Near-Term Pathways to Reduce Emissions from Ethane Crackers

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White Paper

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About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Contents

Executive summary v

Introduction 1

Methodological approach 2

Current landscape and impacts 2

Community concerns 5

Demand for lower-footprint products 6

Climate targets 7

Benefits of early action 7

Producers and operators 7

Engineering companies and infrastructure partners 8

NGOs and policymakers 8

Near-term low-footprint pathways 9

Hydrogen fuel switching 10

Beneficial electrification 11

Energy efficiency 12

Emerging solutions 12

Emissions and economic analyses 13

Emissions reduction potential 13

Techno-economics 14

Co-benefits 15

Low-carbon product market 16

Helping low-carbon technologies compete 17

Pursue actionable steps 18

Conclusions 20

References 21

Appendix A. Potential carbon dioxide reductions across the cracker fleet 30

Appendix B. Economic Modeling 32

Appendix C. Non-energy benefits 34

Acronyms and abbreviations

ATR: autothermal reformer

CAPEX: capital expenditure

CH_4: methane

CO: carbon monoxide

CPChem: Chevron Phillips Chemical

CCUS: carbon capture, utilization, and storage

EAC: environmental attribute certificate

EPC: engineering, procurement, and construction

GHGs: greenhouse gases

GW: gigawatt

H_2: hydrogen

LC: low carbon

MW: megawatt

NGLs: natural gas liquids

NGOs: nongovernmental organizations

NO_x: nitrogen oxides

OPEX: operating expenditure

O&M: operations and maintenance

ppm: parts per million

O_3: ozone

TG: tail gas

MM tpa: million metric tons per annum

PM: particulate matter

VOC: volatile organic compound

Executive summary

Key findings

- Addressing the substantial emissions from ethylene production—including greenhouse gases (GHGs), hazardous chemicals, and particulates—through innovation can provide an edge for U.S. producers over growing global competition, tap emerging consumer demand for products with lower environmental footprints, reduce health impacts for communities near plants, and help meet state and company climate goals.
- Although the current ethylene downcycle has depressed margins and delayed large capital investments, announced commercial projects at scale signal top near-term solutions, including hydrogen fuel switching, beneficial electrification of compressors, and emissions mitigation.
- The long timelines (years) for major plant projects mean that now is the time to demonstrate and justify lower-emissions technologies and develop their markets. This way, when the downcycle ends, these projects can be ready to compete for capital investment.
- A market for lower-carbon products is growing but can be expanded by showing that industry is able to quantify and transparently communicate low-carbon attributes, connect the demand with products from the demonstrations, and provide evidence that demand growth and higher margins can help offset higher production costs.
- Collaboration will be crucial, as multiple entities need to work toward the shared goal of decarbonizing the ethylene industry. These include cracker operators, their engineering partners and technology developers, funding organizations, and state governments.

Low-cost U.S. shale gas gives U.S. producers of building-block chemicals a competitive advantage on both cost and carbon emissions intensity. Ethylene is one of the most versatile of these chemicals and is used to make products as diverse as packaging, pipes, antifreeze, and housewares. Overseas competitors, however, are chipping away at the advantages, and customers are also increasingly asking for products with a lower environmental footprint.

The global ethylene downcycle that has persisted since around 2020 has depressed margins and delayed both large capital investments and emissions reduction projects that are part of large projects. The Iran conflict involving the Strait of Hormuz has disrupted global supply chains for olefins since late February 2026, and while this has improved margins for U.S. producers, capital investments are still paused due to large market uncertainties. If this capital investment downtime is used to develop and justify lower-footprint solutions and boost the market for low-carbon products, these solutions will be able to

compete for capital when the market outlook improves and another wave of investment arrives. But additional work is needed to reduce costs, grow the emerging market for lower-footprint products, improve integration and infrastructure, and bolster business cases.

Multiple pathways are maturing to reduce emissions for the steam crackers that produce ethylene. This paper explores near-term opportunities (2–5 years) to demonstrate, validate, and improve the economics of these technologies. Announcements of recent commercial projects at scale give evidence of leading near-term solutions and the technologies pursued include **hydrogen fuel switching**, **beneficial electrification of compressors**, and **emissions mitigation**. Energy efficiency and integration are foundational to deploying these technologies, based on the announcements and our interviews with cracker operators and engineering companies. These solutions could combine to reduce carbon dioxide (CO_2) emissions 85% or more along with efficiency and integration advances, per claims in project announcements. Efficiency, fuel switching, and compressor electrification could yield around 60% of those reductions, according to the analysis in this paper. Post-process emissions mitigation technologies such as carbon capture could further reduce emissions, albeit with additional cost and integration hurdles. While several projects have been paused due to economic conditions, their progress provides learnings for the development, demonstration, and future deployment of lower-footprint technologies.

Investment in demonstrations is particularly important for lowering implementation costs in the near term, improving competitiveness in the nascent market for low-carbon products, and gaining insights into integration efficiencies. This could hasten cracker CO_2 emission reductions, which is important considering the time value of emissions: CO_2 can persist in the atmosphere for hundreds of years, and every 5-year delay requires up to 13 times more reductions in the future.

The advances and impacts for ethane cracker technology deployment could contribute to longer-term sustainability improvements in the chemical industry, and that is the topic of other forums. The objective here is to spur a conversation about how to improve the business case(s) for viable solutions so they can compete for capital in the industry's next upcycle. Thought leaders at ethylene cracker operators, technology providers, state and local policymakers, NGOs, utilities, and investment institutions all have a role to play.

Introduction

The chemical industry is a foundational economic engine of the U.S. economy. It supports a quarter of the U.S. gross domestic product, generates $633 billion per year in profit, and provides over 554,000 direct and 4.1 million indirect jobs (ACC 2025). The industry enables 96% of U.S.-manufactured goods via over 70,000 products (CISA 2022) and provides innovative solutions to societal needs (Yankovitz et al. 2026).

Globally, the chemical industry has struggled with a supply-demand imbalance in recent years. This has depressed revenue and profitability for many major products, including ethylene and its host of derivatives (Tullo 2026). The return on capital has sunk to its lowest point in 25 years (Yankovitz 2026), and the impacts are present across the broad family of ethylene derivatives.

While these dynamics have put pressure on all producers, those in the United States have been somewhat insulated due to the dominance of natural gas and natural gas liquids as a feedstock for ethane crackers, which provide both a cost and carbon emissions advantage. Abundant, relatively low-cost ethane makes U.S. crackers among the most competitive globally (Wood Mackenzie 2020). Compared with ethane-based crackers, the coal and naphtha-based processes in Asia-Pacific and Europe have 200% and 40% higher CO_2 intensity, respectively (Statistica 2026). China largely uses coal but is diversifying with other feedstocks.

The recent supply chain shock from the Iran conflict is a chance for U.S. producers to consider new projects earlier than expected. Value chains associated with Middle East crackers produce 15% of global polyethylene capacity and account for 43% of exports (Foster 2026). Oil-based naphtha, which largely feeds crackers in Asia and Europe, must transit the Strait of Hormuz, and the increasing costs of feedstocks and energy are compressing margins in most regions. In the United States, this is increasing cracker operating rates, exports, and margins, as global customers seek to replace the supply bottled up at the Strait and improve supply chain reliability. Indeed, Dow announced a doubling of the price for polyethylene recently (ChemNet 2026) and other domestic cracker operators may follow suit. Producers will consider ways to get more production from current assets, but will likely also ask how to meet longer-term demand and the technology solutions to serve evolving customer requirements.

These global developments increase the urgency of innovation and demonstrations of advanced technology. Although the chemical industry has improved efficiency and reduced emissions in recent decades, it still has a long way to go to meet stakeholder expectations and must further slash emissions and health impacts. A report on the top 50 plastics production facilities connected hazardous air pollutant emissions with health impacts in nearby communities (Shaykevich et al. 2024). Those facilities emit 63 million tons of greenhouse gases (GHGs)/year, as much as 15 coal-fired power plants. The whole chemical industry emitted 5% of U.S. GHGs and 20% of industrial direct emissions at 274 million metric tons in 2020 (DOE 2022). Production of the top six chemicals accounts for 65% of the GHGs, and ethylene is second on that list after ammonia (Huyett et al. 2025).

Pursuing deep reductions in the environmental footprint of ethylene is compelling now as customers are asking for it, competitors are responding, and fenceline communities are highlighting the health impacts. (In this paper, footprint refers solely to the environmental and health impacts and not the physical footprint.) If U.S. operators do not respond promptly, they may miss a market opportunity, give up market share, face increasing hurdles for community acceptance and permitting, and bear future regulatory risks. Community pushback can be a concern for permit renewals and expansions (Ferrell 2024).

Technology solutions are available for reducing carbon emissions and are part of recent, commercially proposed projects at scale. There are also parallel opportunities to reduce other pollutants like nitrogen oxides (NO_x), volatile organic compounds (VOCs), and hazardous organic and metal emissions, but the economics, integration, infrastructure, and market alignment all need to be improved for implementation. Indeed, achieving big-step reductions is likely to require partnerships between operators and engineering companies to spur innovation, various types of assistance from funding entities and NGOs, and support from federal, state and local governments to quantify the health benefits and provide durable, supportive policies.

Methodological approach

This paper explores near-term (2–5 years) ethylene footprint reduction options. The perspectives presented are informed by interviews with over 40 experts across ethylene operators, engineering companies, industry observers, national labs, NGOs, benchmarking firms, and academia. Their perspectives on what can be accomplished in the near term covered a wide range of topics over a period of several years. Recent events and the options for leading operators to respond were discussed in the latest interviews. This paper conveys key aspects of their input on what is actionable, where improvements are needed, and the paths that should be pursued to advance technologies that will meet evolving customer demands, address competition, and significantly lower the environmental impact of production.

The purpose is to engage thought leaders of leading ethylene producers, engineering companies, legislators, NGOs, and utilities on viable solutions, routes to lower hurdles, potential partnerships, and what is actionable today. Although the prolonged ethylene downcycle is expected to bottom out around 2028 or 2029 (Chang 2025), supply-chain disruptions from the Iran conflict may end it sooner. As it takes years to complete major plant projects, it is important to use this time to demonstrate and justify lower-emissions technologies and develop their markets. The next sections of this paper frame the current landscape for capital investments, the advantages of early action for different stakeholders, and the technological pathways to reduce those emissions. Following that, the paper analyzes emissions and economic benefits that justify the transformation and describes both how to pursue actionable steps and who needs to pursue them.

Current landscape and impacts

Development of the steam cracking process (also known as crackers) to make ethylene launched the modern, integrated petrochemical industry in the 1920s (ACS 2025). Ethylene is one of the most versatile chemical building blocks, with products as diverse as packaging, pipes, antifreeze, and housewares, via the product families shown in figure 1 (ACEEE 2025). The shale gas revolution of the 2010s led to new and expanded U.S. facilities making ethylene, and capacity increased by 50% (Devanney 2017). This is largely due to the availability of inexpensive natural gas and natural gas liquids (NGLs), which are low molecular weight hydrocarbons (including ethane) that can be condensed from natural gas.

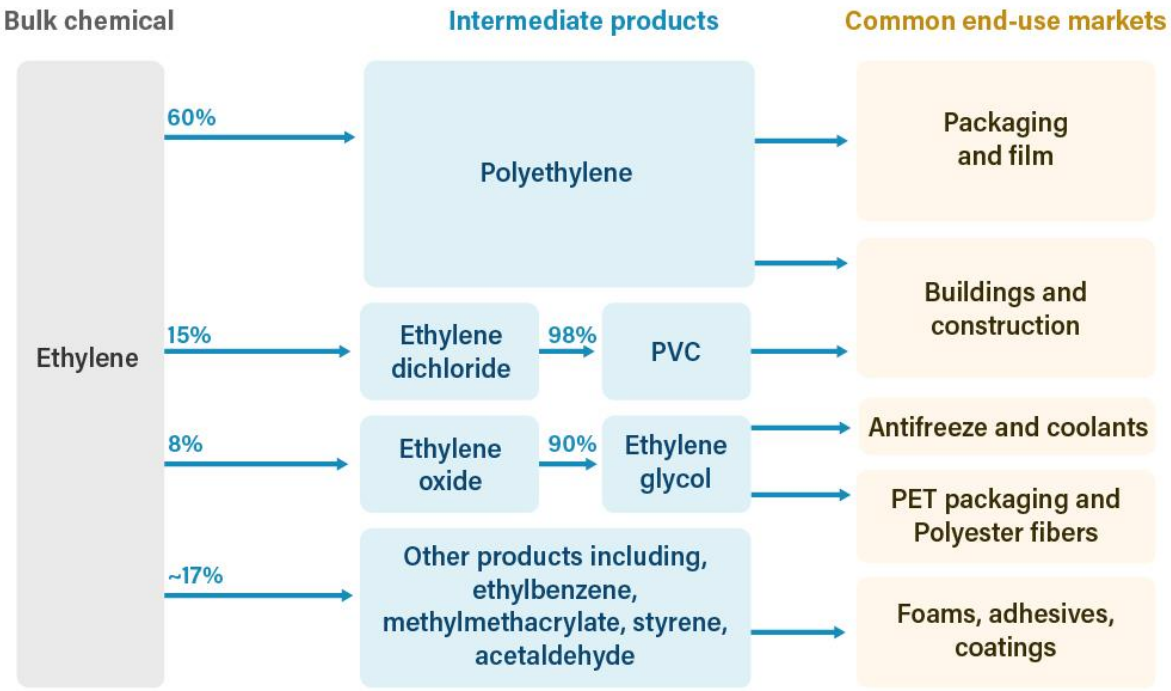


Figure 1. Simplified polymer family supply chain for ethylene. Source: ACEEE 2025.

The maze of highly integrated and optimized equipment at a cracker can be simplified, as in figure 2. Here, two atoms of hydrogen are stripped from ethane in parallel furnaces at >850 °C, forming ethylene. The ethylene is then compressed and purified before production of downstream products like polyethylene.

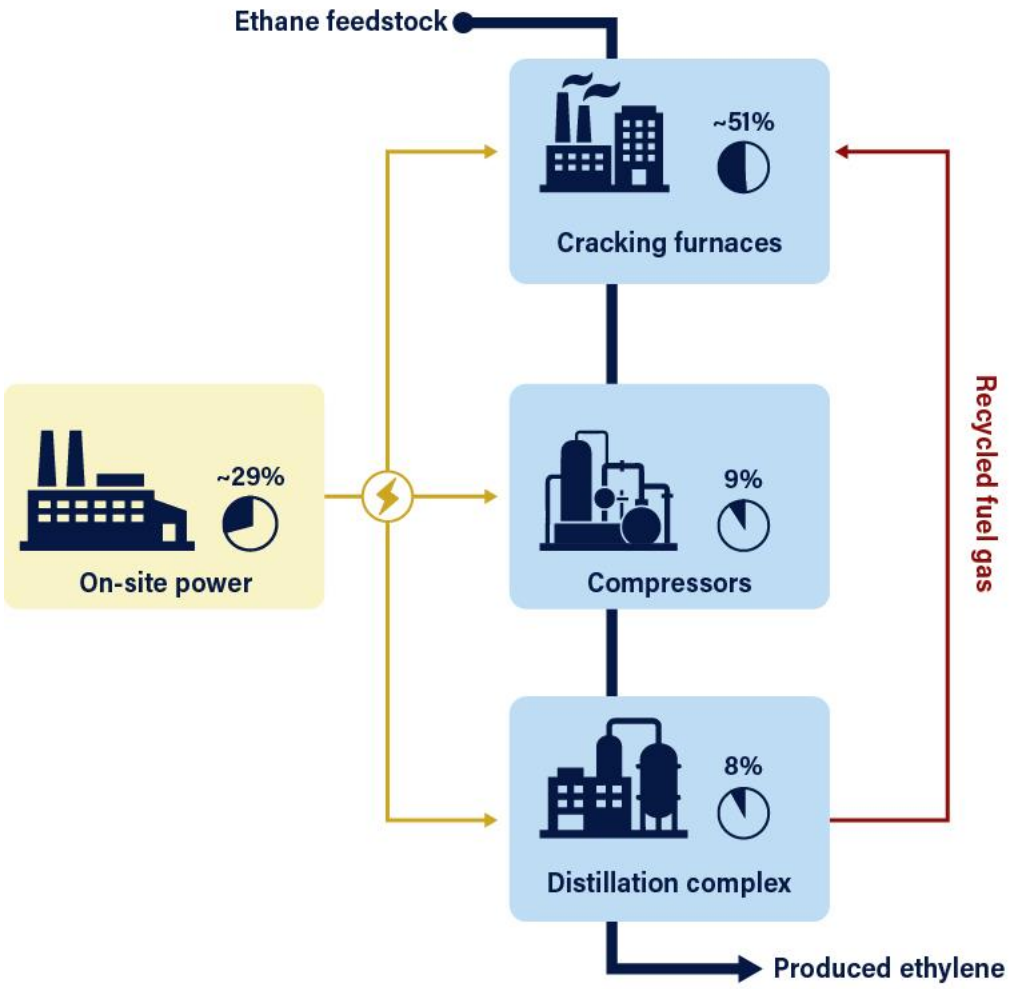


Figure 2. Simplified illustration of the main ethane cracker process blocks and the associated share of emissions. Source: Adapted from DOE 2023.

In the United States, over 30 crackers produce ethylene, and many are on the Gulf Coast, as shown in figure 3. The Gulf Coast is advantaged due to low-cost energy, feedstock availability, proximity to domestic customers, and shipping infrastructure for domestic and global markets. The accessibility of shale gas NGLs also sparked cracker builds in new areas, including Shell's Monaca, Pennsylvania, facility. However, with combined CO_2 emissions of 41 million metric tons per annum (MM tpa) across U.S. crackers at full capacity (DOE 2023) and emissions of other pollutants, there are reasons for cracker operators to reduce their emissions footprint. We explore some of these below.



Figure 3. Map of several U.S. ethane cracker locations and their approximate ages. This does not show the Shell Monaca Ethane Cracker in Beaver County, Pennsyvania, or the Westlake Corp. Ethane Cracker in Calvert City, Kentucky.

Community concerns

Community coalitions are pushing for greatly reduced emissions, waste, and health impacts from ethylene plants, and they are active in permitting discussions (Shaykevich et al. 2024; Palmer 2024). Emissions of hazardous air pollutants are of concern to fenceline and downwind communities (DOE 2022b). Chronic exposure to levels of nitrogen (NOx) or sulfurous oxides above exposure limits of 150 ppm and 100 ppm, respectively can harm respiratory systems, especially for those with asthma. Cracker emissions are typically well below those levels, but excursions during shutdowns, startups, and unplanned events can significantly exceed permit limits and account for a large portion of annual plant

emissions (Zirogiannis et al. 2018). Volatile organic compounds (VOCs) an irritate the eyes, lead to headaches, and damage organs (liver, kidney), and some are suspected carcinogens. The NO_x and VOC emissions can react with sunlight yielding ground-level ozone (O_3) that can have respiratory impacts. Particulate matter (PM) emissions, particularly the smaller particle $PM_{2.5}$ emissions, emitted for example during decoking operations, have known cancer risks (National Academies 2024). Particulate matter of less than 10 microns in diameter can get deep into human lungs and smaller particles may even get into the bloodstream (EPA 2026).

The majority of emissions are to air. As over 752,000 people, many disadvantaged socioeconomically, live within 5 km of crackers, they experience an extra health burden (Johnson et al. 2023). Emissions of these hazardous pollutants are of concern for their health (National Academies 2024), and there are higher cancer incidence rates near petrochemical facilities (Lin et al. 2018). The permitted emissions limits for the recently constructed ethane cracker at Shell Monaca are shown in table 1. The magnitude of emissions per cracker will vary, but across all 30+ crackers in the United States, the combined emissions are a large reduction opportunity.

Table 1. Ethane cracker emissions
The new 1.5 million metric tons per annum (MM tpa) ethane cracker at Shell Monaca in Pennsylvania has permitted emissions as shown below.

Air pollutant	**Permitted emissions** (tons per annum)*	**Health and climate impact**
Carbon monoxide (CO)	984	CO emissions of 200,000 cars**
Volatile organic compounds (VOCs)	516	Negative health impact
Nitrogen oxides (NOx)	329	Respiratory and other health risks, ozone creation
Sulfurous oxides (SOx)	22	Respiratory impacts, acid rain
Particulate matter	169 (PM10) 164 (PM2.5)	Negative health impact
Hazardous air pollutants	32	Risk of cancer and other serious health impacts
Carbon dioxide (CO_2)	2,300,000	Yearly emissions of 500,000 cars

* *Source*: PA DEP 2023
** Calculated with the EPA's GHG Equivalencies Calculator

The transition to lower-footprint technologies is an opportunity to avoid repeating past injustices and disparities *and* promote a more equitable, health-promoting energy and manufacturing system. The transition is also an opportunity to ask where multiple pollutants can be reduced in parallel. Proactively pursuing reductions can reduce liability and promote public acceptance, while minimizing project delays that occur when fenceline and downwind communities raise emissions concerns during permitting.

Demand for lower-footprint products

Because consumers are increasingly aware of the persistence of chemicals in the environment and impacts on human health (EPA 2025; Bagenstose 2023; WHO 2023), minimizing emissions is important for public acceptance and reduced liability. There is an emerging market for products with lower environmental footprints. The global market for "greener" products is near $5 trillion (WEF 2025). Companies are partnering to expand and accumulate demand, with sustainability as a source of business value (PWC 2025). The embedded emissions in products are also becoming steadily more important, as supply chain emissions impacts (Scope 3) are increasingly incorporated in companies' sustainability commitments. Companies that actively enable growth in these emerging markets will establish a foothold that can help justify new technology investment in the future.

Slow domestic demand growth and ethylene overcapacity, along with NGL supply growth, led to ethane and NGL exports. For the importers in environmentally constrained markets such as Europe, this allows producers to provide low-carbon products and meet regulatory restrictions with their current, higher emissions crackers. Ethane exports have tripled since 2018; about two-thirds of the increase is going to China and India, and one-third is going to Europe (EIA 2025). Ethylene exports have also tripled; the largest portion is going to Europe, and the second largest to China. At current levels, as much as 11% of China's cracker capacity could be fed by low-cost U.S. ethane (Sagel 2024). These building-block chemical exports may have the unintended consequence of causing U.S. companies to compete with lower-carbon products that are made abroad using cost- and carbon-advantaged ethylene that originated in the United States. Recognizing this portion of the lower-carbon market could help producers see the magnitude of this emerging niche and support investments to serve customer needs.

Climate targets

Despite changes in the visibility of sustainability goals, the number of companies committing to net-zero carbon emissions is up 9% (Verney 2025). Additionally, nearly half of U.S. states remain committed to long-term emissions reduction targets (U.S. Climate Alliance 2025), and several have increased their climate ambitions. Many global companies are also continuing their actions to reduce their climate impact in response to ongoing pressure from customers, state and local governments, transnational entities like the European Union, and stockholders (Hsueh 2025). Companies that can deliver low-carbon products have substantial trade opportunities. A recent analysis of 4,000 companies around the world showed that 84% are maintaining or accelerating their decarbonization efforts, and recognizing that sustainable products earn 6–25% more than non-sustainable products is one of the drivers (PwC 2025).

Benefits of early action

There are a number of reasons why now is the time to develop, demonstrate, and improve business cases for low-carbon (LC) technologies and infrastructure. Those reasons vary by audience and are explored below.

Producers and operators

Demand for LC products is growing. By enabling this growth and providing input on the development of metrics (e.g., the carbon intensity of products), producers can help ensure they do not miss this market opportunity. The production of demonstration plants could align with the growing demand while helping to clarify market needs, accelerate learning curves and scale, and decrease price—all of which will grow the appeal to a broader market. Deploying now would also aid footprint quantification, protocols, and labeling. Today's best technology solutions will show the path for even better solutions in the future while nurturing the early market for LC products.

Multiple global competitors are probing the LC market because of the higher margin potential it offers, and they are reducing their footprints, defining protocols, and lining up value-chain partners. While the United States has an energy *and* carbon intensity advantage now, global competitors are already making inroads. Support in several regions, including China and the European Union, is driving innovation in technologies that may establish the standards, metrics, and processes of the LC market; alternatives defined from demonstrations and exploration of the technology space could secure intellectual property and establish a commercial counterweight. From a competitive view, it is better to engage early rather than to try and claw your way into a market after customer and supplier relationships are established. Early movers can anchor the market around optimum, sustainable solution(s) and inform labeling.

It can take years to develop, engineer, justify, and implement large capital projects for crackers. Improving the justification case for projects to reduce pollutants now and putting them on the capital list can help ensure they are not missed in the next investment cycle, as the next large opportunity may be 15–20 years away.

Fenceline and downwind communities want pollutant reductions now. Developing technology solutions to reduce multiple pollutants, pushing demonstrations, and communicating the reductions will hasten benefits for communities and allow them to understand future projects they should support (and argue for in tax abatement discussions).

The startup and running of crackers create tension between the value they create and the emissions they produce (Baddour 2024). Operators face the challenge of delivering products to meet customer demands, running the cracker below permit limits, hitting economic targets, and showing value and lower environmental impact for nearby communities in light of tax breaks. Numerous companies initiated research and development (R&D) following the principles of Green Chemistry and Engineering, which seek to avoid the generation of toxics in the first place (Ciacchella et al. 2026). For example, Dow and BASF jointly developed a game-changing process for converting hydrogen peroxide to propylene oxide (HPPO) that inherently yields no useless by-products and saves large amounts of energy. Investing in low-footprint pathways is a critical opportunity to apply similar game-changing R&D at scale.

Engineering companies and infrastructure partners

Optimization of energy sources, waste heat and repurposing, and resupplying the current uses of energy and feedstock will be crucial to the economics, reliability, performance, and competitiveness of LC technologies for ethane crackers. This LC transition can only happen if engineering, procurement, and construction (EPC) partners play a leading role in developing and optimizing the technology. Where energy sources are moved from one place to another (e.g., tail gas from an energy source for compressors to the furnace), optimization is especially critical. Early demonstration projects will help find the best path through the complex array of variables and benefit EPCs by providing opportunities to develop and apply solutions currently in their portfolio. Several of the solutions will require substantial improvements in infrastructure and supply chains for hydrogen (H_2) made from low-carbon electricity and carbon capture; this can benefit EPCs, operators, utilities, and other suppliers.

NGOs and policymakers

The time value of emissions is important. Reductions made sooner can reduce health impacts that accumulate with time. Some pollutants persist and their impact grows exponentially. For example, 25% of GHG emissions can persist for hundreds of years after emission (Joos et al. 2013). For every 5-year delay in reducing emissions, it is estimated that up to 13 times more future reductions are needed (Bradley 2024). Hence, avoiding 24 MM tpa of CO_2 emissions via H_2 fuel switching and compressor electrification soon (see the Emissions Reduction Potential section below) is more effective than reducing over 312 MM tpa 5 years later.

Demonstrations and deployment of the best LC technologies can spur supportive ecosystems, implementation knowledge, and infrastructure that enable advances. Supply chain, market acceptance, installation networks, finance, and policy all must be ready in addition to cost parity (Lechtenfeld et al. 2025). Early engagement by NGOs and policymakers in clarifying life-cycle standards, reporting, and communication protocols and systems will be beneficial, as these take a long time to establish. NGOs and policymakers can also play an important role in encouraging collaboration: Getting support across

the supply chain is complex, yet participation from multiple parties in demonstrations can effectively clarify the best ways to evolve metrics and the best means to follow performance.

Near-term low-footprint pathways

Multiple lower-carbon pathways are advancing, including fuel switching, electrification, exhaust mitigation, alternative feedstocks, and new chemistries. As these progress, it is important to focus on cracker efficiency, economics, and competitiveness, as all are crucial to success (Coleman 2017). For example, high selectivity in the conversion of ethane to ethylene must be maintained as it is crucial to yield and economics; it also minimizes side products, coking, and additional emissions. Furthermore, as 10–25% return on capital is commonly needed (DOE 2023), GHG emission reduction projects alone may languish on the capital list unless a very strong driver in efficiency, economics, meeting new market needs, and/or competitiveness spurs implementation.

There are numerous technology options within the pathways, and some are more mature and at greater scale. Figure 4 shows a non-exhaustive illustration of the development funnel, with a narrowing of options as techno-economics and other parameters are applied. Techno-economics, deployment hurdles, commercial alignment, and adoption-readiness narrow the options list for investment. The literature describes technology and adoption readiness in greater detail (Gallani et al. 2024; DOE 2023).

Several technologies are listed in recent announced projects, and this signals that they met multiple commercial thresholds, even if the projects were delayed due to market conditions or the rollback of incentives. Global chemical companies are probing multiple pathway and technology options that fit best in various geographies. For example, several companies are partners in electrified furnace/cracker demonstrations in Europe while also advancing fuel switching options with H_2 as well as biomass-based ethylene in North America. The numbers in the circles in figure 4 signal commercial projects using the technologies. Energy efficiency is central to all the technology solutions because it effectively aligns with LC and economic priorities and can help relieve feedstock and energy supply issues: The energy and gas used in crackers can be 20% or more of the economic cost of ethylene production (Thunder Said Energy 2025). This underscores the energy efficiency importance.

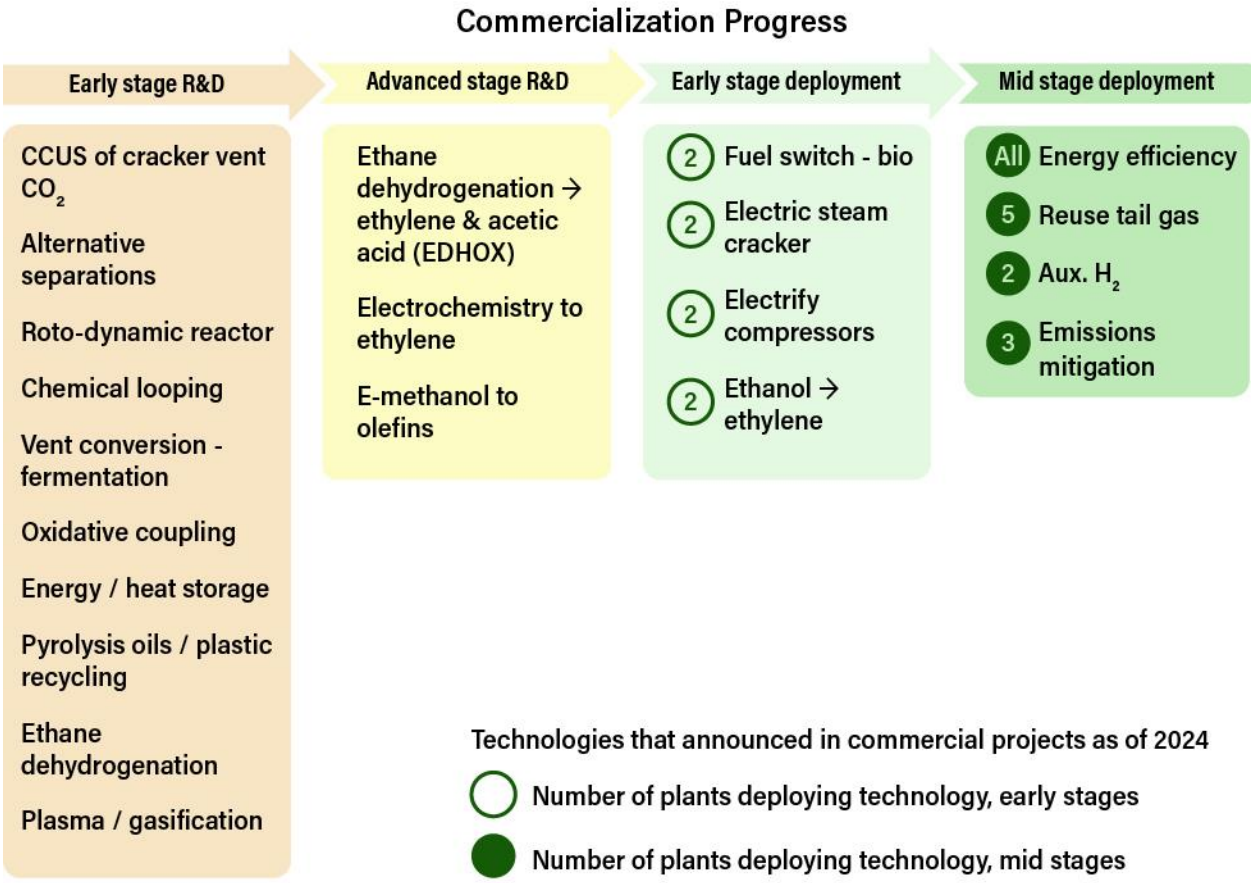


Figure 4. Illustrative technology development funnel for low-carbon technologies. The number of announced commercial projects using the more developed technologies globally, as of late 2024, is indicated to the left of each technology strategy.

Hydrogen fuel switching

The degrees of H_2 use in a cracker include tail gas (TG) reuse, auxiliary H_2, and separation/recovery of H_2 from the methane (CH_4) in TG via an autothermal reformer (ATR). The viability of using auxiliary H_2 to fully meet cracker energy needs where the H_2 is produced from natural gas and CO_2 abated via carbon capture, utilization, and storage (CCUS) depends on economics, CO_2 pipelines, storage facilities, class VI well permits, and public acceptance. The projects that received commercial approval for H_2 fuel switching benefit from being located where the CCUS hurdles are low and partners are facilitating infrastructure, storage, and parallel markets. This is helpful for providing a higher level of CO_2 emissions reduction as it can mitigate emissions associated with an ATR or remaining process emissions. Hydrogen fuel switching is a top option in the United States, as H_2-rich TG is an attractive reuse option, there are H_2 pipelines along the Gulf Coast, and CCUS is plausible.

Several projects planned to use TG combined with auxiliary H_2 in furnaces:

- ExxonMobil's Baytown project (Brelsford 2023) would increase cracker capacity, reuse TG H_2, reform TG methane, and get auxiliary H_2 by reforming natural gas in an ATR.
- Dow's Fort Saskatchewan, Canada, project would increase cracker capacity, reuse TG, reform TG CH_4, and add H_2 (from natural gas) using an ATR (Katz 2023).

- The Chevron Phillips Chemical (CPChem) in Sweeny, Texas, project would increase H_2 burning capabilities, use a low-emissions furnace with heat recovery, and electrify a major compressor to reduce energy and CO_2 emissions (Hong 2024).

After initial progress, several of these projects were paused due to a rollback of incentives. Dow's project at Fort Saskatchewan was restarted and is now set to begin producing in 2029 (King 2026).

Some crackers burn their TG "as is" in their furnaces, while others use TG to generate steam to power downstream compression and separation. The TG being used for steam and power could be more efficiently used instead in the furnace with suitable equipment upgrades. Shell's new cracker is designed to burn TG in the furnace and achieve higher H_2 use (up to 85 mole %). To achieve a higher degree of H_2 use, upgrades of burners, tips, the fuel delivery system, and NOx mitigation and accounting systems (as noted below) may be needed. The prevalence of TG reuse in these cracker projects suggests favorability for H_2 firing as a commercially viable path at scale for CO_2 reductions.

The common driver for these investments across companies is expanded plant capacity, and the H_2 switching projects also meet customer demand for LC products:

- ExxonMobil's Baytown project proposed a 50% capacity increase and leverages blue H_2 for LC ammonia.
- Dow's net-zero project would increase capacity, expand ethane supply infrastructure, and serve the LC market.
- The CPChem new furnaces would double capacity, use 30% less energy, emit less NO_x, and decrease CO_2 by 30% (Bruess 2025).

Beneficial electrification

A number of ethylene producers and their engineering, procurement, and construction (EPC) companies are exploring compressor electrification to compensate for the reduced steam generation that results when TG is instead used in the furnace. The CPChem project includes the electrification of a major compressor. There are three major compressors typically. A coarse capital estimate for electrification of all three, should they not already be electrified, would be roughly $200 million with a power demand around 130 megawatts (MW). Beneficial electrification results when carbon-free electricity is used (Rightor et al. 2020).

A study on naphtha crackers and compressor electrification showed that condenser optimization and energy integration could preheat boiler feedwater, improve efficiency, and lead to CO_2 reductions of 25% (Torcato et al. 2025). Electrification could start with smaller compressors, as their power demand is lower, the equipment delivery delays are shorter, and the cost adder is reduced. A life-cycle analysis (LCA) and techno-economic analysis suggested that electricity use for downstream separations (e.g., compression) could reduce net GHG emissions without big net increases in the cost of ethylene (Shin et al. 2025). BASF recently started up a 1 million tpa cracker in Zhanjiang, China, that features electrified main compressors supplied with 100% renewable energy (BASF 2026). Several approaches are used to ensure reliable electricity supply, including power purchase agreements and grid and site integration. Energy storage is an additional approach to consider.

Electrification of the cracker furnace (e-cracker) is the focus of several consortia in Europe because TG from the naphtha crackers is low in H_2 and CCUS options are typically not available. E-crackers are favored there due to costly natural gas, the cost of carbon emissions, government incentives, and high stakeholder pressure on CO_2 reductions. The electricity/natural gas price ratio in Europe is also more

favorable; it ranges from 1.5–3.5 (EHPA 2024), lower than the 4–5 range in the United States (Hoffmeister 2024).

The BASF/Linde/SABIC consortium notes that furnace electrification could reduce CO_2 emissions by 90% (BASF 2024). Their e-cracker started in 2024 with two separate pilot furnaces to process approximately 4 tons of naphtha per hour using 6 MW. The pilot synopsis states that both concepts demonstrated excellent performance, with the indirect heating approach filling gaps for medium-to-high temperature applications (752–1,652°F, or 400–900°C) and the direct approach being well suited for applications above 1,112°F, or 600°C (Hoefel et al. 2026). The Dow/Shell/TNO e-cracker project launched a pilot unit with electric coils in June 2022, with a 90% CO_2 reduction target (Dow 2022). For the United States, the high electrical demand for a commercial cracker (~1 gigawatt, which is roughly the power demand of Baltimore, Maryland), the electricity cost; the uncertainty around time-of-day rates, the grid mix, and storage; and the availability of cheaper options (H_2 firing) suggest a high hurdle for fully electrifying furnaces.

With electrification of major energy uses, the option of demand response comes into play. This could allow operators to run at higher rates when the electricity costs are low and allow electric companies to incentivize operators to make adjustments (relying in part on energy storage and local renewables) during grid emergencies. Multiple scenarios are plausible with a range of benefits (Braga dos Santos et al. 2023).

Energy efficiency

Efficient use of energy, feedstocks, and other resources is a strong driver for optimization in crackers, but energy efficiency varies considerably by region (Worrell et al. 2000), as does the cost of energy, supply reliability, and incentives and regulation. Energy efficiency varies across U.S. crackers due to cracker age, technology, integration, and company priorities. A sizeable opportunity remains. For example, as part of the CPChem design, Technip developed a low-emission furnace design that optimizes preheating of fuel gas combustion air and thermal efficiency in the feedstock transfer line, and it resulted in a 30% CO_2 reduction (Hydrocarbon Processing 2025). Lummus's net-zero cracker design improves energy efficiency by reusing heat for preheating and improves H_2 recovery for combustion in the furnace (de Barros et al. 2024). Energy and thermal efficiency are not just a significant opportunity for current assets but will also be central to achieving cost and performance parity for new technology solutions.

Emerging solutions

Exhaust mitigation. Exhaust mitigation via direct capture of vent emissions from a cracker is possible but not yet demonstrated at scale. Demonstrations at scale for coal-fired power plants offers crossover experience, but the lower CO_2 concentration of crackers suggests more challenging separations. The demonstrations of CO_2 capture at coal fired power plants revealed challenges that require attention, including economics, reliability, as well as low capture and utilization rates (Jenkins 2015; Mattel and Schlissel 2021). Real capture costs are likely above $200/ton.

Capture of CO_2 from the ATR associated with the generation of auxiliary H_2, and potentially other remaining emissions, were part of the solution set in the Dow and ExxonMobil announced projects. This signals that mitigation can complement CO_2 reductions from primary technologies. Yet, the cost burden is still high and efficiency, integration, and leveraging with other operations such as pipeline, storage still need to be advanced to decrease that burden. While conversion of the exhaust CO_2 to ethanol via

fermentation (Lanzatech 2025), electrochemistry (Twelve 2025; Halford 2024), and hydrogenation catalysis (Ye et al. 2025) is being explored, the cost challenges similarly need to be addressed.

Alternative ethylene processes. Advances in alternative ethylene processes, including de-fossilization (Nature 2026) with chemicals from plant or atmospheric sources, is being explored and should be followed to gauge applicability. In Brazil, Braskem produces bio-ethylene derived from sugarcane residues. This process is advantageous there as it leverages the massive sugarcane industry, infrastructure, and supply chains to supply an abundant, reliable, and sustainable feedstock (Oliveira et al. 2019). Dow was an early partner with Braskem in the Brazil process, and is in a partnership with New Energy Blue, exploring turning agricultural waste (corn stover) into bio-based polyethylene (Special Chem. 2023).

Developments are continuing on selective routes to ethylene, including ethane dehydrogenation. Advances in selective catalysts and CO_2 as a soft oxidant offer promise, but there are still numerous technical and economic challenges remaining (Fairuzov 2021). The dehydrogenation approach, for example, offers the promise of low capital intensity, including a less-intensive separation suite of processes, and a lower CO_2 footprint. Photochemical activation is also being explored to lower activation energy, and this is an example of the creative use of synergies to lower application hurdles.

Thermal energy storage: Advances in thermal energy storage (TES) should be explored. Crackers use vast amounts of heat and reusing it can have efficiency and emissions reduction advantages (see Technip above) that enable the transition to clean energy (Gillooly 2025). Rondo started a 100-MWh heat battery in California (Rondo 2025) that converts solar-powered electricity from a 20-MW solar array into heat (up to 1,500°C) that can be discharged rapidly on demand for industrial processes. The scale, temperature range, agility, and ability to improve both the energy and thermal efficiency are of interest for crackers.

Aggregating LC demand. Several groups are working to aggregate demand for lower-footprint products to nurture the LC market, demonstrate the growth opportunity, and verify the lower carbon product intensity with environmental attribute certificates (EACs) and a process of advanced procurement often referred to as “book and claim” (GMA 2025; RMI 2025). These certificates decouple the physical asset from the environmental benefit and allow companies to purchase verified emissions reductions wherever they occur (De Luna 2026). This provides industrial companies with the flexibility to scale while addressing supply chain emissions. The approach is being used in iron and steel, cement and concrete, and transportation. Today EACs are also being used in fertilizer sales, which has relevant chemical industry connections to ammonia and hydrogen. Early work is progressing in chemicals, and a recent pilot for a buyers’ coalition seeks to accumulate demand and signal the magnitude of growing customer interest (GMA and RMI 2026). Reduction in demand for virgin plastics via substitution, recycling, and elimination is another approach.

Emissions and economic analyses

Emissions reduction potential

The announced commercial projects using H_2 provide a marker for the CO_2 reduction potential of multiple solutions. Claims of CO_2 reduction for the projects vary, depending on the approaches used and their implementation, from 30% (CPChem) to higher than 85% (Dow, ExxonMobil). The latter two use CCUS to achieve even higher CO_2 reductions beyond those from efficiency and multiple steps of H_2 switching. The final reduction figure would need to account for the CCUS capture efficiency (90% for

example), and the emissions associated with generation of auxiliary H_2 from an ATR and power generation. Nonetheless, the magnitude of CO_2 reductions possible and the impact potential if similar reductions were pursued across the cracker fleet are of interest. Totaling the Dow and ExxonMobil project claims gives a 3.5 MM tpa of CO_2 reduction potential. How much CO_2 could be reduced across other U.S. crackers via a similar approach?

To estimate the CO_2 reduction market potential with a similar approach (e.g., higher TG use, auxiliary H_2, and compressor electrification to start), we used cracker age as a coarse deciding point for upgrading. (Realistically, there are multiple factors.) If 100% of middle-aged crackers; 50% of recent, modest-capacity crackers; and 25% of newer, high-capacity crackers were upgraded, that would involve more than 50% of U.S. cracker capacity. Using literature parameters and assumptions (see Appendix A for details), an CO_2 reduction of around 60% is plausible, as shown in figure 5. The figure highlights that maximizing energy and thermal efficiency and increased tailgas reuse are great places to start because they can yield a reduction of over 40%. They can also be economically positive (see below) and have high technology and adoption readiness. The level of tailgas use in crackers across the fleet is difficult to discern, so the ultimate reductions possible have some uncertainty. Similarly, the integration synergies between these and other technologies have numerous uncertainties and are not optimized, which is why demonstrations are needed. To achieve greater reduction and address associated emissions (e.g., from an ATR), CCUS or other emissions mitigation technologies could be employed. Ethane crackers operating prior to 1980 were not included as they could be shut-down candidates, and they have estimated combined emissions of 3.6 MM tpa CO_2.

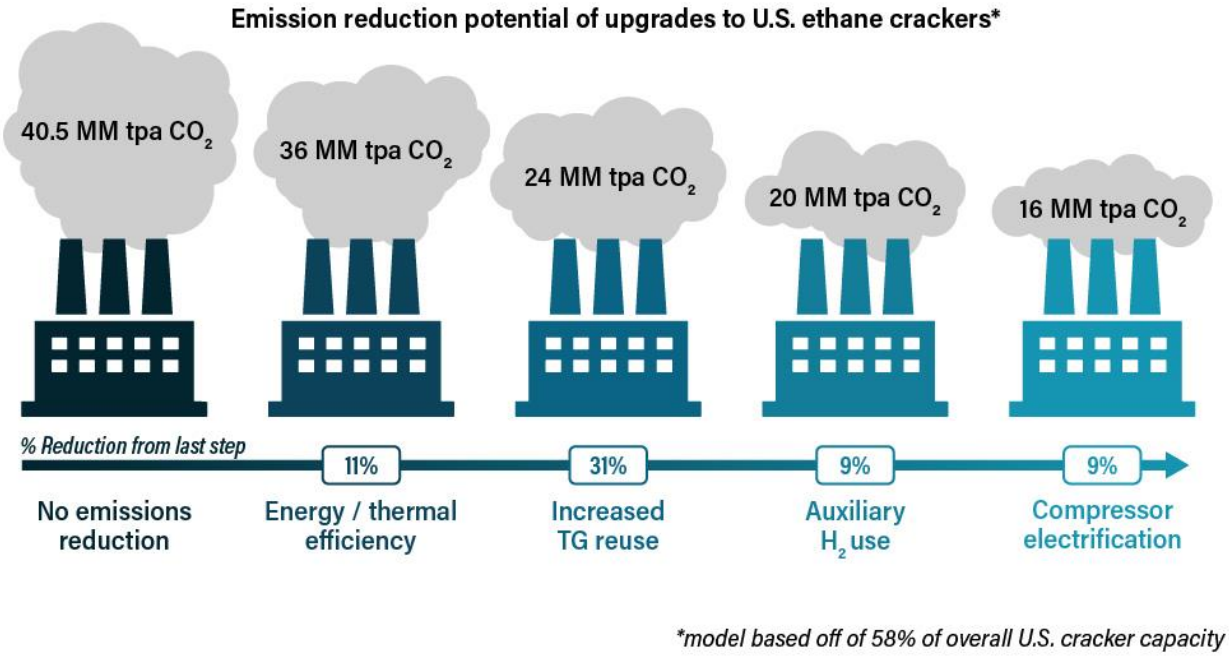


Figure 5. Potential CO_2 reductions at select crackers for successive implementation of the emissions reductions noted on 58% of the U.S. cracker fleet.

Techno-economics

Overcoming technical hurdles for alternative technologies and increasing scale is necessary but not sufficient. Technologies must also provide similar or better performance compared to incumbents and be close to parity in costs (Gaston 2023). Even then, the market needs to be ready to support the

technology deployment (adoption readiness, DOE 2025) and projects may be delayed until a strong business driver, like a capacity expansion or a unique product opportunity, spurs investment.

From a technology perspective, all three stages of burning H_2 are viable, demonstrated at scale, and plausible. Yet, as a simple economic model illustrates, the economics and strength of market drivers put even these projects on the bubble. To understand the economic impact of various stages of hydrogen use (tail gas, supplemental H_2, H_2 from conversion of the CH_4 in the tail gas), an Excel net present value (NPV) model was created. This allowed analysis of the influence of capital and operating expenses, capacity expansion, H_2 pricing, and other factors. For H_2 pricing, the market values for both blue (H_2 from natural gas with carbon capture and storage) and green (from electrolysis, using renewable electricity) were explored. The model also gave a basis for a sensitivity analysis. Figure 6 compares the NPV of a major plant expansion with a standard furnace upgrade (see Appendix B for detailed assumptions). Replacing a portion of the natural gas with TG is strongly NPV positive. The additional cost of blue H_2 reduces the NPV and using green H_2 drives the NPV strongly negative.

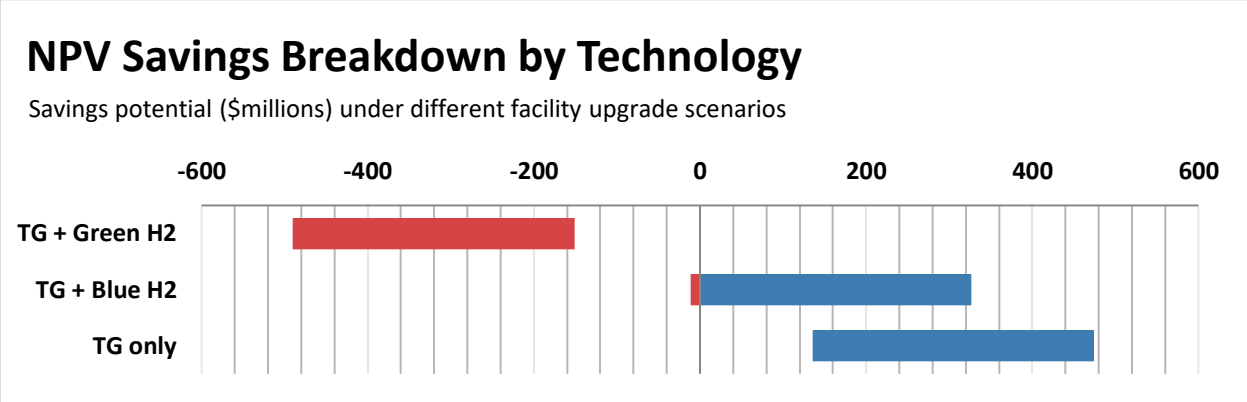


Figure 6. Sensitivity analysis of the savings potential for various ethane cracker upgrade scenarios compared with a standard furnace upgrade. See Appendix B for sources.

The scenario for TG + blue H_2 signals that the cost of blue H_2 could be a concern in some instances, but that, overall, a project could be in the NPV positive range. The analysis indicates that the production price of H_2 needs to drop significantly, well below $1/kg as that is four times the cost of natural gas on an equal-fuel basis. With auxiliary H_2 at 15% of cracker needs, the production cost of blue H_2 would add $66 million in operating costs, and more for third-party H_2.

The dependence of several commercial projects on incentives serves to underscore that the economics for the higher stages of H_2 use are borderline and highly dependent on incentives. ExxonMobil's project had a $332 million grant from DOE, but the company cancelled the project when the incentive was voided (Egan 2025). Dow's net-zero project lined up $1.3 billion in incentives on a $6.8 billion project, but construction was paused from April 2025 until late January 2026, when market conditions improved (Canadian Press 2025). This all signals that although the technology meets hurdles, but the economics for higher H_2 use are still challenging.

Co-benefits

A review of upgrade options is a fitting opportunity to examine the potential for parallel emissions reductions with neighborhood benefits, energy efficiency opportunities, and nonenergy benefits that can improve economics (see Appendix C). It is also an advantageous time to explore opportunities to integrate existing infrastructure.

Reducing multiple pollutants in parallel would be an important co-benefit. Combusting more H_2 may increase NO_x, but ultra-low NO_x burners and control of the fuel mixture can reduce NO_x by 50–60% with a short catalytic bed (de Barros et al. 2024). Additionally, including more H_2 in the fuel mixture can necessitate adjustments to the accounting and bookkeeping methods so that NO_x emissions are reported more accurately (Douglas 2022). Reduction in NO_x was one of the benefits noted in CPChem's project (Bruess 2025). Crackers in ozone nonattainment zones such as Harris County, Texas, may need to reduce NO_x and VOCs, so NO_x reduction projects could remove a production constraint, aid economics, and decrease community impact. Reducing NO_x and VOCs is a good starting point for multi-pollutant reductions as both have regulatory restrictions in nonattainment zones.

Beyond the emissions benefits, compressor electrification could decrease the dependency on steam, improve efficiency, decrease maintenance costs, reduce noise/vibration, and improve availability (dos Santos et al. 2021). As noted above, compressor electrification could backfill TG use. Many crackers are in petrochemical clusters where integration across facilities improves efficiency, repurposes waste, and leverages assets and supply chains. Further integration across LC energy, feedstock, and emissions treatment and reuse is a competitive opportunity. Studies suggest that integration could reduce emissions mitigation costs 9–11% (Tiggeloven et al. 2025) and reduce the overall environmental footprint 3–5% (Gong et al. 2025). Integration at scale while efficiently using the high-pressure steam and waste heat from the cracker furnaces, and ensuring reliability and resilience, are challenges that need to be addressed. The implementation of electric compressors at the BASF cracker in China, demonstrations, and advances from engineering companies will provide experience in these areas.

Finally, improved emissions and health impacts can facilitate the development of large cracker projects, whose economic benefits can be substantial. The Gulf Coast Growth Ventures' new cracker had an estimated $22 billion in associated revenue creation for Texas (DOE 2022b). Dow's new cracker and expansion in Freeport, Texas, had over 3,000 craft employees and subcontractors and created 150 permanent and many more indirect jobs (Fluor 2017). That cracker also has 60% lower CO_2 emissions intensity and 65% lower conversion costs (Dow 2021b).

Low-carbon product market

It is important to recognize and develop the emerging market for LC products, as these customers may be willing to support LC progress by paying a portion of the higher production costs via a “green premium.” This helps producers see that the market is viable, offsets higher production costs, and engages supply chain partners in further meeting the needs of this emerging market. Despite increased visibility and commitments for LC downstream products like ethylene oxide that come with higher margins, the LC market remains embryonic (Warmington 2024). Several approaches are being proposed, including recently introduced legislation on contract for difference (Whitehouse 2025). Dow's net-zero cracker targets “the increasing needs of customers and brand owners seeking to lower the carbon footprint of their products” (Dow 2021). ExxonMobil's LC cracker is part of a larger H_2 hub that seeks to tap the emerging LC market, and there is the potential for double-digit margins assuming supportive policy, technology breakthroughs, and repurposing current assets and infrastructure (ExxonMobil 2025).

In related chemicals markets, Japan and South Korea have signaled a willingness to pay more for LC ammonia to feed their power industry, but uncertainty remains until agreements are finalized. Carbon pricing instruments operate in 39 national, 33 subnational, and one regional jurisdiction, and together they cover one-quarter of global GHG emissions and over $100 billion in revenues (World Bank Group 2025). Countries are using these instruments to shift the value equation towards LC production, and several invest funds from a carbon price in LC industrial technologies. For example, the European Union is committing $43 billion from its Emissions Trading System revenues for an Innovation Fund. Similarly,

Alberta is using revenues from its Technology Innovations and Emissions Reduction regulation to help regulated firms transition away from fossil fuels. Business partnerships and customer precommitments for products can also help lower hurdles (ExxonMobil 2025, 2025b).

Helping low-carbon technologies compete

Multinational petrochemical companies will juggle priorities in the wake of the Iran conflict. Shifting supply chain needs may open doors for capital investment—including in LC projects—but only if business cases can be improved to better compete with lower-cost, proven technology. Numerous parties must work together to lower technical, market, infrastructure, and policy barriers. Table 2 describes some of these barriers. The enablers are provided in the table to spur discussion about potential solutions at the interfaces between technology, market, and policy. For example, effective signals for demand flexibility and rate design that lower cost for certain times of day and enable efficient electrification could help electricity compete with gas on cost (Dammel et al. 2024). Electricity prices have been rising for several years where crackers operate, and they are also more variable than natural gas. The high ratio of electricity to natural gas price (e.g., spark gap) and price uncertainty impede electrification.

Progress is needed on technical hurdles to improve performance, efficiency, and reduce operational costs. For example, to achieve higher H_2 use stages, changes may be needed in the furnace refractory and firebox to address increased moisture, along the lines of glass industry experience (Poirier et al. 2024). Burners/tips designed for up to 100% H_2 are commercial, as are low NO_x burners, but cost reductions would lower the incremental cost relative to incumbent processes. Even with ultralow NO_x burners that reduce NO_x to around 9 ppm, selective catalytic reduction units (SCRs) may also be needed in jurisdictions that require lower levels or where process variation may give concentrations above regulatory limits. Conversion of TG CH_4, H_2, and CO_2 is feasible, and ATRs are commercial—but the cost of producing auxiliary H_2 and mitigating CO_2 needs to drop.

Some barriers result from ill-defined rules of lower emissions. For example, accounting for carbon reduction at the product level and throughout the value chain, and addressing who gets credit for reductions, are all at an early stage. This is an area that will benefit from efforts to aggregate LC demand. The ability to quantify product carbon reductions, present those findings to consumers, and validate a consumer "green premium" could also be stepping stones for recognizing the reduction of other pollutants. Uncertainty as to the volume and durability of the demand for lower-emission products presents numerous challenges that need to be addressed.

Partnerships across multiple entities are the most effective way to engage multiple stakeholders, leverage resources, and promote the continuity needed to make durable progress. Multiple state governments and utilities have been active in lowering barriers and supporting implementation to accelerate industrial electrification (Hoffmeister 2025). The policy approaches used could be a starting point for discussion to address the barriers for ethylene decarbonization. Table 2 lists a starting group of entities that could make an impact.

Table 2. Barriers to low-carbon cracker deployment and potential ways to address them

Area/parties	Approaches	Barrier	Enabler opportunity
Technical: Operators, EPCs, funders	Tail gas reuse	High H_2 stage burners, tips, fuel system unknowns, and costs	Demonstrations, improved integration, quantification of carbon reduction, communication of results
		Replacing TG at compressors	Systems optimization, quantification of non-energy benefits, beneficial electrification
		Auxiliary H_2 costly	Purchase agreements, co-production
	Fuel switching	Upgrades stalled by long equipment lifetimes	Improved supply chain capacity, leverage purchasing across operators, EPCs, and clusters
	Compressor electrification	Spark gap	Power purchase agreements with low rates, on-site renewables, demand-response
		Low-carbon electricity availability and reliability	On-site renewable energy generation, long-duration electric and thermal energy storage
Policy: NGOs, legislators, associations	Rules of the carbon road	Rules ill-defined and wide range of approaches to carbon intensity and LCA estimates	Support partnerships to advance clarity, transparency, and market acceptance. Expand work on protocols and with EACs, and work to ensure durable, supportive policies.
		Rapidly rising electricity costs	Rate design, demand flexibility, state clean heat standards, long-duration electricity, and thermal energy storage incentives
		Multi-pollutant reduction justification weak	Tie local, state tax avoidance incentives for multi-pollutant reductions
	Auxiliary H_2	Blue H_2 costs unpredictable	Solidify infrastructure, incentives, responsibilities
	Community outreach	Pollutant levels, pushback on permitting	Communicate multi-pollutant reduction initiatives aligned with permitting proposals
Market: NGOs, operators, funders	Green premium	Nascent market for low-carbon products	Support labeling initiatives, methodology, standards, and aggregate demand and validate with operators
		Premium uncertain	Tie demo production to market validating premium, show benefits to consumers

Pursue actionable steps

Dedicated efforts are needed to address the barriers listed in table 2. Collaboration across companies that operate crackers, supply chain partners, and those that share industrial cluster infrastructure is needed. For progress, proactive steps need to be pursued in the next 3–5 years, as shown in table 3.

Developing a durable, supportive, predictable policy environment is crucial, as it provides a stable foundation for investment, defines rules, and levels the playing field. For the latter, it is vital that policies be harmonized globally. Partnerships can leverage resources, capabilities, infrastructure, and support from a variety of entities to lower risk, advance the techno-economics, and show that LC technologies can not only compete but also provide a competitive advantage.

Table 3. Decision-maker actions to accelerate low-carbon business case development

Decision-makers	Supportive actions
Cracker operators, EPCs	• Build and improve the business cases for low-carbon technologies and products • Create partnerships and plan, coordinate, and pursue demonstrations of viable low-carbon technologies that drive performance, cost reductions, and both energy and non-energy benefits • Quantify the emissions reduction potential across the supply chain, and collaborate with partners on labeling, reporting, and transparent data warehouses • Work with NGOs, supply-chain partners, and academics on footprint-reduction quantification methodologies and reporting • Probe routes to lower costs on low-carbon fuels and energy via long-term agreements, integration, demand response, and on-site renewable energy and storage • Engage and train practitioners, working with communities
Supply-chain partners, NGOs	• Develop the market for low-carbon products by clarifying needs, working with aggregators of demand, connecting early demand-pull with product from demonstrations, and ensuring readiness for products • Provide input on and facilitate labeling, transparency, and common reporting methodologies and software systems to enable easier accumulation of demand • Help clarify the dimensions of growing customer demand and how the levels of customer interest in reductions compare with the value of the reductions • Advance market approaches such as preferred procurement (Lewis et al. 2021) and environmental attribute certificates (De Luna 2026)
Buyers of products	• Engage in efforts to establish differentiated demand for low-carbon chemicals • Incorporate carbon intensity and other low-carbon metrics in procurement practices
Legislators (state and federal)	• Support partnerships that drive demonstration projects and explore infrastructure improvements needed for deployed solutions • Describe and codify realistic, durable, clear "rules of the road" for quantifying carbon intensity, with common LCA definitions, harmonization with global frameworks (Rissman 2024; National Academies 2024), and guardrails • Define and support market approaches such as Contracts for Difference (Look et al. 2025) • Align tax incentives with company delivery of multi-pollutant reductions • Facilitate progress on pollutant reductions via reporting and communications to and interactions with communities • Solidify programs and support for infrastructure that delivers low-carbon fuels and energy, including CCUS/blue H_2, renewable energy, and long-duration storage • Spur learning at knowledge intersections and encourage spillovers (Rightor 2023)
Utilities	• Devise rate designs that incentivize electrification, demand-response • Improve support for fenceline power (substations, busbars) and grid connections as operators' power needs expand with electrification • Collaborate with operators on long-duration energy storage, renewable power generation, and energy demand to improve reliability and resilience

State governments can play a key role—especially Texas and Louisiana, which have a large number of crackers—in encouraging demonstrations of lower-footprint technologies and tying incentives to technologies that reduce multiple pollutants. State departments of environmental quality can also facilitate transparent communications of emission reductions so that fenceline and downwind communities see the progress.

Conclusions

Ethylene is a cornerstone of the chemical industry. It yields a host of products that serve customer and societal needs across all market segments. Addressing its environmental footprint can improve the competitiveness of U.S. producers, tap an emerging market for products with lower environmental footprints, and reduce health impacts for communities near plants.

The low-cost shale gas in the United States and related ethane feedstock for ethylene production currently provide a competitive advantage on cost and carbon emissions intensity. However, competitors are chipping away at those advantages. The timeline for developing, scaling, and justifying large capital projects for highly integrated ethylene crackers is years. Today's period of slowed investment is an opportune time to push innovation, nurture the emerging market for low-footprint products, and push labeling and data transparency across value chains. Demonstrations are needed to maximize the benefits and optimize integration for lower-emissions technologies, including multiple levels of H_2 fuel switching and compressor electrification, to maintain the competitive position of U.S. crackers. In parallel, dedicated efforts are needed to aggregate and grow the demand for low-emissions productions, as well as to improve the emissions quantification, labeling, and transparency.

The supply-chain disruptions of the Iran conflict are allowing U.S. ethylene producers to increase cracker utilization and expand margins. As a result, they may be in a better position to participate in demonstrations of low-carbon technologies and to support customer requests for lower-carbon products. When ethylene margins recover, low-footprint technologies will then be ready for incorporation into capital investments. Now is also the time to demonstrate and further develop the business cases for low-footprint technologies.

Acting now would show nearby communities that multi-pollutant reductions are viable. As some pollutants persist and have exponential impacts, it is much more effective to act now than to wait 5, 10, or 15 years. To compete and have access to the growing market for low-carbon products, domestic operators need to enhance their existing low cost and carbon advantages by partnering to demonstrate technologies, reduce cost, improve integration, and grow the market-pull for low-carbon products.

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Appendix A. Potential carbon dioxide reductions across the cracker fleet

To examine the carbon dioxide (CO_2) reduction potential if hydrogen (H_2) use steps in commercially announced projects (e.g., ExxonMobil Baytown and Dow Fort Saskatchewan) were replicated across a significant portion of the U.S. cracker fleet, we made rough estimates using the parameters below. Cracker age was a key factor for upgrading (among many). If 100% of middle-aged crackers; 50% of recent, modest-capacity crackers; and 25% of newer, high-capacity crackers were upgraded, that would involve more than 50% of U.S. cracker capacity. Key parameters for this analysis are shown below.

Table A1. Assumptions for CO_2 reductions across the cracker fleet

Proportions of the cracker fleet adopting H2 stages

	M tpa Et	Number	Percentage upgraded	Mtpa upgraded
Middle-aged crackers of capacity >400 kta	15.8	15	100%	15.8
Newer crackers with modest capacity	6.4	9	80%	5.2
Crackers built after 2016 with large capacity	14.8	9	50%	7.4
Older crackers (pre-1980)	3.6	7	NA	NA

Assumptions and parameters

	Units	Value	Source(s)
Ethylene market growth	%	2	Globaldata
Average energy efficiency savings of furnace upgrade	%	20	Technip
Upstream percentage of energy	%	75	Industry conversations
CO_2 intensity	kg CO2/kg Et	1	Industry conversations
CH_4 lower heating value	Mj/kg	47.1	Engineering Toolbox
H_2 lower heating value	MJ/kg	120	World Nuclear
CO_2 ethylene	t/t	1	Industry conversations
H_2 production	t/t	0.06	Industry conversations
CH_4 production	t/t	0.06	Industry conversations
Supplemental H_2 needs	%	10	Industry conversations
H_2 yield from CH_4	kg/kg	3.33	Industry conversations

Assumptions and parameters

ATR conversion efficiency	%	85	Lin
ATR with CCS	kg CO2/ kg H2	2.4	ScienceDirect
CO_2 emitted from natural gas	kg/ gas scf	0.055	EPA
Reduction w CCUS	%	92	Industry conversations

Appendix B. Economic Modeling

The parameters used in our net present value analysis are detailed below.

Table B1. Modeling assumptions for CO_2 reductions across the cracker fleet

Name	Units	Value	Source(s)
Methane conversion/use	tons	*103,674*	Calculation
Energy efficiency from furnace upgrade	%	25%	Technip
Ratio CO_2 to ethylene (tons per CO_2/tons per C_2H_4)	ratio	1.2	Ren 2006
Starting capacity - cracker ethylene production (capacity increase)	million tpa	1.50	Industry conversations
Ending capacity - cracker ethylene production (capacity increase)	million tpa	2.25	Industry conversations
% of NG (and CO_2) reduction	%	42%	Industry conversations
Blue H_2 abated	tons	*104,357*	Calculation
Green H_2 abated	tons	*270,857*	Calculation
Emitted via Blue production	*tons*	*166,500*	Calculation
Emissions factor for producing H_2 via 93% carbon capture rate	*kg CO_2/ kg H_2*	*3.70*	IEA
CO_2 from NG displaced	*tons*	*270,857*	EPA
Hydrogen fuel needs	*kg*	*45,000,000*	Calculation
Natural gas energy needs	*kg*	*98,181,818*	Calculation
Balance of energy needs	*MJ*	*5,400,000,000*	Calculation
Revenue			
Name	**Units**	**Value**	**Source(s)**
Sale price of ethylene	$/ton	$1,060.00	STATISTA
Utilization rate of plant	%	80%	PLG Consulting
Emissions factor	kg CO_2/kg H_2	11.40	GREET Model
Total emissions for H_2 produced (no CCUS)	kg	513,000,000	Calculation
CO_2 captured via CCUS	tons	346,500	Calculation
Gross margin	%	25%	Variable from industry conversations
CAPEX			
Name	**Units**	**Value**	**Source(s)**
Upgrade furnace, burners, and piping (NG) *(sensitivity analysis variable)*	million $	$400–600	Variable from industry conversations
Upgrade furnace, burners, and piping (H_2) *(Sensitivity analysis variable)*	million $	$600–800	Variable from industry conversations
OPEX			
Name	**Units**	**Value**	**Source(s)**
Blue H_2 production cost	$/kg	$1.80–2.60	BNEF/DOE Analysis

Green H_2 production cost	$/kg	$4.10–7.10	BNEF/DOE Analysis
Amount of fuel (NG) reduced from energy efficiency	%	30%	Technip
Remaining energy needs of cracker	%	15%	Industry conversations
O&M (percentage of CAPEX)	%	5%	Industry conversations
Price of natural gas	$/MMBTU	$4.00	EIA (TX NG Prices)
Amount of Fuel	MMBTU	34,128,000	Calc (MJ to MMBTU)
Total amount of fuel w/ energy efficiency (MMBTU)	*MMBTU*	*23,889,600*	Calc (energy efficiency reduction)
Total amount of fuel w/ energy efficiency (MJ)	*MJ*	*25,200,000,000*	Calc (energy efficiency reduction)
Total energy of fuel	*MJ*	*36,000,000,000*	Calc (mass x ethylene conversion rate)
(Conversion rate)	*MJ/MMBTU*	*0.000948*	EIA
Mass of fuel/ton ethylene	*kg*	*654,545,455*	Calc (tons from cracker to kg)
(Conversion rate)	*kg/t*	*291*	Calc (GJ/ton to kg/ton)
Energy intensity per ton of ethylene	*GJ/ton*	*16*	T. Ren
(Ethylene conversion rate)	*MJ/kg*	*55*	University of Michigan
(H_2 conversion rate)	*MJ/kg*	*120*	University of Michigan
NPV			
Name	**Units**	**Value**	**Source(s)**
NPV timeline	years	20	Variable for modeling
Discount rate	%	10%	Chemicals Liftoff Report

Appendix C. Non-energy benefits

A key hurdle in the adoption of low-carbon technologies is building an economically viable justification case. Often analyzing energy efficiency and non-energy benefits early on can substantially improve economics and highlight additional customer benefits. Examples of non-energy benefits are given below.

Table C1. Examples of non-energy benefits

Operational	Commercial	Customer
Yield	Increased capacity	Quality
Decreased maintenance	Productivity	Lower-carbon product
Safety	Resilience	Lower overall environmental footprint
Load flexibility	Faster restart time	Dependability
Reduced noise	Lower sensitivity to water constraints	New performance ranges
Work environment	Competitive positioning	Ability to recycle/reuse
Waste reduction	Relationships with supply chain partners	
Lower downtime		
Decreased water treatment chemicals		
Improved control/ decreased variability		
Decreased paperwork		

A study from the energy efficiency community showed that across 77 industrial case studies, the impact of non-energy benefits was greater than direct energy savings (Finman and Laitner 2001). And inclusion of the non-energy benefits cut the payback by more than half. For cracker furnace upgrades and the stepwise use of H_2, the biggest benefit may be the capacity addition, as noted in the text. Reusing the H_2 as a fuel for the furnace puts its energy to use in the prime energy consuming operation, which is likely more efficient than a secondary role making steam.

Electric compressors are commercial, with at scale applications in air compressor systems. In general, they provide lower maintenance, noise, and vibration. They also can come up to speed faster, be more controllable, and have lower maintenance costs.