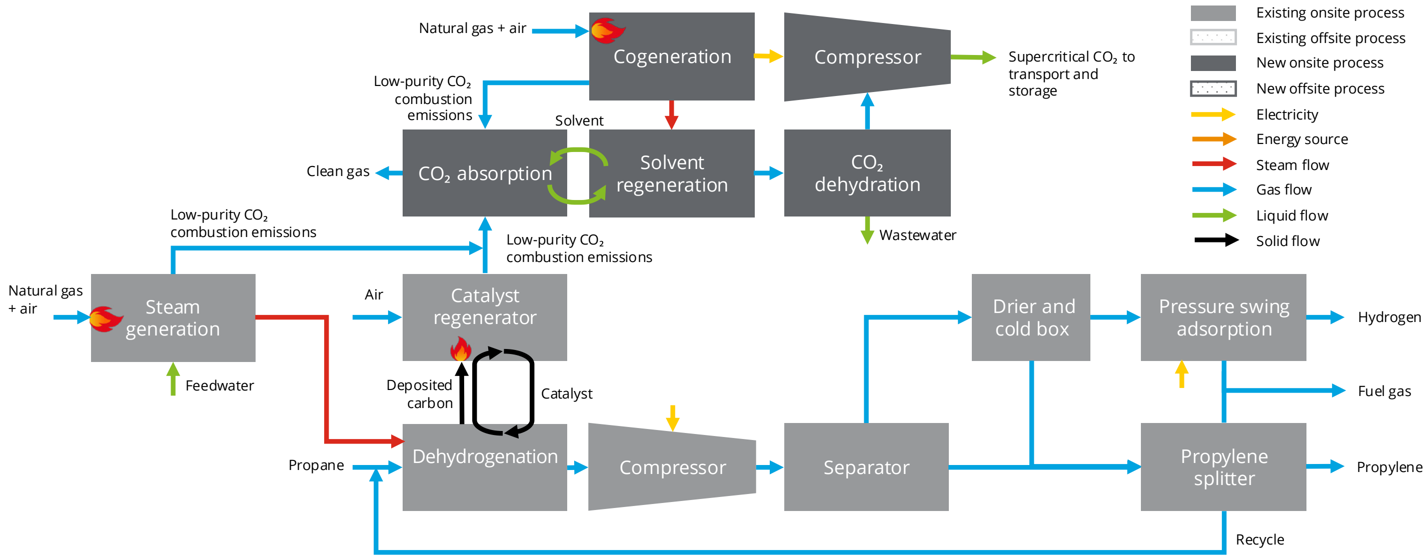
C.3.A. Methanol-to-olefin production facility



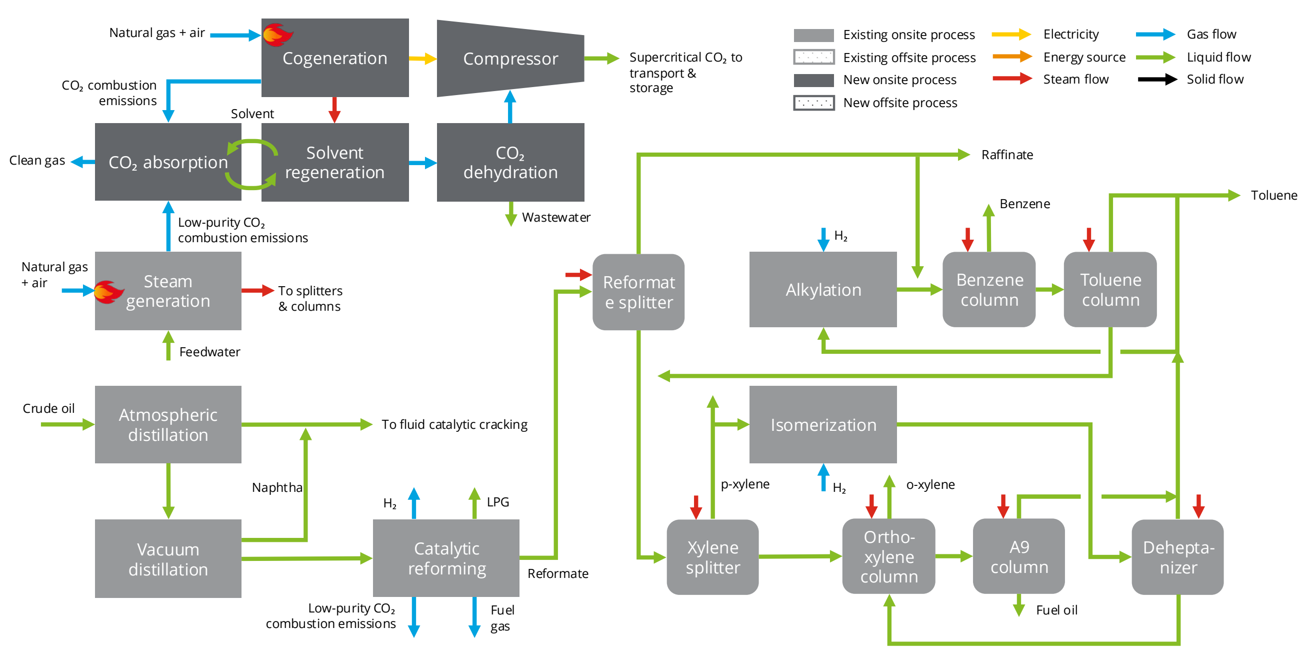
C.5.A. Propylene production facility via fluid catalytic cracking (FCC)



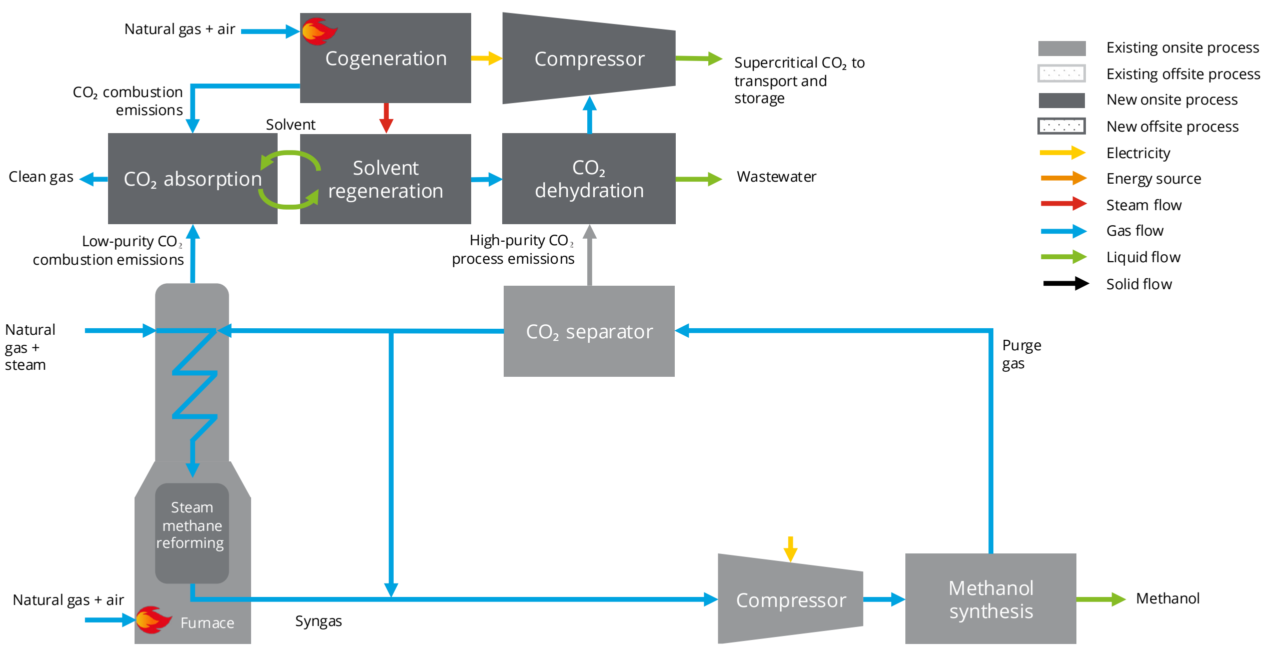
C.4.A. Propylene production facility via propane dehydrogenation (PDH)



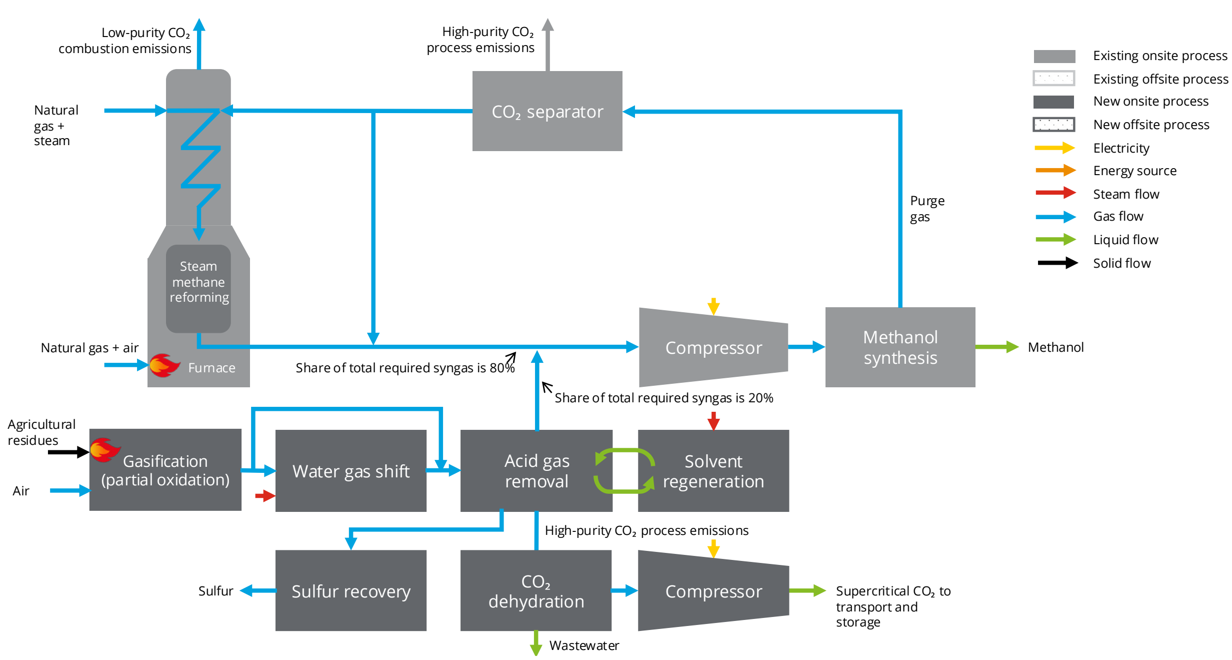
C.6.A. Aromatic complex (reformate feedstock)



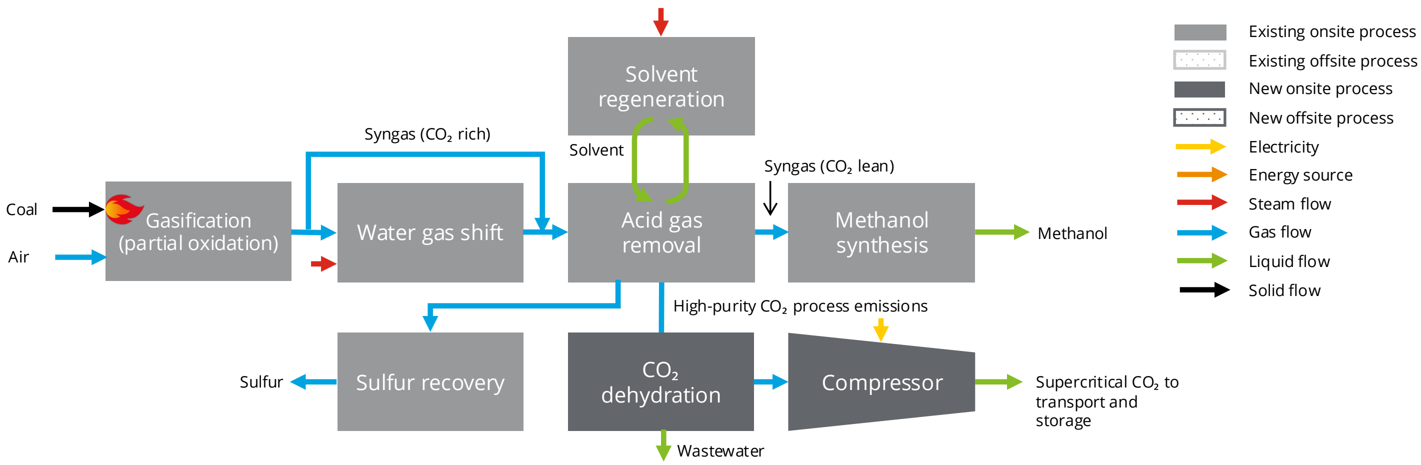
C.7.A. Methanol production facility (natural gas feedstock)



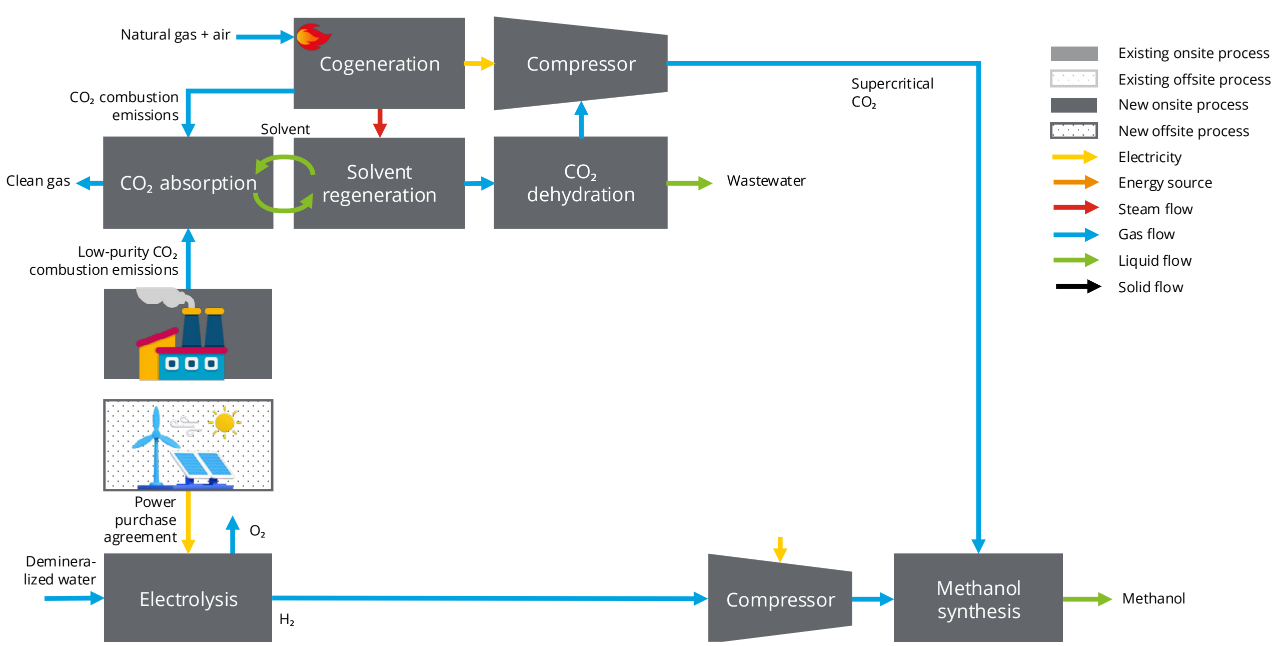
C.7.H. Methanol production facility (natural gas + bio-feedstock)



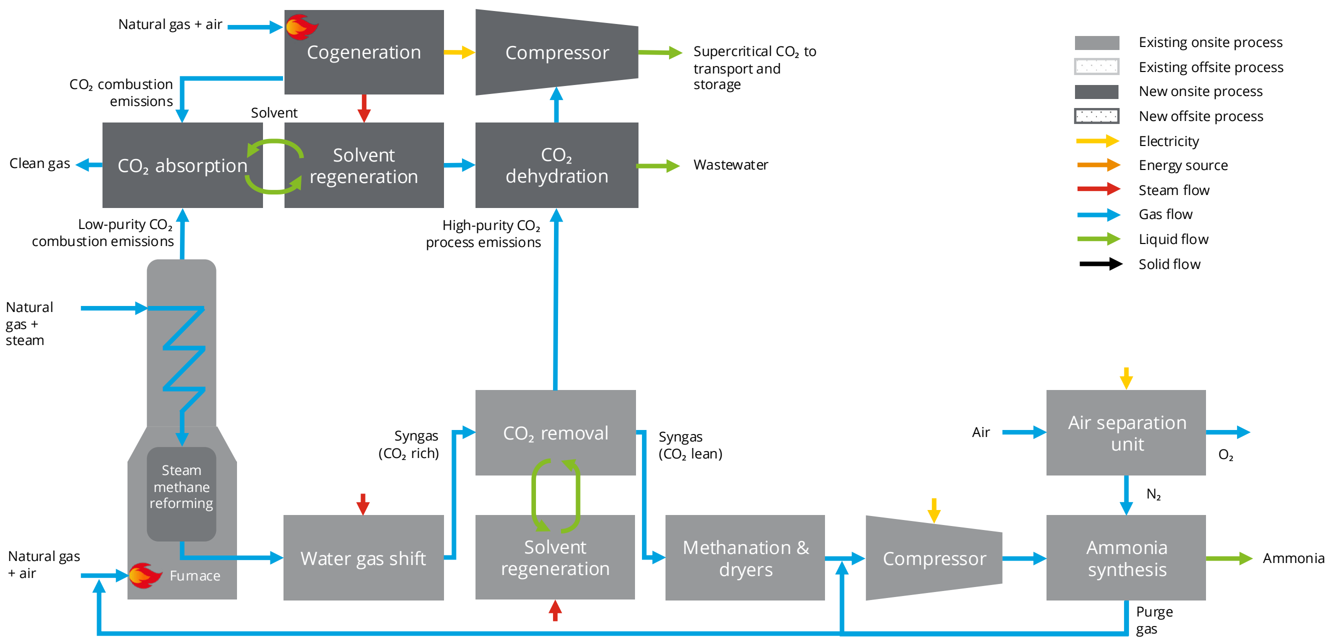
C.8.A. Methanol production facility (coal feedstock)



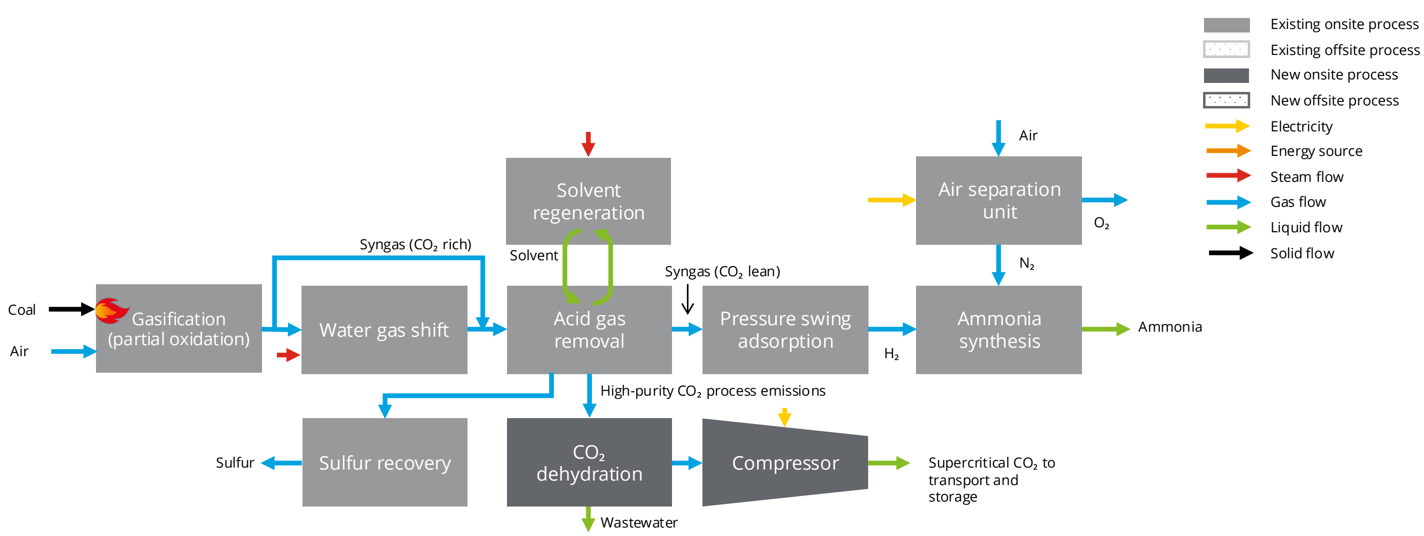
C.9.B. Methanol production facility (H2 & CO2 feedstock) for future new capacities



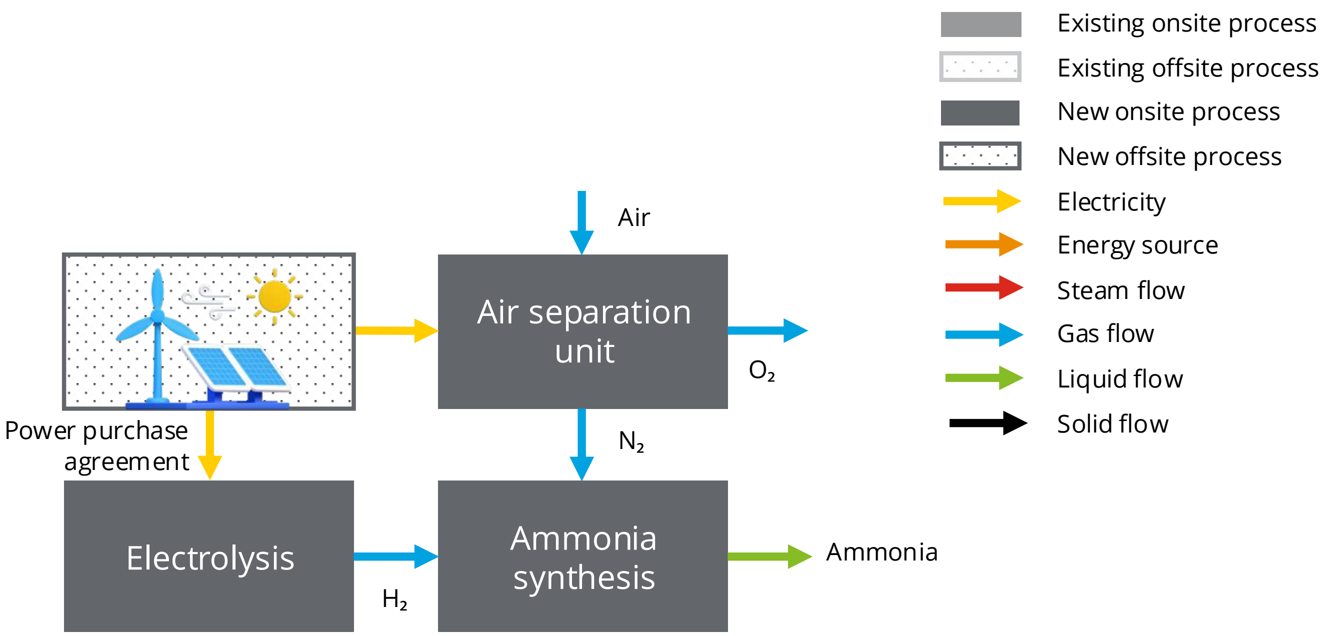
C.10.A. Ammonia production facility (natural gas feedstock)



C.11.A. Ammonia production facility (coal feedstock)



C.12.D. Ammonia production facility (hydrogen feedstock) for future new capacities



Levelized cost of abatement (LCOA) estimates

For each abatement option at the facility level, the LCOA for scope 1 CO_2 emissions is estimated (equation 1). All costs are converted to 2024 US dollars using the Chemical Engineering Plant Cost Index.

For the LCOA estimates, total installed capital costs (CapEx) for abatement, which are assumed to scale with a facility's production capacity raised to the 0.6 power, are estimated based on literature sources, as detailed in the SI for both BB production processes and relevant clean electricity supply technologies. Sub-region-level capacity factors assumed for solar and wind electricity generators are also provided in the SI.

A baseline set of CapEx estimates were developed assuming deployment in a North America context. CapEx for facilities in other study regions were estimated as fractions of the North America estimates (table 15).

Table 15. CapEx assumptions for abatement technologies by region.

Technology	Reference capacity	North America	Europe	Middle East	China
		CapEx (2024$)	CapEx as % of North America CapEx		
CO_2 capture	1.7M tCO_2/yr	\$853 / tCO_2/yr	100%	46%	46%
NG steam cracker	2.3M tEthy/yr	\$2,585 / tEthy/yr	100%	43%	43%
H_2 steam cracker	--	10% of CapEx for natural gas-fueled cracker (for burner replacement)			
Electric steam cracker	--	10% of CapEx for natural gas-fueled cracker (for heating elements)			
Electrolysis	1.1 GWe	\$3,900 / kWe	100%	50%	50%
Recycled plastics	0.05 tPyoil/yr	\$2,205 / tPyoil/yr	100%	50%	50%
Wind power	1 GWe	\$3.2M / MWe	100%	38%	38%
Solar power	0.1 GWe	\$1.5M / MWe	100%	93%	93%
Nuclear power	1 GWe	\$10.0M / MWe	100%	46%	46%

For each abatement technology in each region, the estimated CapEx value is assumed to be for a first-of-a-kind deployment of that technology in the chemical industry in that region. Subsequent deployments of the technology benefit from cost reductions due to learning, as discussed below. In the case of abatement approaches involving procurement of nuclear, wind, or solar electricity, the capital and operating costs for electricity generation are assumed as part of the abatement capital and operating costs.

For annualizing CapEx (equation 2), we use a simplified estimate of capital recovery factor (equation 3). The SI gives assumed region-specific weighted average costs of capital (WACCs), technology-specific lifetimes (N in equation 3), and corresponding capital recovery factor values. For all abatement options, annual fixed operating costs are assumed to be 3% of CapEx (equation 4). Variable operating costs account for electricity, fuel, and feedstock costs (equation 5). Assumed (region-specific) unit prices for the latter are provided in the SI, along with prices assumed for biogenic feedstocks. Levelized costs for CO_2 transport and storage associated with CCS are assumed to vary with proximity of the capture site to a suitable storage basin and the quality of that basin, as detailed in the SI.

Abatement cost (2024$/$tCO^2$) = [Annualized CapEx ($/y) + Fixed OpEx ($/y) + Variable OpEx ($/y)] / [Annual Abated Emissions (tCO_2/y)]	Eqn. 1
Annualized CapEx (2024$/y) = Total CapEx ($) × Capital Recovery Factor (1/y)	Eqn. 2
Capital Recovery Factor (1/y) = WACC/[1-(1+WACC)^(-N)]	Eqn. 3
Fixed OpEx (2024$/y) = Total CapEx ($) × Fixed OpEx (%)	Eqn. 4
Variable OpEx (2024$/y) = [Electricity Consumption (MWh/y) × Price ($/MWh)] + [Fuel and/or Feedstock Consumption (metric tons/y) × Price ($/tonne)]	Eqn. 5
Annual Abated Emissions (tCO_2/y) = Scope 1 Emissions Before Abatement (tCO_2/y) - Scope 1 Emissions After Abatement (tCO_2/y)	Eqn. 6

In assessing abatements at existing production facilities, no consideration was given to assessing the feasibility of retrofits (space availability, services capacity, etc.). The implicit assumption is that there is sufficient physical space, and other requirements are met for installing and operating abatement equipment at each retrofitted facility. Additionally, it is assumed that BB production is not significantly disrupted during equipment installation.

The time from commencement of development of an abatement project to initial commercial operation is assumed to vary between three and seven years, depending on the abatement technology, with annual capital outlays following an s-shaped (logistics) curve. No ramp-up time is assumed for an abated facility to reach its rated operating capacity. The SI gives technology-specific project development times and assumed CapEx logistics curve shapes. CapEx estimates described above are assumed to include interest during construction.

Regional industrywide abatement scenarios

Incorporating results from the facility-level techno-economic modeling, regional assessments of industrywide decarbonization for each building block are constructed under each of the three scenarios: Sustainable United (SU), Green Authority (GA), and Grassroots Green (GG). The assessments consider each abatement technology in isolation (i.e., that abatement technology is adopted by each candidate facility until all facilities have been abated). The rate at which facilities adopt the technology varies between scenarios, as detailed later in this section.

Aggregate metrics

For each scenario, region, BB, and abatement technology option, the following metrics are calculated:

- **CO_2 emissions** ($MtCO_2$ per year) on a "well-to-gate" basis, including scopes 1, 2, and upstream-3 emissions. Upstream scope 3 emissions are excluded for facilities whose feedstocks are by-products of other processes (e.g., pygas and reformate), since emissions associated with the production of the by-products is assumed to be accounted for as part of the processes that produced those feedstocks. No downstream scope 3 emissions are included in our analysis except for Europe when recycled plastics are used as feedstock to make pyrolysis oil that substitutes incumbent fossil fuel feedstock in olefins production. In this case, a credit is assumed for emissions associated with the prevailing practice of incinerating waste plastics that are avoided by recycling. The assumed credit rate is 0.48 tCO_2 per tonne of recycled plastic [REF].
- **CO_2 emissions intensity** (tonne of CO_2 per tonne of chemical product) is the average for all production facilities in a region, considering scope 1 and 2 emissions only. When a facility produces multiple chemical products (e.g., olefins and aromatics), emissions are allocated in proportion to the mass of each product, except in the case of chlorine and caustic co-production, when all emissions are assigned to the chlorine.
- **Annual and cumulative capital deployed** (billion 2024 US$) is estimated from the facility-level techno-economic assessments described earlier and the scenario-specific number of abatement projects in development each year in a scenario (see below).
- **Levelized abatement costs** (in 2024 $ per tonne of CO_2 abated) are estimated at the facility level, as outlined earlier, but with adjustments for cost reductions due to assumed learning that occurs as experience is gained in deploying abatement technologies, as discussed next.

Abatement technology cost learning and deployment rates

For a given abatement technology, the industrywide deployment of that technology is evaluated over time. Capital cost learning (i.e., unit cost reduction) is assumed to occur at different rates across scenarios as increasing numbers of facilities are abated. Some abatement technologies are also assumed to benefit from cost-learning spillover from deployments in other sectors. Literature sources guide estimates of future percentage cost reductions. For most abatement options, the first deployment is assumed to occur in 2030. For abatement of olefins production via electrified crackers and dehydration, serious commercial deployments are assumed to only begin in 2040, considering the early stage of development of these technologies today. For any given abatement option, we assume the initial abated facility will have abatement capital costs as estimated using the approaches described earlier. Subsequent deployments of technology benefit from discounted costs, as discussed next.

For abatement technologies first deployed in 2030, cost learning is quantified as follows. For **solar** and **wind** electricity-generating plants, costs projected for 2030 in the 2024 Annual Technology Baseline (ATB)[35] are assumed for initial deployments in North America. In the SU scenario, which assumes that all facilities existing today are abated by 2050, cost learning follows the ATB projection over time.[8] The ATB cost projections include advanced, moderate, and conservative cost reduction scenarios. The advanced scenario is assumed for SU and the moderate and conservative scenarios for GA and GG, respectively. The 2050 level of ATB cost is assumed to be reached through learning in the **GA** and **GG** scenarios for the same total number of facilities abated as in the SU scenario. In all scenarios (and with all abatement technologies), abatement cost reductions are continued by extrapolation beyond the literature-based reduction levels when new-builds are deployed to meet growing demands.

For **CO_2 capture** and **blue hydrogen** abatement options, percentage cost reductions from initial deployment to complete deployment on all existing facilities is represented in the **SU** scenario by the percentage cost reduction from 2025 to 2050 in the ATB's advanced scenario for natural gas combined cycles with CO_2 capture. All existing facilities are abated by 2050 in **SU**. The **GA** and **GG** scenarios adopt percentage cost reductions from 2025 to 2050 for the moderate and conservative scenarios, respectively, and this level of reduction is achieved after the same total number of facilities are abated by 2050 as in the SU scenario.

In a similar fashion, for **circular feedstocks (pyrolysis)** and **bio-synthesis gas** abatement options, ATB's percentage cost reductions for nuclear plants from 2025 to 2050 are assumed to represent the cost reduction percentage from initial deployment to complete deployment (by 2050) of all existing facilities in the **SU** scenario. The **GA** and **GG** scenarios adopt percentage cost reductions from 2025 to 2050 for the moderate and conservative ATB nuclear cost scenarios, respectively, and this level of reduction is achieved after the same total number of facilities are abated by 2050 as in the **SU** scenario.

Finally, for electrolyzers, percentage cost reductions are adopted from 2030 to 2050 in the SU scenario as projected in (Rupert Way, 2021) in its aggressive case. The **GA** and **GG** scenarios adopt less rapid cost reductions relative to the aggressive case.

For abatement technologies assumed to be first deployed in 2040 (electrified crackers and ethanol dehydration, methanol from green hydrogen and captured industrial CO_2, and ammonia from green hydrogen), cost learning is quantified as follows. For **electrified crackers**, the percentage cost reduction from initial deployment to abatement of the last unabated existing facility is assumed to be the average of reductions projected in ATB for nuclear plants and solar plants from 2025 to 2050. The time between deploying the initial abatement in 2040 until complete abatement of all existing facilities is completed is assumed to be 20 years in the **SU** scenario, the same as assumed for technologies with initial deployment in 2030. The **GA** and **GG** scenarios adopt a similar average of nuclear and solar percentage cost reductions from 2025 to 2050 but for the moderate and conservative ATB scenarios, respectively, and this level of reduction is achieved after the same total number of facilities are abated by 2060 as in the **SU** scenario.

For abatement by **dehydration**, the cost reduction percentage in **SU** from initial deployment to complete deployment (by 2060) of all existing facilities is assumed to be the percentage reduction projected in ATB for nuclear plants from 2025 to 2050. The **GA** and **GG** scenarios adopt percentage cost reductions from 2025 to 2050 for the moderate and conservative ATB nuclear cost scenarios, respectively, and this level of reduction is achieved after the same total number of facilities are abated as are abated by 2050 in the **SU** scenario.

Cost learning for methanol and ammonia from green hydrogen are driven by cost learning for solar electricity and electrolyzers discussed above.

Ethanol dehydration and methanol or ammonia from green hydrogen are technologies considered not suitable for retrofit abatements at existing facilities. Thus, these options are only considered for abatement when new capacity is needed to meet projected demand growth.

Table 16, tabulates the above-described percentage cost reductions assumed from initial abatement deployment to final existing facility abatement.

Table 16. Percentage reduction in abatement unit capital cost (for same abatement capacity) from the initial to the final existing facility abated. The same reduction percentages are applied to capital cost estimates in each of the four study regions.

	Percent reduction in unit capital cost		
Abatement technology	**Sustainable United**	**Green Authority**	**Grassroots Green**
Nuclear	57%	34%	22%
Wind	20%	18%	15%
Solar	48%	45%	38%
CO_2 capture	36%	27%	21%
Gasification	57%	34%	22%
Auto-thermal reformer with CCS	36%	27%	21%
Electrolyzer	70%	55%	39%
Pyrolysis	57%	34%	22%
Dehydration	57%	34%	22%
Hydrogen-fueled steam cracker	53%	40%	30%
Electrified steam cracker	53%	40%	30%

Initial, early-mover, and mature technology deployments

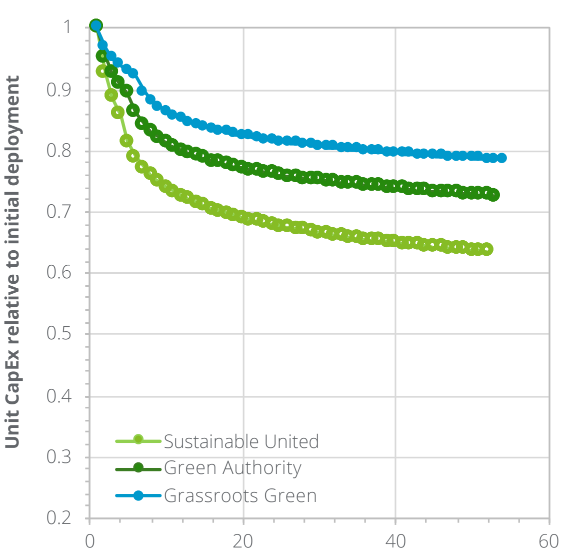
Given that there are limited examples of abatement deployments in the chemical industry today, cost learning is assumed to be relatively slower for early abatement deployments than for later deployments for all technologies (except for mature technologies, where this is not the case, specifically solar and wind). Guidance on the relative learning rates during early versus later deployments is taken from Gunawan (2024),[38] which quantified capital costs forCCS projects of varying maturity based on work by Greig et al. (2014).[39] Greig characterizes:

- "First-of-a-kind" (FOAK) projects as the first in a local region or one of the first 10 globally;
- "Early-mover" (EM) projects as one of the next three in a local region or one of the next 10 globally; and
- "Nth-of-a-kind" (NOAK) projects are those that follow the EM phase.

Using Greig's cost-estimating guidelines, Gunawan indicates that 40% of the cost reduction from the FOAK to the NOAK level is achieved during EM deployments, with the remaining 60% achieved thereafter. These percentages are used to quantify cost reduction rates for each abatement technology.

For the **SU**, **GA**, and **GG** scenarios in each region, the first unit is assumed to be deployed in 2030 (or 2040 in the case of electrified crackers and ethanol dehydration).

Figure 27. Example cost-learning curve for abatement of steam crackers via blue hydrogen fueling in North America



In **SU**, the second and third abatements deploy in 2031 and 2032 (or 2041 and 2042). No cost learning is assumed between the three initial facilities because the tight overlap in project development times would not allow for any significant transfer of learning between projects. The fourth abated facility is assumed to start operating in 2035 (or 2045) and benefits from some cost reduction due to the three-to-five-year gap after the initial deployments. The subsequent three facilities abated are assumed to be early movers, learning down capital costs to 40% of the way to the NOAK cost level. Cost learning with further deployments accelerates thereafter reaching the NOAK level when all existing facilities have been abated.

Consistent with the scenario narratives, in **GA**, a second facility is assumed to be deployed in 2031 (or 2041), with no cost learning from the prior year's deployment. The third facility begins operating in 2035 (or 2045) and benefits from some cost learning. Four early-mover plants are then deployed, and cost learning accelerates thereafter.

In **GG**, a second facility comes online only in 2035 (or 2045) and benefits from learning. Six early-mover abatement projects are then deployed, and cost learning accelerates thereafter.

In all scenarios, where there are abatement projects already under development today at specific existing facilities, these facilities are included in the initial deployments. With abatement technologies for which there are currently no projects in progress, the initially deployed facilities are selected to be those with the lowest estimated LCOA.

Figure 27 shows the resulting cost-learning curves: blue hydrogen abatement of steam crackers in North America. Learning curves for all abatement technologies are provided in the SI.

For each abatement technology, the above methodology for the SU scenario involves deploying abatements at all currently operating facilities in a region by 2050 or 2060, depending on the region.

As discussed in the text, the "initial deployment" called out in figure 27 involves three facilities in the SU scenario, two in the GA scenario, and one in the GG scenario. These are followed by three, four, and five abatement facilities being deployed during the early-mover phase of cost learning.

Other scenario-dependent variables

Cost learning and technology deployment trajectories are the factors that differ most significantly between scenarios, but additional quantitative differences include trajectories of emissions reductions for grid electricity generation (table 17) and of scope 3 upstream emissions associated with natural gas supply (table 18) and with coal mining (table 19). In the case of emissions associated with natural gas supply, the SU scenario assumes reductions in line with oil and gas industry commitments to achieve "near-zero" upstream emissions by 2030.[40].

Table 17. Assumed reductions in grid-average electricity CO_2 emission intensity relative to 2020 level.*

	North America			Europe			Middle East			China		
2020[a]	380 kgCO2/MWh			236 kgCO2/MWh			727 kgCO2/MWh			610 kgCO2/MWh		
	SU	GA	GG	SU	GA	GG	SU	GA	GG	SU	GA	GG
2030	74%	49%	39%	54%	39%	29%	57%	42%	32%	32%	26%	26%
2040	80%	74%	49%	100%	74%	39%	74%	50%	42%	67%	36%	35%
2050	99%	80%	74%	100%	100%	74%	99%	80%	50%	97%	50%	47%
2060	99%	99%	80%	100%	100%	100%	99%	99%	80%	99%	71%	63%
2070	99%	99%	99%	100%	100%	100%	99%	99%	99%	99%	99%	95%
2080	99%	99%	99%	100%	100%	100%	99%	99%	99%	99%	99%	99%

(a) Grid-average intensity in 2020 as estimated from Meng et al. (2023).[41] for North America, Europe, and the Middle East, and from China's Ministry of Ecology and Environment.[42].

Table 18. Assumed reductions in upstream scope 3 emissions associated with natural gas relative to 2020 level.

	North America			Europe			Middle East			China[b,c]		
2020[a]	14 $kgCO_{2eq}/GJ$			11 $kgCO_{2eq}/GJ$			5.3 $kgCO_{2eq}/GJ$			14 $kgCO_{2eq}/GJ$		
	SU	GA	GG	SU	GA	GG	SU	GA	GG	SU	GA	GG
2030	75%	50%	25%	95%	70%	45%	95%	70%	45%	50%	25%	0%
2040	95%	75%	50%	95%	95%	70%	95%	95%	70%	70%	50%	25%
2050	95%	95%	75%	95%	95%	95%	95%	95%	95%	85%	75%	50%
2060	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	75%
2070	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%
2080	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%	95%

(a) Emissions in in 2020 as estimated by Meng et al. (2023).[43]
(b) In the Asia Pacific, 72% of methane emissions are estimated to be technically abatable using current technologies.[44]
(c) China is not part of the Global Methane Pledge.[45]

Table 19. Assumed reductions in upstream scope 3 emissions associated with coal in China relative to 2020 level.

	China		
2020[a]	13 kgCO2eq/GJ		
	SU	GA	GG
2030	25%	25%	10%
2040	45%	45%	25%
2050	50%	50%	40%
2060	65%	65%	55%
2070	65%	65%	65%
2080	65%	65%	65%

(a) Using current technologies, 90% of methane emissions from underground mines in China can be reduced by 65%.[46]

Some model notes

- The model is not a linear programming optimization model. The model evaluates several potential decarbonization technologies, each in isolation for each chemical building block, over the full modeling time horizon to identify the option that provides the lowest estimated levelized cost of abatement at any given point in time.
- Where future new capacity will be built is unknown. When needed in a region to meet projected production levels, the model assumes new facilities will be built in locations that provide the most favorable conditions for the abatement option deployed; for example, in regions with lowest-cost CO_2 transport and storage costs for CCS abatement or in regions with optimal solar or wind capacity factors for options requiring clean electricity.
- Future production levels regionally are assumed to be the same in all scenarios, and no consideration is given to whether low-carbon production facilities might shift between regions; for example, to take advantage of a lower-cost abatement option in one region versus another.
- Similarly, the model takes no consideration of how future BB trade flows might change between regions due to decarbonization imperatives.
- Regional emission intensity reported for each BB is the average across all production facilities for that BB in the region. It does not represent the emissions intensity of circulated chemical products in a region, which may include imports.

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Endnotes

1. https://chemicalmarketanalytics.com/
2. "North America" includes Canada, Mexico, United States
3. "Europe" includes Bulgaria, Czechia, Croatia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Serbia, Former Yugoslavia, Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Lithuania, Other CIS & Baltic States, Turkmenistan, Ukraine, Uzbekistan, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom
4. "Middle East" includes Afghanistan, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates
5. "China" includes mainland China, Hong Kong SAR and Taiwan (China) for this analysis.
6. In this report, the term "China" includes Taiwan (China) and Hong Kong SR.
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4. "North America" includes Canada, Mexico, and the United States.
5. "Europe" includes Bulgaria, Croatia, Czechia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Serbia, former Yugoslavia; Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Lithuania, other CIS and Baltic states, Turkmenistan, Ukraine, Uzbekistan; Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and United Kingdom.
6. "Middle East" includes Afghanistan, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, Turkey, and United Arab Emirates.
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