# Decarbonize and Defossilize: Transformative Policies to Reduce Chemical Industry Carbon Emissions

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April 2024
White Paper

ACEEE

# 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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# Acknowledgments

This report was made possible through the generous support of Energy Innovation. The authors gratefully acknowledge external reviewers, internal reviewers, colleagues, and sponsors who supported this report. External expert reviewers included Ed Rightor from Rightor Consulting and an anonymous reviewer. External review and support do not imply affiliation or endorsement. Internal reviewers included Alexander Ratner, Nora Esram, and Steve Nadel. We also thank the following members of ACEEE's editorial and communications team: Camron Assadi, Mary Robert Carter, Kate Doughty, Rob Kerns, Sean O'Brien, Mark Rodeffer, Nick Roper, Keri Schreiner, Ben Somberg, Ethan Taylor, Roxanna Usher, and Mariel Wolfson.

# Suggested citation

Johnson, Anna, Archibald Fraser, Neal Elliott, and Richard Hart. 2024. *Decarbonize and Defossilize: Transformative Policies to Reduce Chemical Industry Carbon Emissions*. Washington, DC: ACEEE. https://www.aceee.org/white-paper/2024/04/decarbonize-and-defossilize-transformative-policies-reduce-chemical-industry.

# Data and licensing information

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# Executive summary

## Key findings

- The hardest-to-abate and most economically productive industrial sector—chemicals—should form the foundation of domestic industrial decarbonization strategy. The United States needs a holistic strategy to reduce carbon emissions from the chemical industry in line with net-zero climate goals. This strategy should encompass the sourcing and refining of raw feedstock materials, initiatives for end-of-product life, and changes to how the sector uses energy.
- The majority of the chemical industry's carbon footprint comes from the carbon feedstocks that form the base of chemical products. If these chemical products are not durable, able to be efficiently recycled, or capable of decomposing with no net addition of carbon to the atmosphere, then they will contribute to the climate and waste crises by either adding additional carbon emissions to the atmosphere, accumulating in landfills, or degrading in ecosystems.
- More than 50 federal programs across 9 government agencies are involved in some aspect of decarbonizing the chemicals industry, in addition to 11 policy guidance documents that provide strategic oversight (see Appendix A). Despite these efforts, most chemical value chains still lack a coordinated domestic strategy for decarbonizing on a timeline that would meet U.S. and international goals.
- Few federal programs pursue demand-side strategies to increase the use of defossilized chemical products. Renewably sourced feedstocks are only beginning to be implemented in the sustainable aviation fuel (SAF) value chain, where production tax credits and other implementation programs are building a new market.
- Direct demand reduction for carbon-intensive products is an underutilized strategy.
- Building defossilization and decarbonization strategies—specifically for bulk chemical inputs into high-value sectors, such as pharmaceuticals or the auto industry—could allow bulk chemical producers and end-use manufacturers to share the costs and ensure a better balance between demand and supply of less carbon-intensive chemical products.
- Policy levers, including shifting demand toward more sustainably manufactured chemical products or alternatives and making it easier for firms to track indirect emissions up and down their value chains, could be powerful. Such levers could fill the gaps to meet U.S. emissions targets, especially when the policies are tailored to individual high-value chemical product demand sectors and also leverage state and regional policy strategies.

The chemical manufacturing sector is the largest and most complex portion of the U.S. industrial ecosystem, responsible for more than 30% of U.S. industrial emissions (Brennan et al. 2023). It is also closely linked to the fossil fuel sector, the source of the vast majority of chemical feedstocks. The chemical manufacturing sector is also the industrial sector for which the least progress has been made toward setting a path to zero carbon emissions by 2050.

The challenge in the chemicals sector is that the majority of GHG emissions are embedded in their manufactured carbon-based products. Thus, as demand for chemical products increases (as it is forecasted to do), carbon consumed and ultimately emitted into the atmosphere by the industry will also increase. Policymakers must support decarbonization solutions that address **both** the upstream feedstocks supplied by fossil fuels and the downstream carbon emissions of product use.

This white paper examines whether existing domestic federal policies are sufficient to make meaningful progress toward 1) shifting chemical feedstocks to non-fossil-fuel alternatives; 2) decarbonizing the chemical manufacturing processes (primarily process heat); and 3) shifting market demand toward sustainable chemical products.

As Appendix A shows, we assembled a database of federal grants, tax credits, research investments, and policy guidance explicitly intended to support decarbonization of the chemical industry (see Appendix A). We then matched these programs to a set of potential emissions-reduction levers split across these three major categories of emissions reduction strategies (table 1).

**Table 1. Strategies to defossilize chemical feedstocks, decarbonize chemical processes, and change demand for chemical products**

| Category | Strategy |
|---|---|
| Defossilize feedstocks | Alternative feedstocks |
| | Clean hydrogen |
| Chemical manufacturing process decarbonization | Material and energy efficiency |
| | Clean hydrogen |
| | Process heat electrification |
| | Carbon capture, utilization, and sequestration (CCUS) |
| | Alternative production methods |
| Change demand | Material circularity |
| | Material efficiency |
| | New markets for sustainable chemicals |
| | Product substitution or demand reduction |

Decarbonization reduces or replaces operations throughout the value chain that emit carbon into the atmosphere; it is also the term we use here for the overarching result of reduced carbon emissions from the chemical sector. We acknowledge, however, that hydrocarbons form the base of most chemical products, and it is thus impossible to “decarbonize” the materials. Instead, we use the term defossilization to describe the specific strategy of replacing virgin fossil-fuel-sourced carbon with alternative carbon sources, such as those from plants, or from recycled or captured carbons. Defossilizing feedstocks allows the industry to use renewable or circular carbon pathways, rather than continuing to move carbon from fossil to atmospheric storage—as occurs today for the vast majority of chemical products. Defossilizing feedstocks, however, will not be enough to decarbonize the sector overall; for example, switching to biogenic carbon sources today may increase the overall carbon emissions per unit of product by requiring additional fossil-fuel-powered processes to refine new feedstocks, and depending on how the resulting products are disposed (Benavides, Lee, and Zarè-Mehrjerdi 2020).

We found that the majority of federal support targeted at decarbonization of the chemical industry focuses on defossilizing feedstocks and decarbonizing manufacturing processes. Most of these policy approaches, however, are in the research, development, and demonstration phase; few policy tools support broad deployment and implementation of solutions, apart from incentives for clean hydrogen production (a feedstock, and in some cases, fuel for the chemical industry) and sustainable aviation fuel (SAF) production. There is a clear gap, and opportunity for policymakers, to develop a coordinated policy package specifically targeted at decarbonizing the chemicals sector to reach 2050 emissions reduction targets. Chemical decarbonization will require visionary leadership from the federal government to pursue and support technologies and materials *that do not yet exist*. If we continue to take a piecemeal approach to the chemicals sector, we risk having essential chemical value chains being left behind, as well as maintaining a carbon-intensive chemical industry that continues to produce toxic products while contributing disproportionately to the global plastic waste crisis.

We also identify a suite of indirect policy levers that could accelerate decarbonization of the chemical industry. These include carbon pricing mechanisms and other strategies that encourage lower carbon intensity versions of key products.

We close with a discussion of a demand-oriented strategy to decarbonize the chemical industry. Currently, there is a lack of market demand for sustainably produced chemical products as well as a lack of transparent and consistent embodied emissions tracking and reporting.

Pricing higher-value products to reflect carbon intensity in constituent bulk chemicals (e.g., product manufacturers paying a “green premium” for more sustainably produced chemical components) would incentivize bulk chemical manufacturers to optimize for carbon emissions in addition to optimizing for cost. The current international market, however, lacks consistent, transparent systems for measuring and reporting embodied carbon from the production of bulk chemicals from individual facilities as well as throughout supply chains; for example, there is still substantial variation in what is defined as in or out of scope of the chemical industry when measuring product embodied carbon (SBTi and Guidehouse 2023).

We highlight the example of nylon use in the automotive sector as an opportunity where the relative cost to mitigate emissions during nylon’s production process could be significantly more economical for the manufacturer of higher-value products than it is for the manufacturer producing adipic acid, the bulk chemical responsible for the majority of nylon supply chain emissions. This example suggests that higher-value product markets can be efficient and cost-effective drivers of transformative change in the chemicals industry, especially if demand-side coalitions of businesses form to build markets for more sustainably produced bulk chemical inputs into their products. Two key next steps for federal chemical policy should be to identify markets in which demand for sustainably produced chemical products can lead to emissions reduction progress upstream in bulk chemical manufacturing, and to develop actionable roadmaps to drive deep decarbonization in key value chains.

# Introduction

## Defining the chemical industry

The U.S. domestic chemical industry[1] generated $614.2 billion in sales in 2022, supplying crucial materials throughout the economy and constituting the largest export sector in the United States (American Chemistry Council 2023). Chemical manufacturing is heavily reliant on fossil fuels for both feedstocks and process heating. In 2020, 84% of basic chemical sales were for carbon-based products (CISA 2022; table 2). Virgin fossil fuels are the source of the vast majority of the hydrocarbon feedstocks required to manufacture the more than 70,000 chemical products in use today.[2] In the United States, the principal petrochemical feedstocks originate from natural gas, but some product streams (e.g., those originating from aromatic chemicals such as benzene) are also tightly integrated into oil refining (Kopalek 2022). The chemicals sector is responsible for more than 30% of U.S. industrial emissions (Brennan et al. 2023).

**Table 2. Relative demand across chemical product manufacturing and supply chains**

| Chemical sector | Examples | Key demand sectors | 2022 shipments (in $millions) | Percentage of sales | Carbon intensity (tons $CO_2e$/ton representative products) |
|---|---|---|---|---|---|
| Inorganic chemicals | Chlorine, lime, industrial gases, inorganic dyes | Other industries, healthcare, consumer products | 55,852 | 6% | Chlorine, hydrogen, and sodium hydroxide, each = 1.25* |
| Bulk petrochemicals and intermediates | Aromatics (benzene, toluene, xylene); olefins (ethylene, propylene, butadiene); methanol | Other chemical manufacturers and industries | 222,670 | 24% | Methanol = 0.43; ethylene = 0.8; benzene = 1.24; butadiene = 2.29** |
| Plastic resins | Thermosets (epoxy, melamine, polyurethane); thermoplastics (polyethylene, polystyrene, polyvinyl | Construction, electronics, consumer products | 101,971 | 11% | High-density polyethylene (HDPE) = 4.15; polyvinyl chloride (PVC) = 5.41; high-impact |

[1] Defined here as the industry concerned with processing of feedstocks (e.g., cracking or reforming of petroleum) to manufacture basic and specialty chemicals, agricultural chemicals (e.g., fertilizers), and higher-value chemical products (e.g., cosmetics). The boundaries between oil refining and chemicals manufacturing, and chemicals manufacturing and higher-value end-use product manufacturing, are somewhat blurry; for example, pharmaceutical production is sometimes considered part of the chemicals industry and sometimes viewed separately.

[2] Less than 10% of global plastics production in 2023 was from recycled or bio-based feedstocks, and more than 90% came from virgin fossil fuels.

| Chemical sector | Examples | Key demand sectors | 2022 shipments (in $millions) | Percentage of sales | Carbon intensity (tons $CO_2$e/ton representative products) |
|---|---|---|---|---|---|
| | chloride); high-performance thermoplastics (polycarbonate) | | | | polystyrene (HIPS) = 6.31* |
| Synthetic rubber | Neoprene, nitrile rubber, styrene-butadiene rubber | Automotive | 8,435 | 1% | Styrene-butadiene rubber = 5.55; acrylonitrile-butadiene rubber = 5.52* |
| Manufactured fibers | Acetate, rayon, acrylic, nylon | Apparel, automotive | 5,998 | 1% | Polyester (PET) fiber = 4.1*** |
| Specialty chemicals | Customized niche adhesives, sealants, catalysts, coatings, cosmetic additives, flavors, fragrances | Highly varied | 105,765 | 12% | Too variable to characterize simply |
| Agricultural chemicals | Fertilizers, pesticides, herbicides, disinfectants | Agriculture | 48,206 | 5% | Ammonia: 1.6* |
| Consumer products | Soaps, detergents, personal care products, perfumes | Individual consumers | 89,841 | 10% | Too variable to characterize simply |
| Pharmaceuticals | Prescription and over-the-counter drugs, vitamins, vaccines | Pharmacies, individual consumers, healthcare systems | 271,045 | 30% | Too variable to characterize simply |

Sources: If not indicated, American Chemistry Council 2023. * = Flannery and Mares 2023; ** = Nicholson et al. 2021; *** = Ivanović, Hischier, and Som 2021.

Unlike other heavy industrial sectors, in which the bulk of GHG emissions are concentrated in materials processing and energy consumption (Scope I and II emissions), the majority of GHG emissions from the chemical industry result from the fossil-fuel-based feedstocks and the end of life of the products themselves (Scope III emissions) (see figure 1). If demand for chemical products increases, demand for continued extraction of fossil fuels will also increase unless alternative feedstocks such as recycled or bio-based materials replace virgin fossil fuels at scale.

For example, by 2050, even if all petrochemical-based plastics manufacturing processes rely on 100% renewable energy, unchanged product demand trajectories and continued reliance on fossil feedstocks could lead to either unchanging sector emissions or as high as a 1.5-times increase (Bauer et al. 2022). Most chemical industry models that predict net-zero emissions from the entire sector at a rate that is compatible with climate goals will rely on a combination of recycled feedstocks and biomass to replace virgin fossil fuels as a feedstock, although it will likely be impossible to entirely eliminate all use of virgin fossil fuel in this sector (Meng et al. 2023).

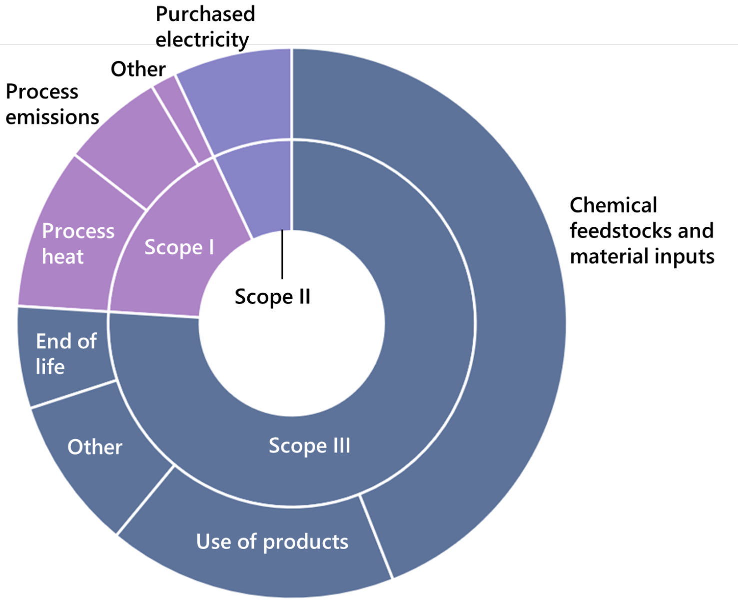


**Figure 1. Sources of chemical value chain emissions broken down across Scope I (18%), Scope II (7%), and Scope III (76%) sources.** ***Sources*****: CDP 2022; McGhee and Olano 2023**

There are additional reasons, beyond carbon emissions, to reduce to the greatest extent possible the overall stock of chemical materials produced and limit the extraction of virgin fossil fuels, especially for use in nondurable chemical products (Wang and Praetorius 2022; Wood and Howarth 2023; Tickner, Geiser, and Baima 2022). Environmental and health burdens will continue to grow with the continued accumulation of plastic waste and continued exposure to toxic chemical additives that are incorporated into many chemical products today (e.g., Fenton et al. 2021). The health burdens from chemical manufacturing are concentrated in vulnerable frontline communities, perpetuating environmental injustices in the United States (Collins, Munoz, and JaJa 2016; Keehan 2018). Decarbonization policy strategy, which also centers defossilization and reduction of waste and toxics, is key to reducing U.S. industrial environmental inequities and to ensuring that the economic benefits to our economy do not continue to come at the expense of the health and well-being of frontline communities.

## A map of decarbonization strategies for the chemical industry

Chemical supply chains are complex and deeply intertwined, which has slowed progress in reducing the sector's emissions (Levi and Cullen 2018). The widespread use of bulk chemicals across the economy makes it challenging to build demand-side coalitions led by public or private sector stakeholders for sustainable products; such coalitions have been possible for less-varied sectors such as iron and steel or cement, where demand for products is heavily concentrated in automotive and construction sectors (Lee 2024). A comprehensive national strategy is still needed to organize goals and incentives, help connect supply- and demand-side efforts across diffuse value chains, and successfully transition the growing chemicals industry in line with a decarbonized future (International Energy Agency 2023a).

Figure 2 shows a mapping of chemical decarbonization strategies; they include key system trade-offs and interacting decarbonization and defossilization levers. For example, if clean electricity supply is limited, users will compete for clean hydrogen as either a fuel (H2-fuel) or feedstock (H2-feedstock). This model also highlights the tight connection between decarbonization strategies that focus on 1) shifting demand for products, and 2) defossilizing feedstocks.

Various strategies can reduce demand for fossil-fuel-based products. Reducing demand for consumer-facing chemical products, such as single-use plastics, can displace a higher percentage of virgin fossil fuels and slow overall growth of the chemical industry if these strategies are paired with investments in scaling up biomass-based or recycled feedstock products. Sustainably sourced biomass for chemical feedstocks provides a renewable carbon source to replace fossil carbon. Given the limits on biomass availability, scaling up recycling systems to create a circular feedstock economy is also essential in all industry emissions reduction strategies. While landfills can serve as a carbon sink for waste plastic, space for landfills is limited, and toxicity and environmental leakage concerns remain—for example, currently, approximately 12% of all plastic produced escapes waste management systems and litters the environment, breaking down into microplastics that release toxic particles and carbon (Meng et al. 2023). Displacing chemical products that are difficult to recycle, such as PVC plastic, with more recyclable alternatives can increase the proportion of recycled feedstocks used to create products, assuming recycling systems also are made more effective. Scaling up the flow of recycled feedstocks would reduce the need for virgin fossil fuels, and thus reduce the volume of fossil carbon that is emitted to the atmosphere, either through incineration of chemical waste (waste-to-energy) or eventual breakdown of chemical products in the environment (e.g., Ward et al. 2019).

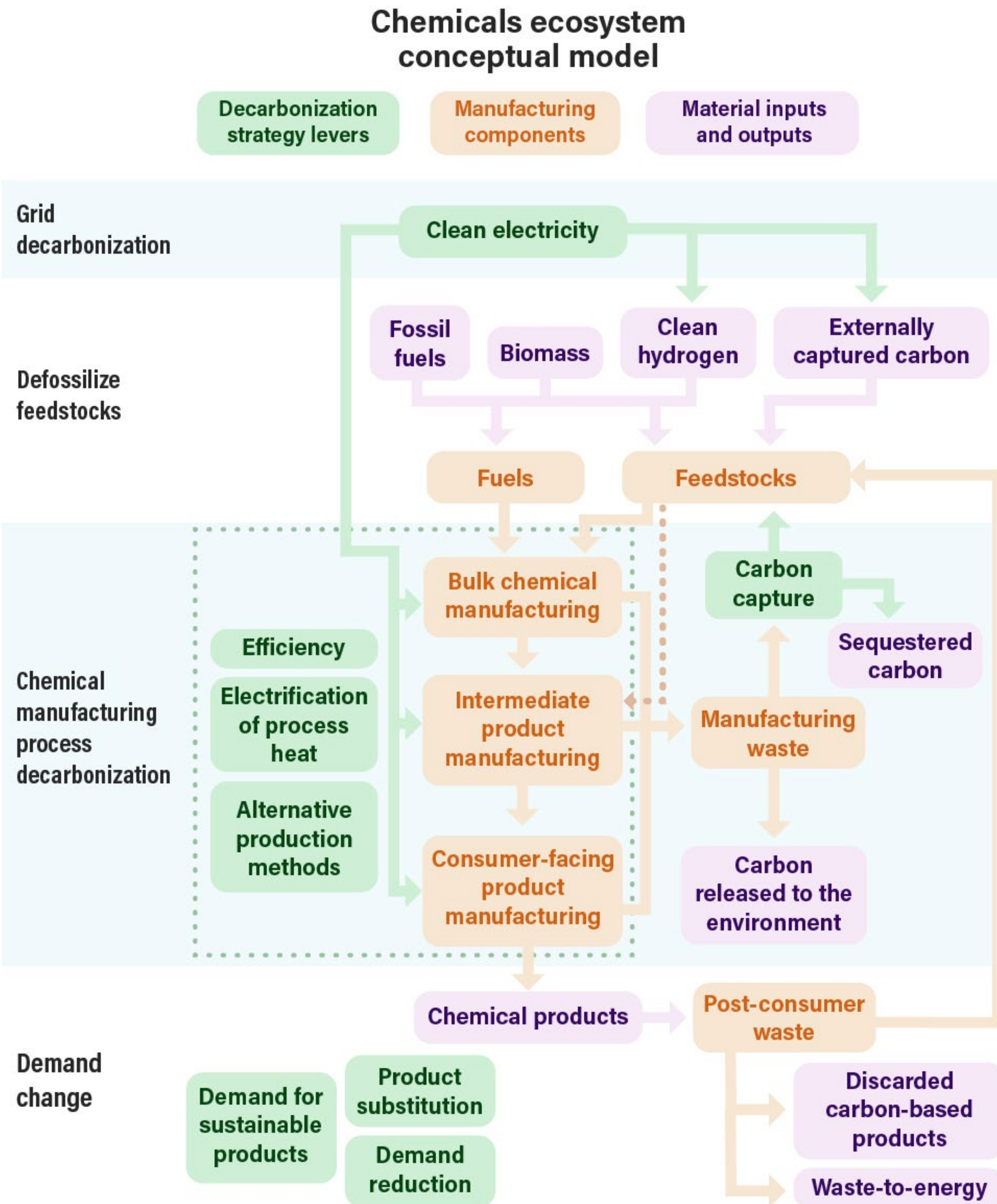


Figure 2. A map of how potential decarbonization levers (green boxes) fit into the chemical manufacturing ecosystem, characterized by process stages (orange boxes) and material inputs and outputs (purple boxes)

# Analysis of current federal chemical industry decarbonization policies

As Appendix A shows, we assembled a database of federal grants, tax credits, research investments, and policy guidance explicitly intended to support decarbonization of the chemical industry. We then matched this information to a set of potential emissions-reduction levers. We identified federal programs that support implementation of decarbonization solutions in the chemicals industry, including research and development of applied technologies.[3]

In all, we identified 54 separate programs across nine different federal agencies. We also identified 11 federal policy and regulatory guidance documents related to decarbonization of the chemical industry. These support Scope I, II, and III emissions reduction efforts in the chemical industry, monitoring and regulating toxic chemicals and pollution, basic chemistry research, and cross-cutting industrial program implementation.

**Table 3. Summary of chemical industry emissions reduction levers targeted by federal programs**

**Workstream 1: Defossilize feedstocks**

Research and development and infrastructure build-out to support a transition away from fossil-fuel-based carbon feedstocks and fuel sources in the chemicals industry. **Federal policy documents:** *Sustainable Chemistry Report* and the *Bold Goals for U.S. Biotechnology and Biomanufacturing* report.

| Strategy | Research and development | Deployment and commercialization |
|---|---|---|
| Defossilized carbon feedstocks | Terrestrial and Algal biomass research development and deployment (RD&D); Clean Fuels & Products Shot; Bioenergy Research Centers; ChemCatBio Consortium; Industrial Efficiency & Decarbonization Office's (IEDO) Enabling Technologies for Low Carbon Fuels and Feedstock Program; Agile BioFoundry (ABF) Consortium; Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) Consortium; Billion-Ton Study; Feedstock-Conversion Interface Consortium (FCIC); Bioenergy Technology Office's (BETO) Lignin Utilization research; Recycle Underutilized Solids to Energy (REUSE) Program | Fueling Aviation's Sustainable Transition (FAST)-Sustainable Aviation Fuels (SAF) program, SAF Grand Challenge, U.S. Department of Agriculture (USDA) Ethanol and Biofuel Technical Assistance, USDA Fertilizer and Biorefinery expansion programs, Sustainable Aviation Fuel (SAF) Tax Credit |

[3] Out of scope areas include general investments into grid decarbonization and cross-cutting technologies nonspecific to the chemicals sector (e.g., carbon capture pilots not implemented on chemical facilities). We have included a sample of federally funded basic scientific research (such as the Bioenergy Research Centers), but a more comprehensive survey of basic and fundamental chemistry research can be found in the federal *Sustainable Chemistry Report* (Joint Subcommittee on Environment, Innovation, and Public Health Sustainable Chemistry Strategy Team 2023). There are also additional federal investments in projects relevant to chemical decarbonization through offices such DOE's Loan Program Office (LPO) (Shah 2021) that we chose not to include, focusing instead on federal programs explicitly designed to address challenges in the chemicals sector.

| | | |
|---|---|---|
| Clean hydrogen | HFTO's Industrial and Chemical Applications Research; Office of Fossil Energy and Carbon Management's (FECM) Clean Hydrogen Production, Storage, Transport, and Utilization to Enable a Net-Zero Carbon Economy program | H2 Hubs, 45V Hydrogen Production Tax Credit, Clean Hydrogen Electrolysis Program |
| **Workstream 2: Chemical manufacturing process decarbonization** | | |
| Federal efforts to lower chemical production process emissions. Current programs are targeted at efficiency; clean hydrogen; process heat; carbon capture, utilization, and storage (CCUS); and alternative production pathways, such as electrification. **Federal policy documents:** *Pathways to Commercial Liftoff: Chemicals and Refining; Pathways to Commercial Liftoff: Clean Hydrogen; U.S. National Clean Hydrogen Strategy and Roadmap;* and *Industrial Decarbonization Roadmap.* | | |
| **Strategy** | **Research and development** | **Deployment and commercialization** |
| Efficiency | National Laboratory catalysis research programs | Industrial Assessment Centers* |
| Clean hydrogen | Clean Hydrogen Manufacturing Recycling Research, Development, and Demonstration Program; FECM's Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy | H2 Hubs, 45V Hydrogen Production Tax Credit, Advanced Energy Project Credit (48C) |
| Process heat electrification | Industrial Heat Shot, Non-Equilibrium Energy Transfer for Efficient Reactions (NEETER) Center | Industrial Demonstrations Program, Advanced Reactor Demonstration Program, Rapid Advancement in Process Intensification Deployment (RAPID) Institute |
| CCUS | National Carbon Capture Center | Carbon Capture and Sequestration Tax Credit (45Q), Carbon Capture Large-Scale Pilot Projects, Regional Direct Air Capture (DAC) Hubs |
| Alternative production methods | | Loan Program Office (LPO), Industrial Demonstrations Program, Rapid Advancement in Process Intensification Deployment (RAPID) Institute |
| **Workstream 3: Change demand** | | |
| At present, there are no federal efforts to reduce overall chemical demand, and most federal research is focused on recycling. Some states, such as California, are pursuing or have already enacted extended product responsibility (EPR) legislation. **Federal policy documents:** The Department of Energy (DOE) *Strategy for Plastics Innovation*. | | |
| **Strategy** | **Research and development** | **Deployment and commercialization** |
| Material circularity | DOE's *Strategy for Plastics Innovation*, Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE) consortium | REMADE (Reducing EMbodied-energy And Decreasing Emissions) Institute |

| | | |
|---|---|---|
| New markets for sustainable chemicals | National Institute of Standards and Technology's (NIST) Chemicals Program | Federal Trade Commission's Green Guides; Environmental Product Declaration Assistance; First Movers Coalition*; Department of Defense's (DOD) Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) |
| Product substitution or demand change | Environmental Protection Agency's (EPA) Pollution Prevention (P2) Grant Program | International Tariffs on Embodied Carbon (similar to the European Union's (EU) Carbon Border Adjustment Mechanism); EPA's P2 Grant Program; USDA BioPreferred Program |

**Programs followed by * indicate broader, cross-cutting programs without a specific chemical focus that may nonetheless provide valuable support for a particular chemical decarbonization strategy. Programs followed by ** are high-profile programs led by governmental stakeholders other than the U.S. federal government. In Appendix A, table A1 includes expanded program information.**

## Most federal programs are aimed at supporting defossilized carbon feedstocks, clean hydrogen production, and decarbonization of chemical manufacturing processes

The majority of federal support explicitly targeted at chemical industry decarbonization focuses on defossilizing feedstocks and decarbonizing the manufacturing processes themselves. While decarbonization of industrial processing in other industrial sectors is primarily about decarbonizing process heating, in the chemical industry there is also substantial room to decarbonize by implementing innovative new chemical production pathways that are inherently low carbon. Currently, very few ways exist for federal programs to directly support deployment of new low-carbon process technologies that are not related to carbon capture, hydrogen production, or SAF. Most industrial electrification technologies that would apply to chemical manufacturing are not directly incentivized at the federal level.

Some chemical decarbonization policy support is available through tax credits. The 10-year 45V Hydrogen Production Tax Credit provides greater value depending on the carbon intensity of the hydrogen production pathway, with the goal of incentivizing industry to shift toward clean hydrogen production. The SAF tax credit is available for fuels produced with a minimum reduction of 50% lifecycle GHG emissions. Tax credits also support critical clean energy supply chains, including the Advanced Energy Project Credit (48C), which provides a 30% investment tax credit to support projects producing hydrogen infrastructure. The Carbon Capture and Sequestration Tax Credit (45Q) also supports chemical manufacturing decarbonization by incentivizing carbon sequestration or utilization projects.

Grants are another large part of the federal toolkit, with key examples for the chemicals industry including hydrogen hub development and deployment funds and the Industrial Demonstrations Program, for which 153 of the yet-to-be-awarded concept papers received were in the chemicals and refining sector, totaling more than one-third of the 411 concept papers reviewed (U.S. Department of Energy 2023).

Programs aimed at defossilizing carbon feedstocks—the manufacturing stage with the broadest investment portfolio—target a few different strategies. The bulk of the existing programs to address defossilizing carbon feedstocks supported research and development of either algal, biofuel, or biomass feedstocks. The remaining research and development-phase defossilized carbon feedstock programs are focused on capturing and recycling waste $CO_2$. The only defossilize carbon feedstock programs we identified that have reached the deployment and commercialization phase are targeted toward the SAF value chain; these include a SAF Tax Credit and a range of grant programs meant to support the infrastructure required to produce, transport, and store SAF.

Process heat decarbonization is also of particular importance for the chemical industry, cutting across all value chains. Initiatives such as the U.S. Department of Energy (DOE) Industrial Heat Shot effort support research and development of alternatives to fossil fuel combustion for industrial process heat. One such alternative is electrification. A little over 30% of the chemical industry's heating demand is for under 300°C, the temperature range that can be directly electrified today with commercially available technologies. Electrification can also address major sources of manufacturing process emissions, such as steam methane reforming and the Haber–Bosch process for ammonia (55 million tons of $CO_2$ combined) and steam cracking to create olefins and aromatics (41 million tons of $CO_2$).[4] While the United States is supporting implementation of electrified ammonia production via hydrogen hubs, all electrified cracker demonstrations to date are occurring in other countries (Gallucci 2023). Emerging drop-in technologies, such as heat batteries, have the potential to electrify assorted other high-temperature process heating needs in the industry (Rissman and Gimon 2023). A range of emerging innovative technologies also are being piloted, with the potential to electrify the production of a variety of chemical products by fully supplanting current production pathways with new approaches (e.g., electrolysis and catalysis strategies).

Broader organizing guidance around defossilizing chemical feedstocks also comes from The Clean Fuels & Products Shot, a DOE initiative announced in spring 2023 as an expansion of the SAF Grand Challenge. This new initiative will support a variety of cross-cutting needs around development and scaling of sustainable carbon feedstock sources and technologies to efficiently convert these resources into fuels or chemicals. The initiative's goal is to meet 50% of hydrocarbon chemicals demand from sustainable carbon sources by 2050, including through forestry or agricultural waste, municipal solid waste, recycled materials, captured carbon, energy crops, or algae (Bioenergy Technologies Office 2023; Office of Energy Efficiency & Renewable Energy 2023).

## Few federal programs seek to change demand for chemical products

Direct demand reduction for carbon-intensive chemical products is an underutilized strategy in existing federal efforts. Only a handful of federal programs pursue this approach in the chemicals sector, despite a wide range of potential demand-side policy strategies, including improving material circularity, building markets for more sustainable products, and directly reducing demand for unsustainable products. Well-developed federal demand-side strategies are active in other sectors, however, such as the Buy Clean initiative for concrete, steel, and other construction materials (Esram, Srinivasan, and Eisen 2023).

[4] Numbers from 2021, in the United States, taken from figure 7 of Brennan et al. 2023. The two processes combined generate 96 million tons of $CO_2$ per year, the equivalent of emissions from more than 21 million gas-powered vehicles in that same period (approximately 8% of all cars registered in the United States).

In the heavily reliant downstream plastics sector, DOE published a *Strategy for Plastics Innovation*, which provides policy guidance to improve the deconstruction and upcycling of plastics. In line with these goals, three federal research programs that we identified focus on redesigning materials and product to improve material circularity and material efficiency. These programs address recycling systems to increase the recyclability of plastic waste to be repurposed as feedstocks, including bio-based plastics (Adin et al. 2023). However, there is no federal effort to eliminate single-use plastics or reduce overall plastics demand.

The U.S. Environmental Protection Agency (EPA) EcoLabels and standards programs is one of the only federal efforts to support a market for more sustainable chemical products. This program provides sustainability information to consumers around some classes of consumer chemical-based products—for example, paints, copy paper, and packaging (United States Environmental Protection Agency 2023a). Currently, most sustainability criteria are focused on chemical toxicity, but the EPA has proposed expanding the certifications to also cover lower-embodied carbon chemical products (primarily achieved via recycled content), albeit only as a voluntary step in certification (United States Environmental Protection Agency 2023b).

Another U.S. Department of Agriculture (USDA) effort is the BioPreferred program, which supports the domestic biofuel and product industry. While these programs provide some information on product sustainability to support consumer choices, they do not themselves guarantee a premium market for the more sustainably produced goods, nor do they provide support for a more rigorous, transparent, and consistent accounting of embodied carbon emissions across chemical value chains.

Instead of reducing demand, most large chemical and food and beverage companies that rely on plastic packaging are planning to eliminate plastic waste through enhanced recycling systems and renewable feedstocks (U.S. Plastics Pact 2022). So far, policy leadership to address the downstream challenges of materials circularity has progressed only at the local and state levels.[5]

International efforts to negotiate a global plastics treaty will likely focus on improved recycling systems, but they are also working toward strategies to reduce virgin fossil-fuel-based plastic production and to place restrictions on certain chemical materials seen as especially problematic from a health and waste management perspective (Volcovici 2023). U.S.-based standards and EcoLabels programs could potentially complement these efforts domestically, especially via expanded certification standards that also encompass the carbon footprint of chemical products.

The federal government is also supporting the infrastructure build-out required to enable more sustainable chemical product alternatives in the fuels sector. One such effort is the USDA's Higher Blend Infrastructure Incentive Program, which expands the infrastructure needed to support broader use of biofuels and increases market demand for more sustainable fuel products (United States Department of Agriculture 2023).

## Sustainable aviation fuels: Learning from integrated supply and demand policies

Few programs comprehensively address challenges that integrate across chemicals' supply and demand, such as pairing new standards or certifications for products with incentivized use of best available process decarbonization technologies by manufacturers. One noticeable exception to this is the rapidly growing federal strategy for addressing SAF, which accounts for less than 1% of airline fuel used today.

[5] For example, state-level extended producer responsibility (EPR) bills address packaging and single-use plastic food and beverage containers. California, Oregon, Colorado, and Maine have all passed EPR bills focused on plastic packaging (SPC 2023).

However, shifting from diesel-based aviation fuel to bio or recycled feedstocks is seen as the best decarbonization lever available for this industry, which is responsible for 2% of global carbon emissions today (International Energy Agency 2023b; Mission Possible Partnership 2022).

As part of the SAF Grand Challenge program, collaborative efforts across several federal agencies[6] seek to reduce the cost and dramatically expand the production and use of SAF. The majority of this program's initiatives focus on increasing the supply of defossilized feedstocks and improving production processes. However, demand-side efforts are also included to build greater support for SAF use by aviation end users and improve efficiencies in fuel use by airlines while simultaneously increasing SAF supply. These federal efforts are also being matched by private investments (Gelles 2023) and international commitments. For example, airlines, fuel suppliers, and air transport operators have formed alliances to commit to purchasing SAF, and the EU recently set binding targets on SAF use by European airports (World Economic Forum 2023; Meijer and Abnett 2023). While significant investments are still required to meet the U.S. domestic production target of 3 billion gallons per year by 2030, the integrated federal strategy in place to get there is unique in the chemicals sector.

# Discussion

## The chemical industry needs a comprehensive decarbonization plan

The chemical industry is responsible for more than a quarter of U.S. gross domestic product and almost 10% of U.S. exports (American Chemistry Council 2023). Decarbonization of this sector will require policy developments on multiple fronts given the volume of products and the intersecting waste, toxicity, and climate threats that business-as-usual strategies pose. The Inflation Reduction Act of 2022, the Bipartisan Infrastructure Law of 2021, and other recent federal investments are important steps toward national and international climate goals. However, continued progress on industrial decarbonization—particularly for chemicals—will require new targeted policies beyond what currently exists, on both the supply and demand sides of the chemicals market.

***The hardest-to-abate and most economically productive industrial sector—chemicals—should form the foundation of domestic industrial decarbonization strategy.***

The United States lacks a coordinated roadmap to decarbonize the chemicals industry. As we have shown in our review of existing programs, a significant number of efforts are spread across federal agencies, but there is no national action plan that captures the complexities of varying chemical value chain products and can scale new processes. For example, while there are many federal programs aimed at developing defossilized feedstocks, the only major implementation support for defossilized feedstocks is in the SAF value chain. Barring additional tax credits or guaranteed offtakers for products made from defossilized feedstocks, other sectors of the chemical industry will likely remain hesitant to switch to these more expensive sources of carbon (Rosenboom, Langer, and Traverso 2022). Abundant, low-cost shale gas has led to low-cost energy and feedstocks for domestic chemical facilities, but those same cheap inputs can make the business case for investing in a transition to defossilized feedstocks more challenging.

[6] U.S. Department of Transportation (DOT), Department of Agriculture (USDA), and Department of Energy (DOE), and Environmental Protection Agency (EPA).

***Congress, federal agencies, and chemical industry stakeholders should work together to develop a national strategy capable of meeting emissions reduction targets while ensuring that critical products can be produced safely and sustainably.***

Barring strong federal leadership, the United States risks falling behind its European and Asian counterparts in RD&D investments to modernize the chemical industry. For example, the European Commission's *Transition Pathway for the Chemical Industry* places this hard-to-abate sector at the center of the EU's industrial decarbonization strategy (European Commission 2023b). This effort aligns EU-wide sustainability and regulatory policies, strategies, and action plans toward chemical industry challenges and needs. Separate waste management, biodiversity, food system safety, and regulation and governance reform strategies can all support chemical industry progress toward carbon neutrality, but the transition pathway identifies critical gaps, including the additional enabling policy required to fully leverage these resources.

The embedded nature of chemicals throughout our economy means that as the chemicals sector becomes more sustainable, it can pull the rest of the economy along with it. This will require clear goals, industry buy-in, and substantial additional investment—an estimated $759 billion in additional global investment in comparison to business-as-usual—to achieve a net-zero petrochemicals sector by 2050 (Henze 2022).

## Three federal policy strategies to accelerate chemical industry decarbonization

In addition to developing a comprehensive chemicals decarbonization roadmap, decision makers in Congress and across federal agencies should work to implement a range of strategies in the United States. Following are three federal policy strategies that we have identified as priorities.

### *Invest in the emission tracking infrastructure necessary for a decarbonized chemical industry*

Federal support will be needed to enhance tracking and measuring of embodied carbon emissions in chemical products**.** Current federal legislative efforts to create actionable and accurate carbon emissions data includes the PROVE IT Act (Sen. Coons 2023). This effort is the first step for industry to develop Scope III emissions targets, and it rewards first-movers willing to make the investments to reduce emissions. Currently, bulk chemicals are treated as interchangeable commodities, and facility-level data on product carbon intensities are not readily available. This makes it very difficult for consumers to choose more sustainable products or for procurement policies built on carbon intensity to be implemented.

Carbon emissions data could also help U.S. companies comply with international carbon tariffs, such as the EU's Carbon Border Adjustment Mechanism (European Commission 2023a), which currently applies to fertilizer and could extend to organic chemicals and polymers. The U.S. chemical industry can benefit from these trade policies if production of bulk chemicals is less carbon intensive than in other countries; for example, the vast majority of China's ammonia is produced from coal, making this basic chemical much more carbon-intensive than the natural-gas-based ammonia produced in the United States (Young, Remillard, and Harry 2023). Without a much clearer picture of chemical industry carbon intensity and toxicity hotspots, the United States risks stranding carbon-intensive and toxic assets and falling behind on research and development to create new innovative, sustainable chemistries and manufacturing processes, especially as other key markets for U.S. product exports (e.g., the EU and Japan) move toward mandatory Scope III disclosure rules.

## *Incentivize process heat electrification and the commercialization of new transformative chemical manufacturing pathways*

A quarter of the chemical sector's carbon emissions come from facility energy consumption. Decarbonizing the grid could address up to one-third of these energy emissions; solving the challenge of process heating within facilities will be essential to address the remainder.

Today, production tax credits available to the chemical industry are limited to clean energy generation, clean hydrogen, carbon capture, and SAF production. No comparable federal support exists for technology pathways that avoid carbon emissions through electrifying process heat or replacing virgin fossil fuel feedstocks unless they are applied to manufacturing SAF (Ma 2024). This limits the expansion of decarbonization technologies across the sector, as strategies that convert waste carbon to SAF could also apply to various other petrochemical-based value chains. As table 4 shows, facilities that are demonstrating these processes in other value chains at scale today are all located in other countries, where governments have provided more direct support for scaling up new technologies in the chemical industry across a range of value chains.

**Table 4. Examples of innovative defossilized plastic resin manufacturing processing at demonstration or commercial scale**

| Country | Company | Scale | Start date | Annual capacity |
|---|---|---|---|---|
| Denmark | Braskem and Haldor Topsoe | Demonstration | 2020 | Hundreds of tons of renewable glycolaldehyde per year, precursor to monoethylene glycol (MEG) (precursor to PET plastic)[1] |
| Netherlands | Avantium | Demonstration | 2020 | 11 tons of renewable MEG[2] |
| China | Shougang LanzaTech | Commercial | 2018 | 210,000 tons of ethanol from waste carbon across three plants[3] |
| Three plants planned for either Asia, Europe, Brazil, or the United States | Sustainea | Commercial | 2026 | 700,000 tons of renewable MEG[4] |

Sources: [1]Bailey 2019, [2]Avantium 2024, [3]Shougang Group 2023, [4]Braskem 2022

## *Identify high-value chemical value chains for focused investments and demand-side market support*

The United States should target emission reduction efforts at chemical value chains essential to high-value end markets—such as pharmaceuticals or semiconductors—and build mechanisms to verifiably link sustainable intermediate bulk chemical use to the end user. These higher-value products could provide the initial offtake market for lower-emission but higher-price bulk chemicals.

Establishing a market for more sustainable bulk chemicals is unlikely to happen organically because the end-use market segments are extremely disaggregated.[7] Benzene, a primary bulk chemical, illustrates a typical supply chain arrangement in the chemicals sector. As a precursor to many different intermediate chemicals such as phenol, styrene, and cyclohexane, benzene is split across a wide array of product markets, from cosmetics to tires to fabrics (see figure 3). Each individual market might require a different strategy to drive demand for more sustainable products, and each individual producer will have different business cases for sustainability.

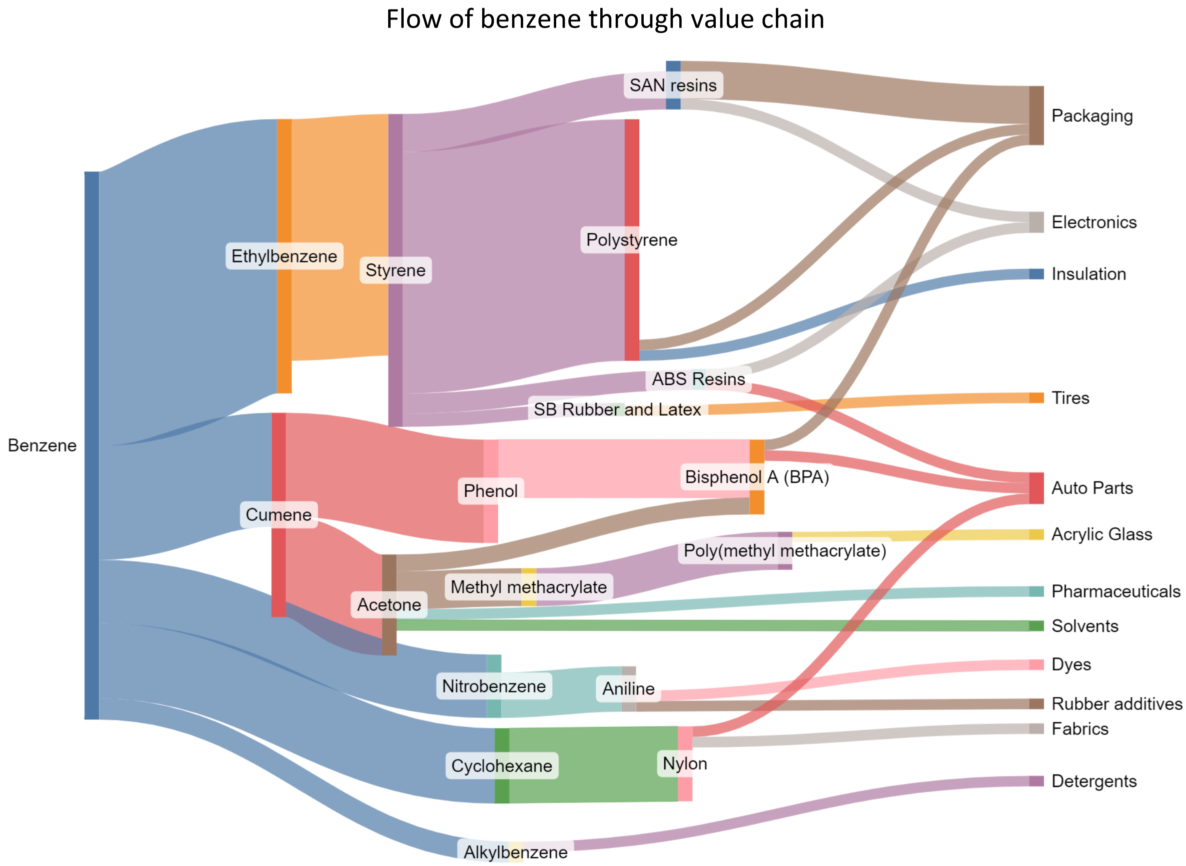


**Figure 3. An example of how a single bulk chemical is split into a wider and wider array of individual chemicals and end-user products. To most effectively integrate supply- and demand-side interventions, we believe that focusing on specific higher-value product market segments and working backward to the most essential bulk and intermediate chemicals will be a more effective initial strategy for catalyzing change at scale across chemical value chains. For sources, see Appendix B.**

[7] In some rare cases, a single major end-use demand consumes the vast majority of a basic chemical; for example, about 70% of ammonia is used for fertilizer.

The high efficiency and low profit margin inherent to bulk chemicals complicates the business case for first movers decarbonizing their manufacturing processes. However, since chemicals are used by such a large swathe of the economy, there are high-margin sectors that could be well positioned to be the offtakers for the initial build-out of sustainable bulk chemical production. In some cases, reducing emissions could be extremely economical per unit of higher-value products.

For example, the cost of abating nitrous oxide[8] emissions from the production of adipic acid, a precursor to nylon, in vehicle manufacturing in China was estimated to add just $0.40 per vehicle (nylon is incorporated into airbags, car seats, and tires). This is compared to the additional $34 per ton of nylon—a 1% cost increase—if the bulk chemical producers themselves shouldered the additional abatement cost burden.

This particular abatement example, however, did not require a full transformation of manufacturing processes that other technologies (e.g., electric crackers; Gallucci 2023) would require, suggesting that the cost increase for bulk chemicals could be much more substantial for other decarbonization strategies. Higher-value product markets, such as vehicle manufacturing, can more easily absorb the investment costs of supply-side interventions and be a driver of emissions reductions if a successful awareness campaign were mounted. For automakers, eliminating nitrous oxide emissions embodied in the nylon used for airbags, car seats, and tires would reduce 5% of total embodied carbon per vehicle, supporting sustainability goals and Scope III emissions reductions goals for automakers (Hasanbeigi and Sibal 2023).

The federal government should identify additional materially important chemical value chains in which demand-side markets can be engaged to enhance market signals for more sustainably produced chemical components. Among the available tools to this end are expanded public procurement programs or technical assistance to key regions and states to help coordinate defossilized feedstock production, as well as clean energy planning strategies that deliver tangible community benefits and build a cleaner, more resilient chemical manufacturing ecosystem.

# Conclusions

The chemicals industry is not on a trajectory to reach net-zero emissions targets by 2050 (International Energy Agency 2023a). In the United States, we lack strong frameworks for driving the overall chemical sector's decarbonization progress in line with these national targets. We also lack policy tools to incentivize the development and deployment of innovative chemistries and production processes that lead to less toxic chemical products. While the bulk of investments will need to come from the private sector, federal support is key for signaling markets, ensuring a suitably broad portfolio of RD&D strategies, and coordinating policy and regulatory strategies across agencies.

Different chemical value chains will require different strategies, based on variation in end-use markets and production pathways. More so than other sectors, the chemical sector requires a wide range of policy approaches to achieve sector-level progress. Certain portions of the chemicals manufacturing ecosystem, such as SAF, have a robust, cross-cutting national roadmap toward decarbonization, with individual policies and strategies touching on all aspects of the manufacturing ecosystem, but more of these sector-specific plans are needed. Additional cross-cutting federal tools are also needed to support

[8] Nitrous oxide is a GHG with a global warming potential 265 times greater than that of carbon dioxide.

consistent Scope III emissions accounting. Such tools are needed to improve purchasers' ability to discern which bulk chemicals are manufactured sustainably as well, and to discern how supply-side investments in sustainability impact their own supply chain emissions and contribute to achieving corporate sustainability goals.

The ubiquity of chemicals in our economy is an opportunity for policymakers to implement a decarbonization strategy that could profoundly benefit communities across the country. Reducing carbon emissions from the chemicals industry could also address other environmental crises, including the expanding footprint of plastic waste and the exposure of frontline communities to toxic emissions from chemical manufacturing plants. Investing in sustainable chemical production in the United States will ensure that this industry continues to contribute to the economy and produce essential products, while limiting long-term damage to human health and the environment.

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# Appendix A. Federal chemical programs

### Table A1. Federal chemical programs

| Agency | Office | Program | Focus | Description |
|---|---|---|---|---|
| Commerce | National Institute for Standards and Technology (NIST) | NIST Chemicals Program | Policy guidance, research, regulation | This program develops databases, standards, research, and measurement tools used throughout the chemical industry; its offerings include the Chemistry WebBook. |
| Department of Defense (DOD) | Office of the Assistant Secretary of Defense | Environmental Security Technology Certification Program (ESTCP) | Research, grants, policy guidance | The program's goal is to identify and demonstrate the most promising innovative and cost-effective technologies and methods that address DOD's high-priority environmental requirements, including those for more sustainable chemistry. Projects conduct formal demonstrations at DOD facilities and sites in operational settings to document and validate improved performance and cost savings. |
| | Office of the Assistant Secretary of Defense | Strategic Environmental Research and Development Program (SERDP) | Research, grants, policy guidance | SERDP invests across a broad spectrum of basic and applied research, as well as in advanced development to improve the DOD's environmental impact, health, and sustainability. |
| | Army | Safe Alternative for Readiness (SAFR) Program | Grants | This U.S. Army program funds demonstration and validation efforts for sustainable alternatives used by the military in coatings, metal finishing, munitions, and other supply needs. |
| | Defense Logistics Agency | Chemical Intelligence Program | Research | This program's goal is to obtain, process, and store digital data of the full formulation for all products (chemicals, articles, weapons, etc.) purchased by the DOD. This information will reduce supply chain vulnerabilities and improve environmental management of chemicals. |
| Department of Energy (DOE) | Advanced Materials & Manufacturing Technologies Office (AMMTO) | REMADE Institute | Research | This public–private partnership works on material design and products to facilitate their efficient recycling. |
| | Advanced Research Projects Agency-Energy (ARPA-E) | REUSE Program | Research | This program supports research to convert high-energy materials currently going to landfills to a high-energy content liquid product capable of displacing energy imports used for fuel or chemical production. |
| | Bioenergy Technologies Office (BETO) | Agile BioFoundry (ABF) Consortium | Research | This research focuses on a set of organisms for the production of sustainable aviation fuel (SAF) via ethanol and lipids, and production of chemical intermediates that can significantly reduce greenhouse gas (GHG) emissions and demonstrate industrially relevant titers, rates, and yields. |
| | | Development of Integrated Screening, Cultivar Optimization, and Verification Research (DISCOVR) Consortium | Research | Research to scale-up integrated biorefineries. |

| Agency | Office | Program | Focus | Description |
|---|---|---|---|---|
| | | Billion-Ton Study | Research | This series of analyses builds on the *2016 Billion Ton Report* and addresses carbon sequestration, environmental justice, climate change, and end uses such as SAFs. |
| | | Feedstock-Conversion Interface Consortium (FCIC) | Research | An integrated and collaborative network of nine U.S. DOE National Laboratories dedicated to addressing the technical risks that integrated pioneer biorefineries face. |
| | | Lignin Utilization research | Research | This work focuses on developing industrially relevant processes and tools for viable lignin valorization. |
| | | Chemical Catalysis for Bioenergy (ChemCat Bio) consortium | Research | This research aims to accelerate catalyst and process development for bioenergy applications, with a focus on SAF, marine/heavy duty fuels, and renewable chemicals. |
| | | Clean Fuels & Products Shot | Research, grants, policy guidance | The Energy Earthshot™ initiative focuses on decarbonizing the chemicals supply chain by advancing cost-effective technologies that use alternative sources of carbon. |
| | | BOTTLE consortium | Research | Jointly funded with the AMMTO, this effort will continue to develop biobased plastics designed with superior recyclability and biodegradability, as well as new methods to recycle and upcycle existing plastic waste. |
| | | Sustainable Aviation Fuel (SAF) Grand Challenge | Research, grants, policy guidance | This collaboration with DOT, USDA, and DOE aims to reduce cost, enhance sustainability, and expand domestic production and use of SAF to meet greater than 10% of domestic aviation fuel demand by 2030, and 100% of domestic aviation fuel demand by 2050. |
| | Biomass Research and Development Board | Sustainable Aviation Fuel Interagency Working Group | Policy guidance | An interagency team led by the DOE, DOT, and USDA works with EPA, other government agencies, and stakeholders from national labs, universities, nongovernmental organizations, and the aviation, agricultural, and energy industries to guide federal RD&D for SAF, including the SAF Grand Challenge. |
| | Energy Efficiency and Renewable Energy (EERE) | Industrial Heat Energy Earthshot | Research, grants, policy guidance | Industrial Heat Shot™ aims to develop cost-competitive industrial heat decarbonization technologies with at least 85% lower GHG emissions by 2035. |
| | | Clean Hydrogen Electrolysis Program | Grants | This program aims to establish a research, development, demonstration, commercialization, and deployment program for purposes of commercialization to improve the efficiency, increase the durability, and reduce the cost of producing clean hydrogen using electrolyzers. |
| | | Clean Hydrogen Manufacturing Recycling Research, Development, and Demonstration Program | Grants | The Clean Hydrogen Manufacturing Recycling Program is designed to provide federal financial assistance to advance new clean hydrogen production, processing, delivery, and storage, and to use equipment manufacturing technologies and techniques. |
| | | Strategy for Plastics Innovation | Policy guidance | This DOE-coordinated strategy for plastics research is focused on four areas: deconstruction, upcycling, recyclable by design, and scale and deploy. |
| | Fossil Energy and Carbon Management (FECM) | Natural Gas Decarbonization and Hydrogen Technologies (NGDHT) Program | Research and interagency coordination | The program coordinates with other DOE offices to support the transition toward a clean hydrogen-enabled economy through the decarbonization of natural gas conversion, transportation, and storage. |
| | | Carbon Dioxide Conversion | Grants and research | This effort targets lab- and bench-scale projects to advance carbon conversion technologies. |

| Agency | Office | Program | Focus | Description |
|---|---|---|---|---|
| | | Regional DAC Hubs | Grants and research | This nationwide network of large-scale carbon removal sites aims to address legacy carbon dioxide pollution and complement rapid emissions reductions. |
| | | UpGrants Program | Grants | This program supports products made from $CO_2$, with $100 million available to states, local governments, public agencies, and utilities to purchase products derived from converted $CO_2$ emissions. Product life-cycle assessments (LCAs) are approved by National Energy Technology Laboratory (NETL). |
| | | Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy | Research | This program focuses on use of hydrogen systems to convert various waste materials—such as biomass, plastics, common household garbage, and other wastes—into clean energy. |
| | Hydrogen and Fuel Cell Technologies Office (HFTO) | Industrial and Chemical Applications Research | Research | The effort focuses on industry-led projects to demonstrate use of clean hydrogen as a feedstock or direct reducing agent to decarbonize ammonia and steel production, in collaboration with other offices. |
| | Industrial Efficiency & Decarbonization Office (IEDO) | Enabling Technologies for Low Carbon Fuels and Feedstock | Grants | Decarbonized combined heat and power (CHP): RD&D and technical assistance for hydrogen or renewably fueled CHP for industry. |
| | | Rapid Advancement in Process Intensification Deployment (RAPID) Institute | Research | This research effort focuses on creating efficient, integrated processes via advanced reactors and separators that can utilize low-carbon energy sources and sustainable feedstocks. |
| | | Cross Sector Technologies | Research | This work supports high-impact, applied research, development, and pilot demonstration (RD&D) projects that will help drive the transformational cross-sector technologies and innovations required to reduce energy use and GHG emissions across the industrial sector. |
| | | Industrial Technology Innovation Advisory Committee | Policy guidance | This committee advises the Secretary of Energy with respect to the Industrial Emissions Reductions Technology Development Program. |
| | | Energy- and Emissions-Intensive Industries | Research | This research funding is aimed at achieving carbon pollution-free electricity by 2035. |
| | Loan Programs Office (LPO) | Loan Program Office (LPO) | Loans and grants | The LPO provides financing to large-scale energy infrastructure. |
| | Manufacturing and Energy Supply Chains (MESC) | Advanced Energy Project Credit (48C) | Tax credit | This is a 30% investment tax credit for manufacturing projects producing fuel cell electric vehicles, hydrogen infrastructure, electrolyzers, and a range of other products. |
| | National Energy Technology Laboratory (NETL) | National Carbon Capture Center (NCCC) | Research | Created by the DOE but managed and operated by Southern Company, the NCCC conducts research and testing to accelerate commercialization of technology to reduce GHG and to utilize captured carbon dioxide as a feedstock. |
| | Office of Clean Energy Demonstrations (OCED) | Industrial Demonstrations Program | Grants | This program provides competitive financial support to owners and operators of energy-intensive industrial facilities for high-impact, transformational projects to significantly reduce GHG emission. |
| | | Carbon-Capture Large-Scale Pilot Projects | Grants | Carbon Capture Large-Scale Pilots aim to significantly reduce $CO_2$ emissions from electricity generation and hard-to-abate industrial operations. |

| Agency | Office | Program | Focus | Description |
|---|---|---|---|---|
| | | Hydrogen Hubs | Grants | These grants target commercial-scale deployment of clean hydrogen helping to generate clean, dispatchable power, create a new form of energy storage, and decarbonize heavy industry and transportation. |
| | Office of Nuclear Energy | Advanced Reactor Demonstration Program | Grants and research | The program focuses on demonstration projects for advanced reactors through cost-shared partnerships with U.S. industry. |
| | Office of Policy (OP) | Industrial Decarbonization Coordination | Policy guidance | This effort aims to support long-term climate strategy development and interagency coordination. OP also focuses on the Energy Earthshots Initiative, the National Climate Strategy documents, Communities Local Energy Action Program (LEAP), and resources for energy communities. |
| | Office of Science | Bioenergy Research Centers | Research | This effort focuses on developing research across four centers to advance bioenergy sustainability, feedstock development, deconstruction and separation, and conversion. |
| | Office of Technology Transitions (OTT) | Pathways to Commercial Liftoff Reports | Policy guidance | These reports focus on the chemicals and refining sector's opportunities for decarbonization, including which technologies are commercially available. |
| Department of Transportation (DOT) | Federal Aviation Administration (FAA) | Fueling Aviation's Sustainable Transition through Sustainable Aviation Fuels (FAST-SAF) | Grants | This program provides grant funding for projects relating to the production, transportation, blending, or storage of SAF, with the goal of accelerating SAF production and use, and reducing the aviation sector's GHG emissions. |
| | | Fueling Aviation's Sustainable Transition – Technology (FAST-Tech) | Grants | This effort offers grant funding for projects that develop, demonstrate, or apply low-emission aviation technologies, which are technologies that significantly improve aircraft fuel efficiency or reduce GHG emissions during the operation of civil aircraft. |
| | | Continuous Lower Energy, Emissions, and Noise (CLEEN) Program | Research, grants, policy guidance | This program is the FAA's principal environmental effort to accelerate the development of new aircraft and engine technologies that will reduce noise, emissions, and fuel burn. |
| | | Aviation Sustainability Center (Ascent) | Research, grants, policy guidance | This cooperative aviation research organization is co-led by Washington State University and the Massachusetts Institute of Technology. |
| Environmental Protection Agency (EPA) | Environmental Protection Agency (EPA) | Toxics Release Inventory – Toxics Tracker | Regulation/guidance | This EPA database allows communities and researchers to track toxic release inventory (including GHGs). |
| | | P2 Grant Program | Regulation/guidance, grants | Pollution Prevention (P2) grants provide technical assistance to businesses to help them develop and adopt source reduction practices. |
| | Office of Chemical Safety and Pollution Prevention | Environmental Product Declaration Assistance | Policy guidance | This assistance is aimed at supporting the development and standardization of environmental product declarations, including measurements of the embodied GHG emissions of construction materials and products. |
| | | Low Embodied Carbon Labeling for Construction Materials | Policy guidance | The effort aims to develop and carry out a program to identify and label construction materials and products that have substantially lower levels of embodied GHG emissions. |
| | | Chemical Health Risk Review | Regulation/guidance | The EPA is responsible for reviewing all new chemical submissions before they enter commerce to determine whether the chemicals may pose unreasonable risks to human health or the environment. |

| Agency | Office | Program | Focus | Description |
|---|---|---|---|---|
| Federal Trade Commission (FTC) | Green Marketing Office | Green Guides | Regulation/guidance | These publications offer companies regulation information and guidance on environmental product marketing. |
| Internal Revenue Service (IRS) | Internal Revenue Service (IRS) | 45V Hydrogen Production Tax Credit | Tax credit | This tax credit is a new 10-year incentive for clean hydrogen production, with up to $3.00/kilogram. Projects can also elect to claim up to a 30% investment tax credit under Section 48. |
| | | Carbon Capture and Sequestration Tax Credit (45Q) | Tax credit | This tax credit is for carbon dioxide captured for storage and utilization for qualified facilities through 2032. |
| | | Sustainable Aviation Fuel (SAF) Tax Credit | Tax credit | The SAF credit is $1.25 for each gallon of SAF in a qualified mixture. To qualify for the credit, the SAF must have a minimum reduction of 50% in lifecycle GHG emissions. There is also a supplemental credit of one cent for each percentage point that the reduction exceeds 50%. |
| U.S. Department of Agriculture (USDA) | Rural Business-Cooperative Service | Biofuel Infrastructure and Agriculture Product Market Expansion (Higher Blend Infrastructure Incentive Program) | Grants | These grants aim to increase the sales and use of higher blends of ethanol and biodiesel by expanding the infrastructure for renewable fuels derived from U.S. agricultural products and by sharing the costs related to building out biofuel-related infrastructure. |
| | Rural Development | Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program | Loans and grants | This program provides loan guarantees up to $250 million to assist in the development, construction, and retrofitting of new and emerging advanced biofuel, renewable chemicals, and biobased product technologies. |
| White House | National Science and Technology Council | Sustainable Chemistry Report: Framing the Federal Landscape | Policy guidance | This state-of-science report includes gaps and opportunities for the federal government relating to "sustainable chemistry." The Sustainable Chemistry report will develop a strategic plan for how the federal government can leverage these opportunities in order to make significant progress in addressing the identified data gaps. |
| | Office of Clean Energy and Innovation | Office of Clean Energy and Innovation | Policy guidance | This effort coordinates Inflation Reduction Act (IRA) program implementation and clean energy progress across federal government. |

# Appendix B. Figure 3 data sources and methodology

The benzene Sankey diagram was produced using the free online tool: https://sankeymatic.com/build. Estimates on global benzene production and its flow are compiled from publicly available sources and published journal articles. The chemical supply chain is difficult to model because much of the data are proprietary, the products flow through multiple stakeholders, and the production pathways are complex and intertwined. Developing this model required making assumptions and estimates of production processes.

## Data sources and methods

The initial benzene estimate is 51 Mt/year produced annually; this is sourced from RMI's *Emissions Out the Gate Report* (https://rmi.org/insight/emissions-out-the-gate).

Table B1 includes the sources and input weight calculations used to model the flow of benzene through the value chain.

**Table B1. Modeling the flow of benzene through the value chain**

| Level 2 chemical | Global production capacity estimate (Mt/year) | % of benzene demand | Benzene consumed (Mt) | Input weights/feedstock (to produce 1 unit) | Source | Notes |
|---|---|---|---|---|---|---|
| Ethylbenzene | 33 | 0.647058824 | 26.004 | 28.3 wt.% ethylene and 78.8 wt.% benzene | 2019. *Emissions Out of the Gate* (RMI) | Most ethylbenzene is made from the reaction of ethylene and benzene, and nearly all of it is used to produce styrene. |
| Cumene | 17 | 0.333333333 | 10.88 | 64 wt.% benzene and 36 wt.% propylene | *Emissions Out of the Gate* (RMI), https://www.pnas.org/doi/abs/10.1073/pnas.2218294120#abstract | The cumene process is the dominant route to phenol ($C_6H_5O$) and acetone ($C_3H_6O$). Cumene (C9H12O) is produced as an intermediate, with benzene ($C_6H_6$) and propylene ($C_3H_6$) being used as feedstocks. |
| Nitrobenzene | 6 | 0.117647059 | 6 | 100wt% benzene and nitric acid | *Emissions Out of the Gate* (RMI) | This is primarily an intermediate to produce aniline. Aniline is produced industrially in two steps, first via nitration of benzene ($C_6H_6$) using nitric acid ($HNO_3$) to form nitrobenzene ($C_6H_5NO_2$), followed by hydrogenation of nitrobenzene to form aniline (C6H7N). |
| Cyclohexane | 7.6 | 0.149019608 | 7.144 | 94 wt.% benzene | 2013. https://pu | Nearly all cyclohexane is produced via the |

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| | | | | | bs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | hydrogenation ($H_2$) of benzene ($C_6H_6$). This estimate is comparable to RMI's 2019 global production estimate of 7 Mt. |
| Alkylbenzene | 2 | 0.039215686 | 2 | 100wt% benzene | *Emissions Out of the Gate* (RMI) | |
| **Level 3 chemical** | | | | | | |
| Styrene | 27.4 | 0.423356863 | 22.886672 | Ethylbenzene 106 wt.%, (ethylbenzene composed of 28.3% ethylene, 78.8% benzene) | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | This consumes nearly all ethylbenzene. Note: The greater than 100% within input weights accounts for some production loss. |
| Phenol | 10.4 | 0.192705882 | 9.828 | 94.5 wt.% benzene and 48.6 wt.% propylene | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | This is an estimated growth rate of 4%, with 10 Mt yr-1 demand estimate for 2012 quoted. |
| Acetone | 6.1 | 0.188382353 | 9.577 | 157.5 wt.% benzene and 81 wt.% propylene | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | This is produced from benzene and propylene, and is a feedstock for bisphenol A (BPA). |
| Aniline | 4.9 | 0.08454902 | 4.312 | 88 wt.% benzene and 71 wt.% nitric acid | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | Aniline is quoted to account for 10% of benzene demand. Aniline is produced industrially in two steps, first via nitration of benzene ($C_6H_6$) using nitric acid ($HNO_3$) to form nitrobenzene ($C_6H_5NO_2$), followed by hydrogenation of nitrobenzene to form aniline ($C_6H_7N$). |
| **Level 4 chemical** | | | | | | |
| Polystyrene | 27.4 | | 22.9 | 100wt.% styrene | https://pubs.acs.org/ | |

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| | | | | doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | |
| Acrylonitrile butadiene styrene (ABS) resins | 10.4 | 1.9305 | 20 wt.% acrylonitrile, 25 wt.% butadiene, and 55 wt.% styrene | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | 1 acrylonitrile = 1.1 propylene + 0.445 ammonia. Butadiene is a coproduct of ethylene in $C_4$ steam cracking. So ABS benzene demand is solely derived from % benzene from styrene. |
| Styrene acrylonitrile (SAN) resins | 6.1 | 3.66 | 25 wt.% acrylonitrile and 75 wt.% styrene | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | |
| Styrene-butadiene (SB) rubber and latex | 5.5 | 3.2175 | 75% styrene and 25% butadiene | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | https://www.spglobal.com/commodityinsights/en/ci/products/styrene-butadiene-latexes-chemical-economics-handbook.html |
| Bisphenol A (BPA) | 5.5 | 7.05375 | 88 wt.% phenol and 29% acetone | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | |
| Methyl methacrylate (MMA) | 3.2 | 3.5784 | 71% acetone, 40% methyl alcohol, and 21% ammonia | https://pubs.acs.org/doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | This is a chemical intermediate to manufacture other methacrylic monomers, such as PMMA. Also used as a cement in specific medical treatments, orthopedic surgeries (hip, knee), and dental applications. |
| Polyamide 6 (nylon-6) | 7.4 | 7.104 | 102% caprolactam (benzene demand | https://pubs.acs.org/ | https://bibliotekanauki.pl/articles/949465.pdf, |

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| | | | of nylon-6 = 0.96 wt) | doi/suppl/10.1021/acs.est.7b04573/suppl_file/es7b04573_si_001.pdf | Combining both Nylon-6 and Nylon-66 production in Sankey figure. |
| Polyamide 66 (nylon-66) | 7.4 | 7.1 | 66% adipic acid and 52% hexamethylene diamine | https://www.spglobal.com/commodityinsights/en/ci/products/nylon-fibers-chemical-economics-handbook.html | The global market for nylon fibers is expected to grow at an average annual rate of about 2.5% during 2022–27. Nylon resin is turned into nylon fibers, which are used in textile fibers, industrial filaments, and other filaments, such as bulk continuous filament used in carpet manufacture. |