

OPPORTUNITIES AND LIMITS OF CO₂ RECYCLING IN A CIRCULAR CARBON ECONOMY: TECHNO-ECONOMICS, CRITICAL INFRASTRUCTURE NEEDS, AND POLICY PRIORITIES

BY AMAR BHARDWAJ, DR. COLIN MCCORMICK,
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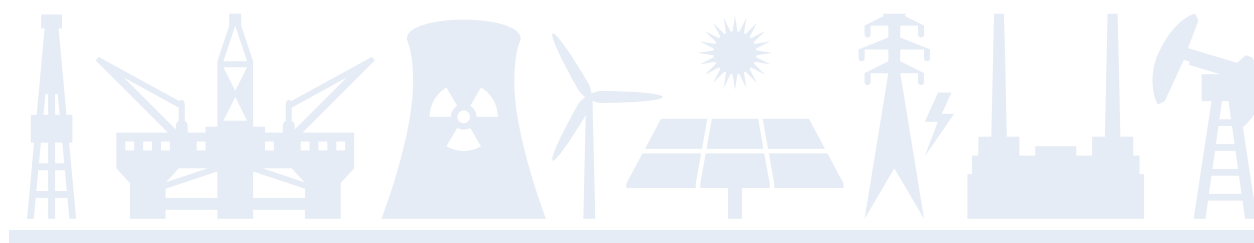
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This report represents the research and views of the authors. It does not necessarily represent the views of the Center on Global Energy Policy. The paper may be subject to further revision.

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EXECUTIVE SUMMARY

Despite growing efforts to drastically cut carbon dioxide (CO₂) emissions and address climate change, energy outlooks project that the world will continue to rely on certain products that are currently carbon-intensive to produce but have limited alternatives, such as aviation fuels and concrete. Recycling CO₂ into valuable chemicals, fuels, and materials has emerged as an opportunity to reduce the emissions of these products. In this way, CO₂ recycling is a potential cornerstone of a circular carbon economy that can support a net-zero future. However, CO₂ recycling processes have largely remained costly and difficult to deploy, underscoring the need for supportive policies informed by analysis of the current state and future challenges of CO₂ recycling.

This report, part of the Carbon Management Research Initiative at Columbia University's Center on Global Policy, examines 19 CO₂ recycling pathways to understand the opportunities and the technical and economic limits of CO₂ recycling products gaining market entry and reaching global scale. The pathways studied consume renewable (low-carbon) electricity and use chemical feedstocks derived from electrochemical pathways powered by renewable energy. Across these CO₂ recycling pathways, the authors evaluated current globally representative production costs, sensitivities to cost drivers, carbon abatement potential, critical infrastructure and feedstock needs, and the effect of subsidies. Based on this analysis, the paper concludes with targeted policy recommendations to support CO₂ recycling innovation and deployment.

Key findings of the analysis include the following:

- **CO₂ recycling pathways could deliver deep emissions reductions.** When supplied by low-carbon electricity and chemical feedstocks, CO₂ recycling pathways have the combined potential to abate 6.8 gigatonnes of CO₂ per year (GtCO₂/yr) when displacing conventional production methods.
- **Some CO₂ recycling pathways have reached market parity today, while the costs of remaining pathways are high.** Electrochemical carbon monoxide (CO) production, ethanol from lignocellulosic biomass, concrete carbonation curing, and the CarbonCure concrete process all have an estimated cost of production (ECOP) lower than the product selling price. These pathways have a combined carbon abatement potential of 1.6 GtCO₂/yr. Most remaining pathways have an ECOP of 2.5 to 7.5 times greater than the product selling price. In particular locations and contexts, ECOP may be substantially lower, but these costs are representative of CO₂ recycling at global scale.
- **Catalyst performance and input prices are the main cost drivers.** The largest component of ECOP is electricity and chemical feedstock costs, and the main cost drivers are those who influence these two cost components. For electrochemical pathways, ECOP is most sensitive to catalyst product selectivity (the ability of the catalyst to avoid unwanted side reactions), catalyst energy efficiency, and electricity



price. For thermochemical pathways, the largest cost drivers are product selectivity, chemical feedstock price, and the price of the electricity used to make the feedstocks.

- **CO₂ recycling at the scale of current global markets would require enormous new capacity of critical infrastructure.** Each pathway at global scale would consume thousands of terawatt hours of electricity, 30–100 million metric tons (Mt) of hydrogen, and up to 2,000 Mt of CO₂ annually. This would require trillions of dollars of infrastructure per pathway to generate and deliver these inputs, including a combined 8,400 gigawatts (GW) of renewable energy capacity and 8,000 GW of electrolyzer capacity across all pathways.

Based on these findings, the authors recommend the following set of policy actions:

- **Ensure CO₂ recycling pathways are fed by low-carbon inputs.** Without low-carbon electricity and feedstocks, CO₂ recycling could potentially be more carbon-intensive than conventional production.
- **Prioritize certain pathways strategically.** CO₂ recycling methane and ethane production are extremely uneconomic and should be deprioritized. All other pathways are more economically promising and could be the focus of a targeted innovation agenda to reduce costs. In addition, the following pathways that have an ECOP less than 5 times the selling price could be prioritized for early market growth: electrochemical CO production, green hydrogen, ethanol from lignocellulosic biomass, concrete carbonation curing pathways, CO₂ recycling urea production, and CO₂ hydrogenation to light olefins, methanol, or jet fuel.
- **Target research, development, and demonstration (RD&D) to catalyst innovation to bring down ECOP and reduce input demand.** Policy makers can promote RD&D to improve the selectivity and energy efficiency of CO₂ recycling catalysts. By decreasing a pathway's consumption of electricity and feedstocks, these innovations would both decrease ECOP and alleviate the sizable critical infrastructure needs.
- **Create demand pull for early market CO₂ recycling products.** Governments can use demand pull policies such as public procurement standards to bolster early markets for the most mature CO₂ recycling pathways.
- **Promote build-out of critical infrastructure.** To provide for the substantial infrastructure needs of CO₂ recycling, policy makers can seek to remove barriers to and catalyze investment in building renewables installations, transmission lines, electrolyzers, and CO₂ transport pipelines.



INTRODUCTION

To mitigate the severe consequences of the climate crisis, the world must reach net-zero greenhouse gas emissions by midcentury and net-negative emissions shortly thereafter.¹ Current decarbonization efforts have focused on efficiency improvements (e.g., US CAFE standards and appliance standards), increased build-out of renewable electricity (e.g., Germany's Energiewende), and electrification of heating and automobiles. Many studies indicate that despite recent progress, existing policies will leave substantial residual emissions in some sectors, such as heavy-duty transportation or heavy industry, that are either expensive or infeasible to completely decarbonize.² Moreover, many products in our day-to-day lives, be they chemicals, fuels, or materials, contain substantial carbon volumes themselves that will eventually oxidize and form CO₂ in the atmosphere.

One way to abate emissions from these sectors involves CO₂ recycling, wherein CO₂ is converted into valuable chemicals, fuels, and materials and used in commercial products.³ The CO₂ used can be sourced from point-source emitters such as fossil power plants or be drawn directly out of the atmosphere or oceans. This can be considered a component of a circular carbon economy that includes CO₂ reduction, reuse, recycling, and removal.⁴ By consuming CO₂ as a feedstock, these pathways could replace difficult-to-decarbonize products and processes with low-carbon, carbon neutral, or net carbon-negative alternatives. Since CO₂ recycling products can help reduce sources of residual emissions, as in the potential case of producing net neutral fuels for the transportation sector, these pathways will be crucial to achieving net-zero emissions.

CO₂ recycling pathways include many processes and products with different costs, viability, and carbon footprints. To contribute meaningfully toward deep decarbonization, CO₂ recycling pathways must be deployed on the gigatonne scale and must operate with extremely low-carbon energy and material inputs.⁵ Investment and commercialization of CO₂ recycling requires a measured approach informed by chemistry, engineering, and economics. A misunderstanding of the merits and limitations of each pathway risks poor use of capital, lost time, and ineffective carbon abatement measures, limiting the abatement achieved through CO₂ recycling pathways. Coordinating an effort of this scale and complexity will require a comprehensive quantitative analysis of the techno-economics of key CO₂ recycling pathways and the critical infrastructure needed to support them. Several previous studies have investigated the techno-economics of various CO₂ utilization pathways,⁶ but they often do not address a wide range of pathways and do not integrate techno-economic findings with infrastructure needs or broader policy implications.

In this study, we investigate the techno-economics, critical infrastructure needs, and effects of subsidies for 19 of the chemical and industrial CO₂ recycling processes with the largest volume of product demand. These include eight electrochemical pathways and eleven thermochemical pathways. We evaluate the potential for these CO₂ recycling pathways to replace conventional production methods and supply current global demand for their products. We model these pathways to consume renewable electricity and use chemical



feedstocks, such as hydrogen, that are produced electrochemically with renewable electricity. We evaluate several characteristics of each pathway: the current estimated cost of production (ECOP, in \$/metric ton product), global carbon abatement potential, marginal cost of carbon abatement, effective carbon price and scale of subsidies needed to make the pathways profitable, and the critical infrastructure necessary to deploy the pathway at global scale. We also use a cost sensitivity analysis across a range of techno-economic inputs to identify specific innovations that can drive cost reductions for the pathways. We make policy and investment recommendations based on these findings to accelerate deployment of CO₂ recycling across sectors at reasonable costs and ultimately realize gigatonne-scale CO₂ recycling for deep emissions reductions.

Selected CO₂ Recycling Pathways

The CO₂ recycling pathways analyzed in this study are listed in Table 1. We investigated 8 electrochemical pathways and 11 thermochemical pathways. Each pathway is defined by the pairing of a chemical process (e.g., CO₂ hydrogenation) and its desired product (e.g., methanol). Several of the chemical processes can be adapted to target various products, and in these cases, we evaluate each process-product pairing as a distinct pathway. The electrochemical pathways include water electrolysis to produce hydrogen and electrochemical CO₂ reduction, in which CO₂ and water react to produce a range of hydrocarbon products. The thermochemical pathways include CO₂ hydrogenation, which uses CO₂ and H₂ feedstocks to produce various hydrocarbons, and Fischer-Tropsch (F-T) synthesis, which uses syngas (CO and H₂) to create various hydrocarbons. The ethanol from lignocellulosic biomass pathway breaks down and ferments the sugars in lignocellulosic biomass feedstocks, such as agricultural residues, to produce ethanol. The urea production pathway is modeled as a Bosch-Meiser process that uses green ammonia and externally sourced feedstock CO₂. The concrete production pathways are each modifications to one step of conventional concrete production in order to incorporate CO₂ into the concrete. We model these as identical to conventional concrete production, save for the modified CO₂ recycling step. A detailed description of each pathway is included in the appendix.



Table 1: Summary of CO₂ recycling pathways evaluated

Desired product	Process	Feedstocks
Electrochemical pathways		
Hydrogen	Water electrolysis	H ₂ O
Carbon monoxide	Electrochemical (Echem) CO ₂ reduction	CO ₂
Methane	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O
Methanol	Electrochemical CO ₂ reduction in ionic liquid aqueous electrolyte	CO ₂ , H ₂ O
Ethylene	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O
Ethane	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O
Ethanol	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O
Syngas	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O
Thermochemical pathways		
Light olefins incl. ethylene	CO ₂ hydrogenation w green H ₂	CO ₂ , H ₂
Light olefins incl. ethylene	Fischer-Tropsch (F-T) synthesis w electro-syngas	CO, H ₂
Methane	Sabatier process w green H ₂	CO ₂ , H ₂
Methanol	CO ₂ hydrogenation w green H ₂	CO ₂ , H ₂
Ethanol	Lignocellulosic biomass fermentation	Lignocellulosic biomass
Syngas	Reverse water gas shift reaction (RWGS) w green H ₂	CO ₂ , H ₂
Jet fuel	F-T synthesis w electro-syngas	CO, H ₂
Jet fuel	CO ₂ hydrogenation w green H ₂	CO ₂ , H ₂
Urea	Bosch-Meiser process w green ammonia and 100% external CO ₂	CO ₂ , NH ₃
Precast concrete	Concrete carbonation curing	CO ₂ , concrete
All concretes (precast, ready-mix, masonry concrete)	CarbonCure process	CO ₂ , concrete



METHODOLOGY

We designed our analysis in the context of using CO₂ recycling pathways to supply current global demand for their products. Our analysis is outlined here and detailed in the appendix. The general categories of analysis for each CO₂ recycling pathway were current production costs, sensitivities to cost drivers, carbon abatement potential, critical infrastructure and feedstock needs, and the effect of subsidies.

Estimated Cost of Production (ECOP) and Sensitivity Analysis

The current estimated cost of production (ECOP, in \$/metric ton product) for each pathway was determined by estimating the electricity cost, feedstock cost (hydrogen, CO₂, CO, biomass, and/or ammonia), fixed operation and maintenance (O&M) cost, and capital cost per ton of product produced. The key techno-economic inputs used for calculating ECOP were electrical energy efficiency, product selectivity and yield, capacity factor, capital cost, electricity price, and feedstock prices. Product selectivity broadly refers to the percentage of input feedstock and/or energy that goes toward making the desired product as opposed to undesired byproducts. More detailed definitions of the different selectivity metrics we used and how they were calculated can be found in the detailed methodology in the appendix.

To determine the ratio of a certain chemical feedstock consumed by a pathway (in tons of feedstock consumed per ton of product), we divided the ideal feedstock consumption ratio by the appropriate selectivity metric. The ideal feedstock consumption ratio is defined by the reaction's stoichiometry (the ratio of molecules of feedstock to molecules of product in the chemical reaction equation). Dividing by selectivity accounts for the additional feedstock that is consumed to produce reaction byproducts. To calculate CO₂ consumption through this method, we used the carbon selectivity of the pathway—the selectivity to the desired product among all carbon-containing products. This allowed us to exclude the hydrogen evolution side reaction in electrochemical CO₂ reduction, which does not consume CO₂. Similarly, to find the H₂ consumption, we used the hydrogen selectivity, which gives the percentage of input hydrogen that goes to the desired product. This excludes CO₂ conversion to CO in many thermochemical pathways, which does not consume H₂.

For a cost sensitivity analysis, the value of each techno-economic input was increased and decreased by 20 percent, with all else remaining fixed, and the resulting percent change in ECOP was noted. In designing the tool for these analyses, we varied input parameters broadly to understand sensitivities; a future analysis will detail the sensitivities to inputs.

Carbon Abatement Metrics and Effect of Subsidies

The intensive carbon abatement (tCO₂ abated/metric ton product) of each pathway was defined as the net decrease in CO₂ emissions that would result from displacing a conventional production process with a CO₂ recycling pathway that produces the same product. Since a CO₂ recycling product and its corresponding conventional product are functionally identical,



we assume that the emissions associated with the combustion or use of the products (gate to grave emissions) are equivalent. Under this assumption, the change in emissions from displacing conventional processes with CO₂ recycling arises entirely within the cradle to gate life cycle scope. Thus, carbon abatement was calculated through a cradle to gate life cycle assessment incorporating the CO₂ consumed in the chemical reaction, the emissions associated with the generation of renewable electricity consumed in the process, the natural gas-derived process heat emissions, the emissions associated with carbon capture to produce CO₂ feedstock, byproduct CO₂ generation, and the counterfactual cradle to gate emissions of producing the product using a conventional pathway. We multiplied the intensive carbon abatement of a pathway by the global demand for its product to obtain the global carbon abatement potential of the pathway in million metric tons of CO₂ per year (MtCO₂/yr).

The marginal abatement cost (MAC) was found by dividing ECOP by intensive carbon abatement for each pathway. The marginal abatement revenue (\$ of revenue/metric ton product) was calculated by instead dividing the product selling price by the intensive carbon abatement of the pathway. By subtracting the marginal abatement revenue from MAC, we determined the net marginal abatement cost after revenues, which we took as equivalent to the effective carbon price needed for the pathway to reach market parity. Using these effective carbon prices, we plotted the sum of the carbon abatement potentials of all pathways that have reached market parity as a function of carbon price. In the case of repeated products, we excluded the pathway with the higher MAC after revenues. We included both concrete production pathways because they apply to different types of concrete. Separately, we calculated the gross subsidies needed to close the cost-price gap for each pathway by multiplying the difference between selling price and ECOP by the global demand for the product.

Global Critical Infrastructure Needs and Resource Consumption

The current global consumption of each pathway's product was used as a basis for all extensive calculations. Using this basis, the critical infrastructure requirements of renewable electricity generation, electricity transmission, electrolyzer capacity, and CO₂ pipeline transport networks were analyzed for each global-scale process with the goal of providing some coarse estimate of potential costs and infrastructure needs. The global TWh of renewable electricity required for electrochemical pathways was calculated using the electricity consumption per metric ton of product for each pathway, the global consumption volume, the electrical energy efficiency, and the faradaic efficiency—the selectivity of input electrical current to the desired product. For thermochemical pathways, the global renewable electricity consumption is the electricity consumed to produce the pathway's feedstocks plus the comparatively smaller amount of direct electricity consumption of the thermochemical plant. Since the vast majority of conventional chemical production and industrial energy use does not come from electricity,⁷ and current electricity mixes are mostly fossil-based, we assume that the conventional processes being displaced by CO₂ recycling use no renewable electricity. Therefore, all renewable electricity consumption from deploying CO₂ recycling has full additionality. The intensive hydrogen consumption of the thermochemical pathways (tH₂/metric ton product) was found by dividing the stoichiometric hydrogen consumption of the pathway by the hydrogen selectivity. This value was then multiplied by global demand for the



product to determine the global hydrogen consumption of the pathway.

For each pathway, we determined the necessary renewable electricity generation capacity in gigawatts (GW) using the global electricity consumption and the capacity factor. We similarly calculated the needed electrolyzer capacity in GW using the electrolyzer electricity consumption associated with the pathway and the capacity factor. We translated these GW capacity values into total capital costs by multiplying the capacity by the unit capital cost (\$/kW). The capital cost of the necessary CO₂ transport pipeline infrastructure for each pathway is based on the global CO₂ consumption of the process. The global CO₂ consumption was found by multiplying the global product demand by the units of feedstock CO₂ consumed to produce one unit of product. The CO₂ transport capital cost was then calculated by multiplying global CO₂ consumption by a CO₂ pipeline network capital cost of \$42/tCO₂/yr capacity.⁸ This capital cost is based on a CO₂ pipeline network capable of transporting 20 MtCO₂/yr, consisting of a 500 km central spine with two 10 km distribution pipelines on each end.⁹ This provides a minimal cost estimate, as lower capacity, smaller diameter pipelines would cost more.

We also determined the total infrastructure costs, GW capacities, and carbon abatement potential summed across all CO₂ recycling pathways. In the case of multiple pathways that produce the same product, we included only the pathway with the largest value being summed and excluded the others from the total. We also excluded ethane pathways from the total, since the current leading use of ethane as a feedstock to produce ethylene would be eliminated if ethylene was produced entirely through CO₂ recycling. Similarly, we excluded electrochemical CO production from the total since the majority of global demand for CO is as a component of syngas, and other pathways separately account for syngas production. We included both concrete production pathways since they apply to different types of concrete. Finally, we calculated the totals with and without methane production, since the extremely large global demand for methane eclipses the contribution of all other pathways and because CO₂ recycling methane pathways were found to have limited prospects of supplying large-scale methane demand.

Inputs and Assumptions

We designed both the electrochemical and thermochemical CO₂ recycling pathways to consume low-carbon electricity, here modeled as renewable energy, and assumed the H₂, CO, and/or ammonia consumed as a reactant in thermochemical pathways are supplied by onsite electrochemical processes powered by renewable energy. All numerical assumptions are detailed in Table A1, A2, and A3 in the appendix. We chose globally representative input values to correspond to the global scale of this analysis.

We assume the feedstock CO₂ is sourced from carbon capture at point-source emitters and delivered to the CO₂ recycling plant via a CO₂ pipeline network at a total cost of \$50 per metric ton of CO₂ (tCO₂).¹⁰ While lower carbon capture costs may be available in certain contexts, these lower costs will not be accessible on average for the global scope and scale of this study. For the thermochemical pathways that consume electrochemically generated feedstocks, we use our own calculated ECOP of the electrochemical feedstock production



pathway (e.g., water electrolysis for feedstock green H₂) as the feedstock price.

Though similar studies often assume renewable electricity prices based on the levelized cost of energy (LCOE) for renewable generators or average power purchase agreement (PPA) prices for renewables, these methods do not reflect the duty cycles of industrial use, contributions of network costs (costs of transmission and distribution), and electricity taxes to the end-use industrial electricity price paid by producers. While producers may have access to PPA-range renewable electricity prices at certain times, in limited contexts, and with low capacity factors, these low prices will not be available on average for the global production scale evaluated in this study. Therefore, for our estimate of the renewable electricity price paid for global-scale CO₂ recycling processes, we must incorporate the duty cycle requirements and contributions of network costs and taxes beyond renewable PPA prices.

To estimate the renewable electricity price used in this study, we take renewable PPA prices in a region to be equivalent to the wholesale price of renewable electricity. We calculate the corresponding industrial price of renewable electricity by increasing the PPA price to reflect the additional contributions of network costs and taxes to industrial prices. Wholesale electricity prices account for 10–70 percent of industrial electricity prices in different countries.¹¹ We assume that renewable PPA prices on average account for the same percentage of the final renewable electricity industrial price in a particular country. To estimate the renewable electricity price used in this study, we assume that CO₂ recycling producers have access to industrial electricity markets and that wholesale electricity prices represent 50 percent of the price of industrial electricity on a global basis. We use an average global renewables PPA value of 4.75 ¢/kWh¹² and divide it by 0.5 to obtain an industrial electricity price for renewables of 9.5 ¢/kWh (\$0.095/kWh). In keeping with this framing, we assume a capacity factor of 50 percent for electrochemical pathways supplied by renewable electricity, which was chosen to represent a combination of wind and solar with complementary output profiles.¹³ Since thermochemical pathways have very small direct electricity consumption and therefore are not as limited by the availability of renewable resource, we assume a higher capacity factor of 90 percent.

An obvious condition from this cost framing is that the true costs of recycling CO₂ will vary substantially across regions and jurisdictions and that some locations may provide high-capacity electricity at much lower costs. These sensitivities and ranges will be published separately.

In our techno-economic analysis, we choose values for faradaic efficiency, carbon selectivity, and hydrogen selectivity that are 20 percent lower than those of the highest performance catalysts reported in the literature. The 20 percent decrease from the highest performance values was applied to reflect that many of the cited catalysis studies at the bench scale do not demonstrate industrially relevant production rates (measured as current density or space-time yield), and industrial demonstrations of these pathways today would not achieve bench-scale performance. We obtain energy efficiencies for electrochemical pathways from the same studies. Our efficiency and selectivity assumptions, along with the associated references, are summarized in Table A1. We assumed an electrolyzer capital cost of \$1,000/kW for water electrolysis.¹⁴ For electrochemical CO₂ reduction pathways, since these technologies have not reached commercial scale and CO₂ electrolyzer capital cost data is therefore not available, we



modeled the electrolyzer based on water electrolyzers with a capital cost of \$1,000/kW. For thermochemical pathways, we obtained capital cost estimates from plant simulations in the literature (Table A2). The annual fixed O&M costs were estimated as a small percentage of the total capital cost (Table A3).

We included the emissions associated with renewable electricity generation in our carbon abatement life cycle assessment. Renewable power has life cycle emissions of roughly 10–40 gCO₂/kWh,¹⁵ and we assume an average renewable electricity emissions intensity of 25 gCO₂/kWh.



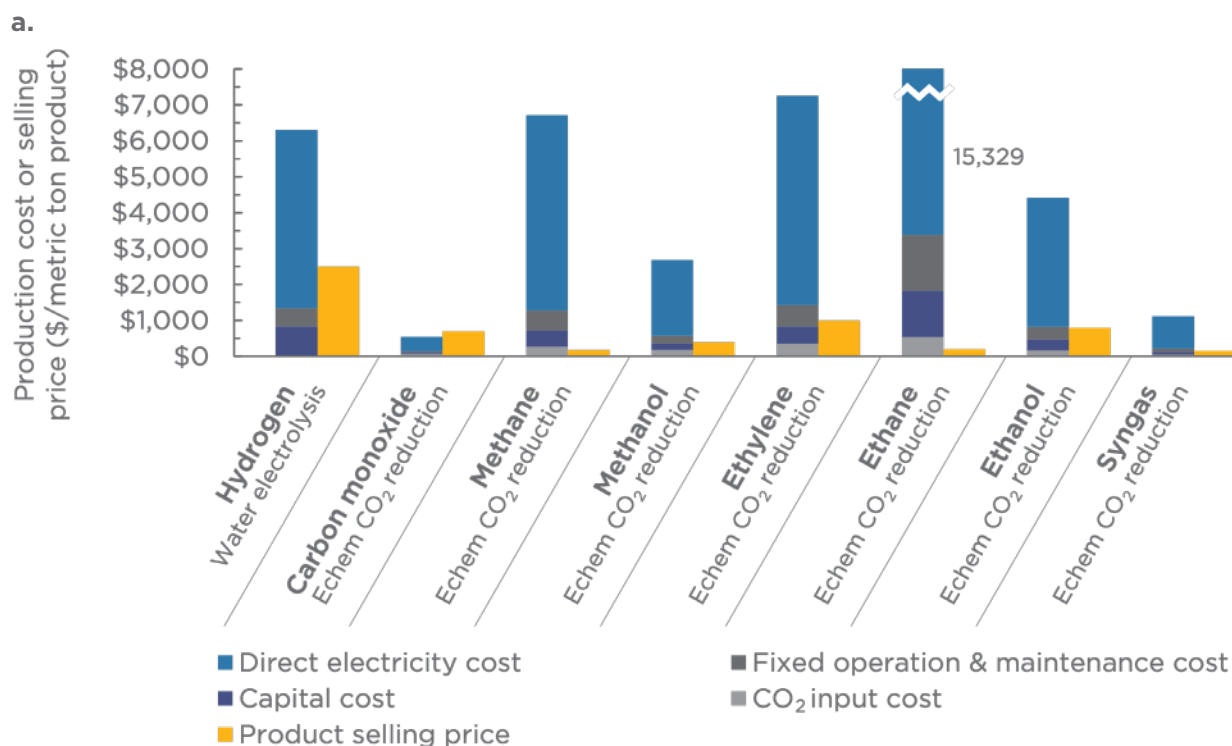
RESULTS

A large and diverse set of pathways take CO₂ as an input to produce value-added products. We reviewed 61 of such CO₂ recycling pathways (Table A5) and further analyzed 19 of the pathways that produce products with the associated highest global demand in Mt/yr (Table 1). We evaluated green H₂ production by water electrolysis—though this does not strictly qualify as CO₂ recycling—because low-carbon hydrogen is a key required input for many CO₂ recycling pathways. Our findings are detailed below, and key findings are summarized in Table A4 in the appendix.

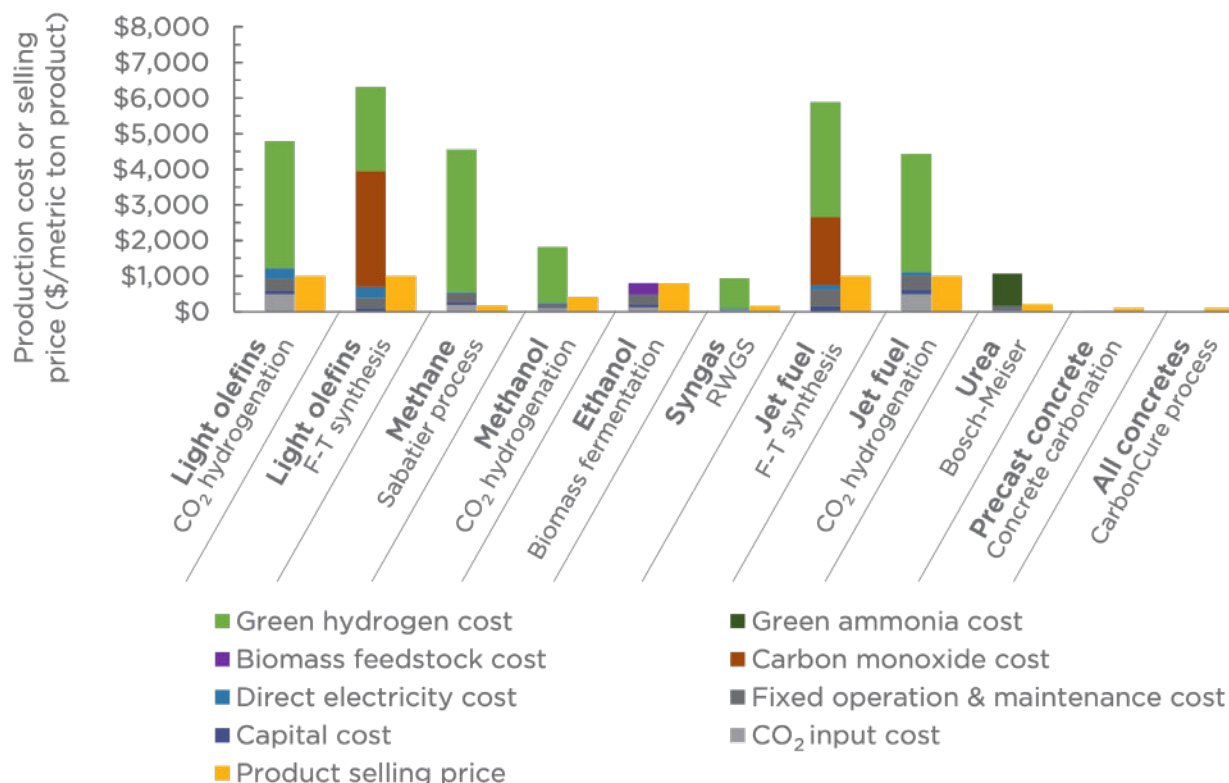
Estimated Cost of Production

The current estimated cost of production (ECOP) gives the cost of producing a ton of product through a particular CO₂ recycling pathway and provides a basis to compare the economics of each pathway. We calculated a globally representative ECOP for each CO₂ recycling pathway. We define a pathway as “profitable” and at market parity if its ECOP is lower than the product selling price. The ECOP comprises capital cost (CAPEX), fixed operation and maintenance (O&M) costs, electricity costs, and costs of various feedstocks. Figure 1 shows the ECOP of each pathway and the breakdown of ECOP between each cost category. **The findings show the ECOP for most pathways is well above the product selling price.**

Figure 1: Estimated cost of production (ECOP) and product selling price for a) electrochemical and b) thermochemical CO₂ recycling pathways



b.



For electrochemical processes, ECOP values are high—most are above \$4,000/metric ton product—and greatly exceed the corresponding product selling prices, which lie below \$1,000/metric ton product. Electrochemical carbon monoxide (CO) production is a notable exception with a low ECOP of \$546/metric ton product, below the CO selling price.

Electricity costs comprise the large majority of ECOP for electrochemical processes.

Electricity is the main (or only) energy input used in electrochemical pathways to convert low-energy CO₂ molecules into high-energy products. Due to relatively high estimated industrial renewable electricity prices today and large amounts of electricity input needed, electricity costs predominate in ECOP. While renewable electricity prices may fall in the future, we do not include projected prices here. Fixed O&M, CAPEX, and CO₂ feedstock costs account for similar portions of the remainder of ECOP.

The thermochemical CO₂ recycling pathways show slightly lower ECOPs than the electrochemical pathways, with most thermochemical ECOP values below \$5,000/metric ton product and smaller margins between ECOP and selling price. Ethanol production by lignocellulosic biomass fermentation has a lower ECOP than the product selling price, making the process profitable. Similarly, the two concrete production CO₂ recycling pathways, which modify a single step of conventional concrete production, add minimal costs to the conventional process, maintaining an ECOP below the selling price.



For thermochemical pathways, the cost of feedstock green hydrogen typically accounts for the majority of the ECOP. Hydrogen consumed as a reactant in thermochemical CO₂ recycling reactions is often the largest source of energy input to the process. Since in this analysis all feedstock hydrogen is produced through renewable-powered electrolysis, the price of renewable electricity plays a prominent indirect role in thermochemical ECOPs. The cost of feedstock CO₂ is typically a minor component of ECOP for thermochemical pathways. For Fischer-Tropsch synthesis processes, which use syngas—a mixture of carbon monoxide and hydrogen—as a feedstock, carbon monoxide and hydrogen costs are the largest component of ECOP. Once again, this feedstock syngas is modeled to be produced through electrochemical CO₂ reduction, making the renewable electricity price an important indirect contributor to ECOP for Fischer-Tropsch.

While electricity costs comprise the largest part of electrochemical ECOPs and green hydrogen/CO are the largest component of thermochemical ECOPs, completely eliminating these costs would still leave ECOPs that are near or above selling price for many pathways. For these pathways to reach market parity, other components of ECOP, such as capital cost and fixed O&M, must decrease along with the major cost components.

A few cost trends are also apparent between pathways. By and large, C₂₊ products—molecules with two or more carbon atoms in a chain—have higher ECOPs than single-carbon (C₁) products, which is to be expected. Electrochemical and thermochemical production of C₂₊ products, such as ethylene or jet fuel, often have a lower energy efficiency and lower selectivity compared to the synthesis of C₁ products due to the high energy barrier to C-C bond formation and competition from the more facile C₁ pathways.

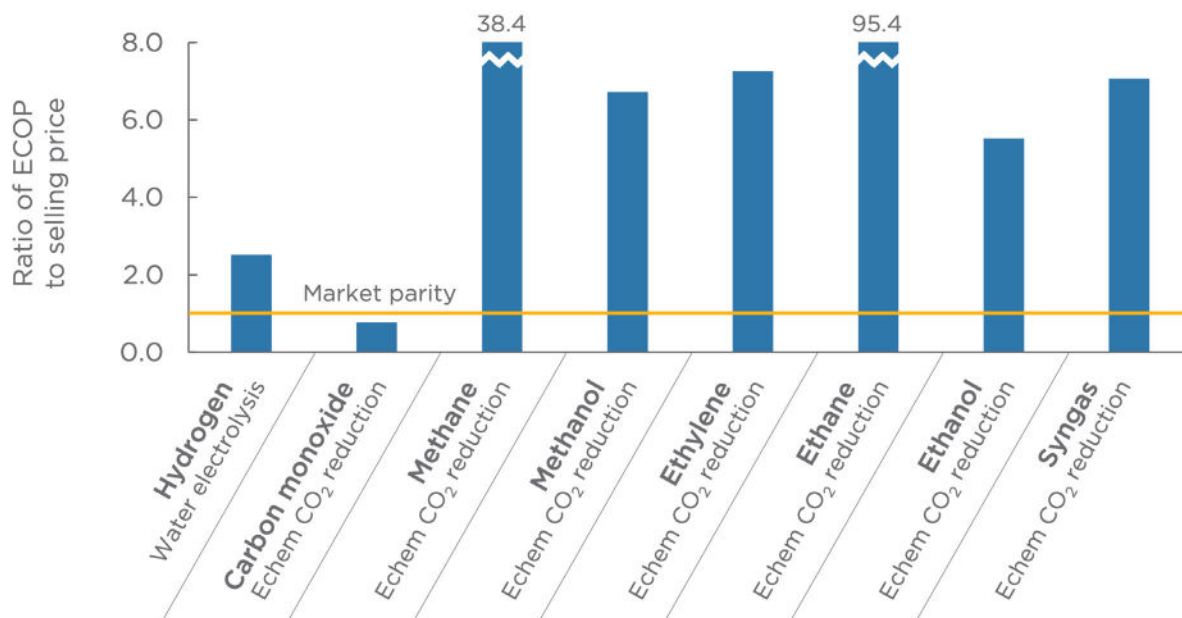
The gravimetric energy density of the products (Table A1) also plays a major role in shaping ECOP trends since more energy-dense products require a larger input of energy to produce, driving up total electricity or feedstock hydrogen costs. Ethanol, for instance, has a gravimetric energy density over 40 percent lower than that of the other C₂ products evaluated and accordingly has a lower ECOP than the other C₂ pathways. The high and low gravimetric energy densities of hydrogen and carbon monoxide, respectively, similarly factor into these products' outlier ECOP values.

The ratio of ECOP to product selling price (Figure 2) provides a clearer comparative view of how close each pathway is to reaching market parity. A ratio of less than 1 indicates that ECOP is lower than the selling price and the pathway has reached market parity, as we see for electrochemical CO production, ethanol from lignocellulosic biomass, and the two concrete production pathways. The methane and ethane production pathways have extremely high ratios, suggesting that it may not be feasible for these pathways to ever reach market parity. **Most pathways have ECOP to selling price ratios of up to 7.5, highlighting a wide gap between ECOP and selling price that demands strong policy efforts to close this gap.** As we will discuss in our policy recommendations, this information can be used to help prioritize the pathways with lower ECOP to selling price ratios that may more readily reach market parity.

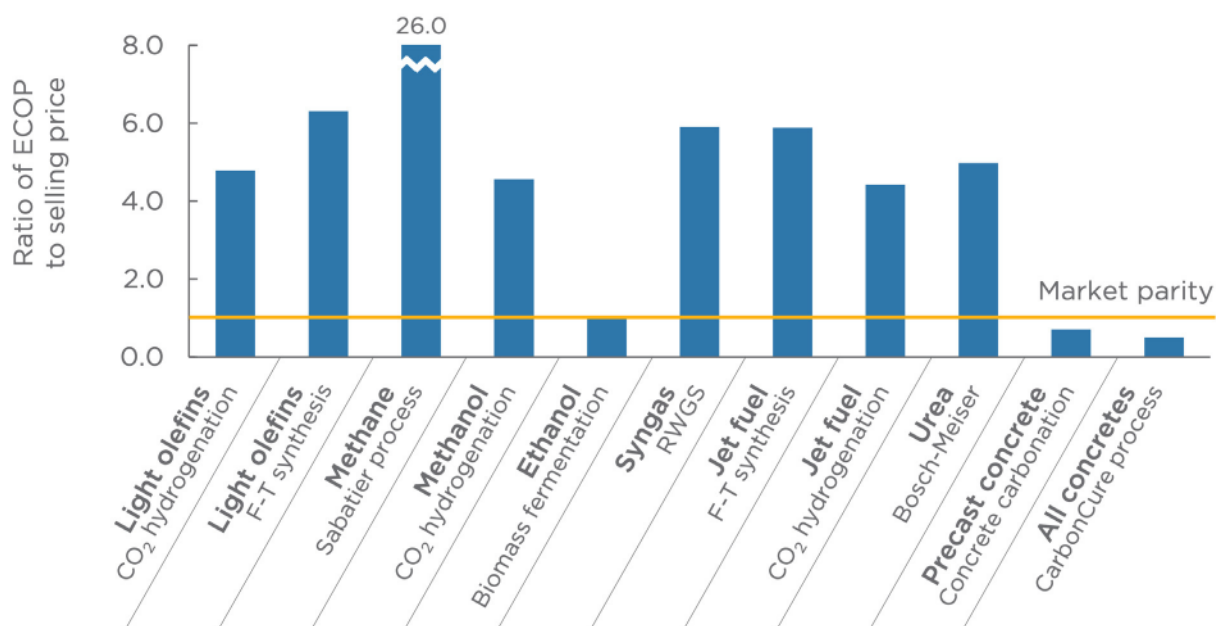


Figure 2: Ratio of ECOP to selling price for a) electrochemical and b) thermochemical CO₂ recycling pathways

a.



b.



Cost Sensitivity Analysis

To achieve market parity, the ECOP of most CO₂ recycling pathways must decrease substantially. To assess which performance improvements or component cost reductions would be most effective, we analyzed the cost sensitivity to key inputs and functional parameters. The parameters evaluated include the electrical efficiency, electricity price, capacity factor, capital cost, various feedstock costs, and product selectivity. The product selectivity broadly describes the percentage of input feedstock and/or energy that goes toward making the desired product as opposed to undesired byproducts, as detailed in the appendix. Figure 3 shows the percent change in a pathway's ECOP that results from increasing and decreasing an input value by 20 percent, with all else equal. The concrete production pathways are excluded since their costs are not defined by the metrics analyzed here, such as product selectivity and feedstock prices. This analysis demonstrates how sensitive ECOP is to an arbitrary but consistent percent change in each input, to help identify the main cost drivers for each pathway. Since this analysis focuses on sensitivity, it does not evaluate the extent or feasibility of cost reductions possible through improvements in each input and does not imply that a particular input value can or will change by 20 percent in the future. The extent of improvements available in the value of each input sets an important limit for ECOP reduction that should be considered alongside cost sensitivity.

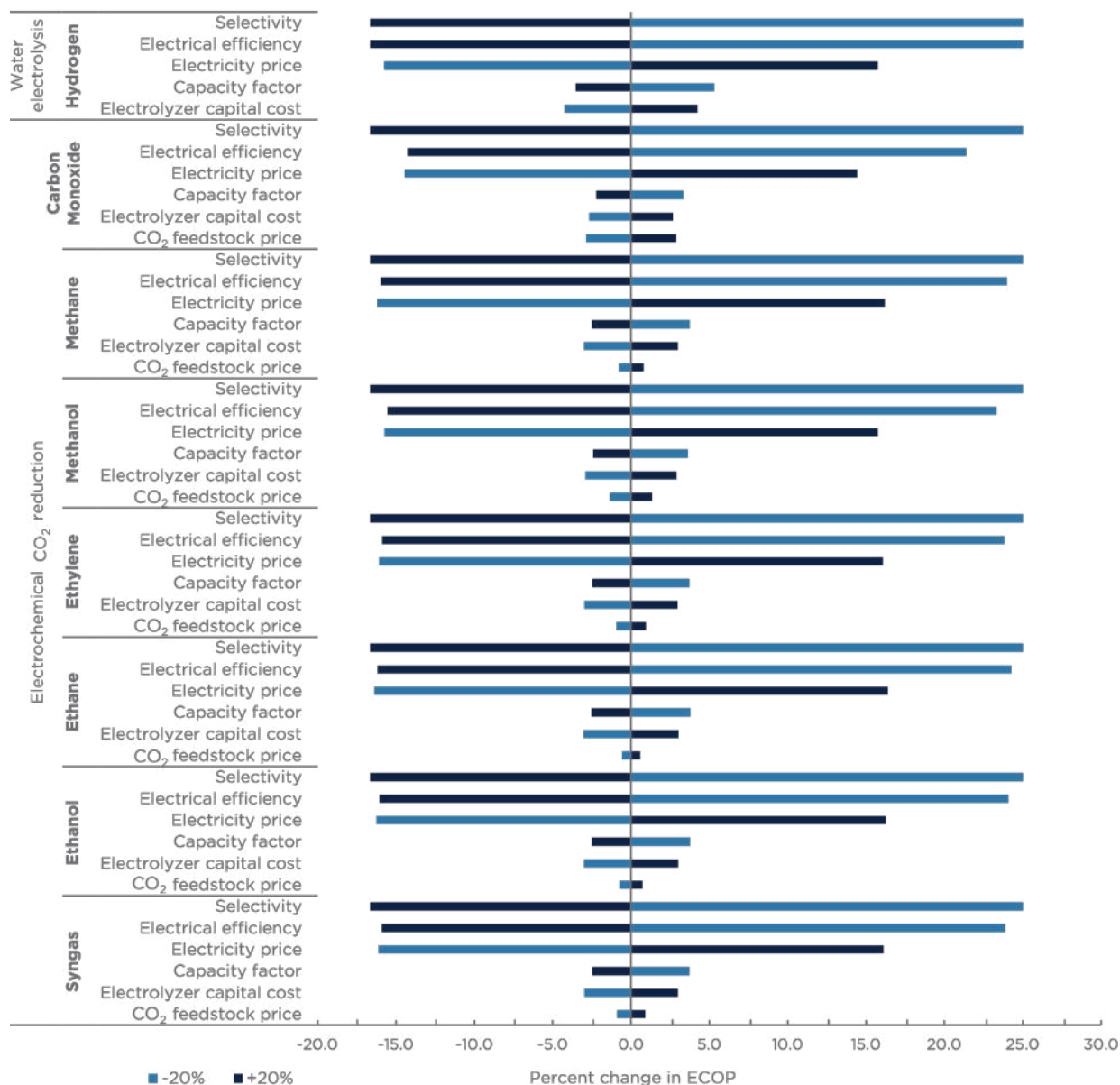
For electrochemical pathways, the most significant techno-economic cost drivers are electrical energy conversion efficiency and product selectivity. This is because electricity represents the largest component of cost, and low efficiency and selectivity directly increase the overall electricity consumption of the pathways through energy conversion and faradaic efficiency losses, respectively. These two inputs are followed closely in importance by the electricity price itself.

In contrast, changes in capacity factor and electrolyzer capital cost have a relatively small impact on ECOP. These inputs directly affect CAPEX and fixed O&M costs, which comprise small portions of ECOP. Similarly, feedstock CO₂ price is typically the weakest cost driver since CO₂ input costs are a small portion of electrochemical ECOPs. This suggests an innovation agenda focused initially on electrochemical selectivity and conversion efficiency as opposed to capital cost reduction for electrolyzers and renewable electricity price reduction.

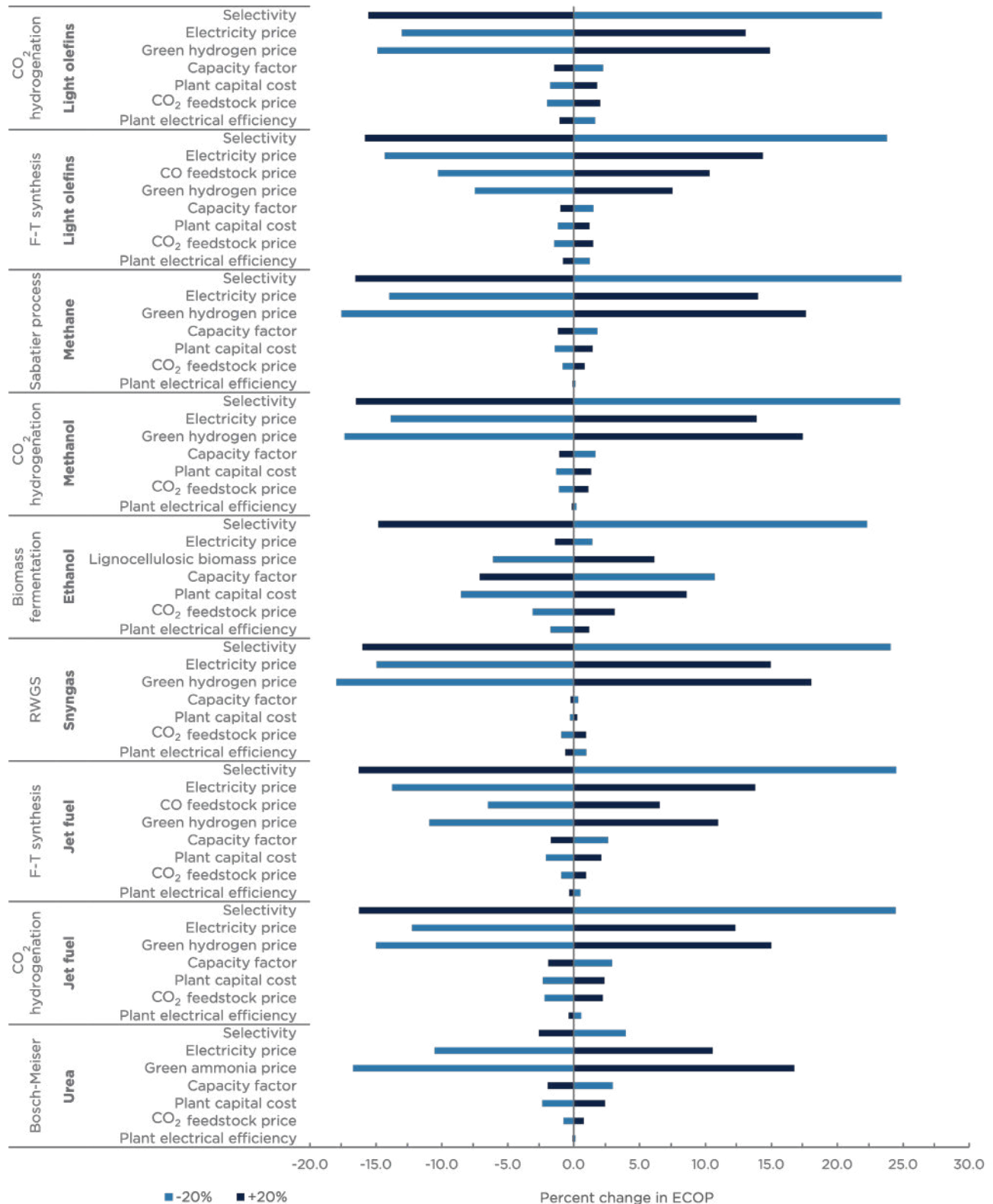


Figure 3: ECOP sensitivity analysis tornado plot for a) electrochemical and b) thermochemical CO₂ recycling pathways, showing percent change in ECOP as a result of a 20 percent increase or decrease in input parameters

a.



b.



For thermochemical pathways, selectivity, electricity price, and green hydrogen price are the main cost drivers. In contrast with electrochemical pathways, most of the thermochemical processes receive the majority of their energy input from the hydrogen used as a reactant in the chemical reactions, with heat inputs and direct electricity use contributing relatively small input energy. As a result, ECOP is particularly sensitive to green hydrogen prices and to electricity prices that highly influence green hydrogen production costs. Since a lower selectivity directly increases hydrogen consumption for undesired reaction pathways, selectivity is the most prominent driver of ECOP. **The capacity factor and capital cost for thermochemical pathways have a comparatively small influence on ECOP,** since CAPEX makes a much smaller contribution to ECOP than hydrogen costs do. The electrical energy efficiency of plant equipment is the least significant ECOP driver for most pathways since the direct electricity consumption of the plant is dwarfed by the energy input from feedstock hydrogen.

For all pathways, the CO₂ feedstock costs have a relatively small influence on ECOP. In real markets, the price of feedstock CO₂ varies considerably based on the source of that CO₂. This paper assumes feedstock CO₂ is obtained through carbon capture from the flue gas streams of point-source emitters such as steel mills and purchased at a price of \$50/tCO₂.¹⁶ A key alternative potential source of CO₂ is direct air capture (DAC), which removes CO₂ directly from the atmosphere. Since DAC does not rely on continued use of fossil fuels as a source of feedstock CO₂, DAC could potentially avoid the upstream emissions associated with fossil fuel production that exist in most point-source carbon capture scenarios, which can be substantial. DAC would provide feedstock CO₂ at higher prices, currently estimated between \$250 and \$600/tCO₂,¹⁷ though this cost could drop appreciably with broader deployment.¹⁸ DAC might provide a fossil-free source of CO₂ as DAC technology matures in the medium to long term. **Since feedstock CO₂ price has a small influence on ECOP, the higher price of feedstock CO₂ from direct air capture would not greatly influence final product costs.** For instance, increasing the CO₂ feedstock price by 400 percent from \$50/tCO₂ to \$250/tCO₂, a price consistent with DAC, would only increase the ECOP of electrochemical CO₂ reduction to ethylene by 19 percent.

Carbon Abatement Potential

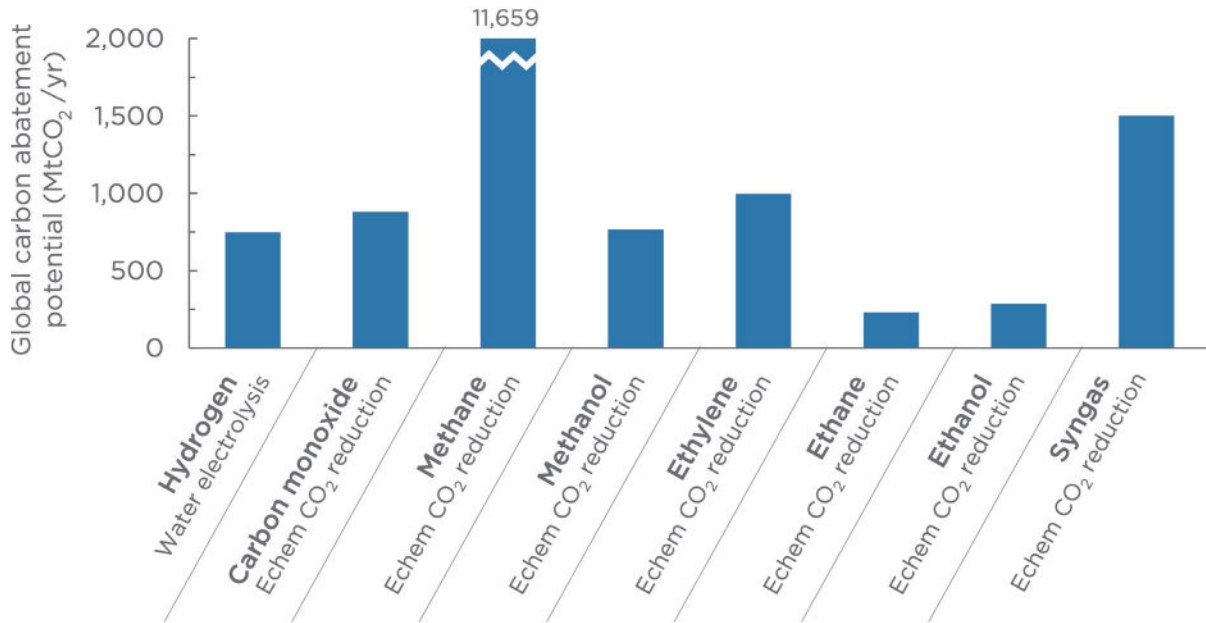
Since reducing CO₂ emissions is the key motivation of CO₂ recycling, we calculated the carbon abatement potential of each pathway (Figure 4). This is based on a life cycle assessment to find the net decrease in emissions that would result from completely replacing conventional production pathways with CO₂ recycling pathways. This analysis incorporated the feedstock CO₂ consumption of the recycling pathway, the CO₂ emissions associated with the recycling pathway, the emissions of the counterfactual incumbent production process that is displaced, and the global demand for the product.

The global carbon abatement potential of most CO₂ recycling pathways lies between 150 MtCO₂/yr and 1,700 MtCO₂/yr (Figure 4a and 4b). These extensive carbon abatement potential values reflect both the product's market size and the pathway's intensive carbon abatement per ton of product. For example, urea has a low carbon content and therefore a low intensive carbon abatement per ton of product, leading to its relatively low carbon abatement potential of 138 MtCO₂/yr. In contrast, the high carbon abatement potentials of the methane pathways largely reflect the product's high global demand.

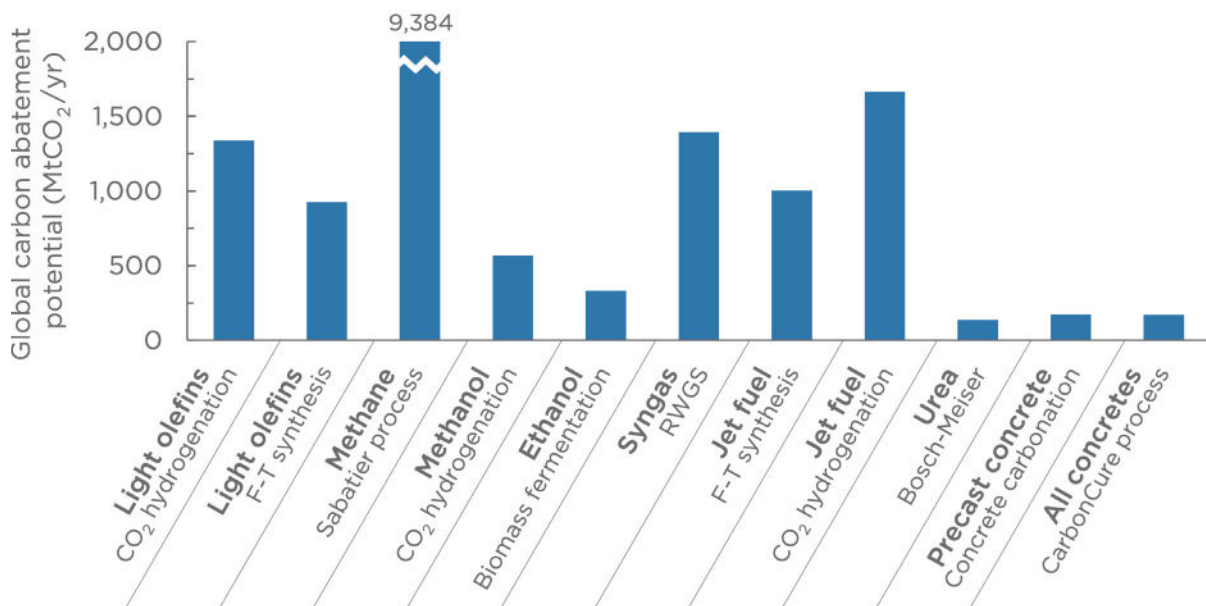


Figure 4: Global carbon abatement potential for a) electrochemical and b) thermochemical CO₂ recycling pathways. Intensive carbon abatement for c) electrochemical and d) thermochemical pathways. Carbon abatement is defined as the net emissions reduction of displacing a conventional production pathway with a CO₂ recycling pathway.

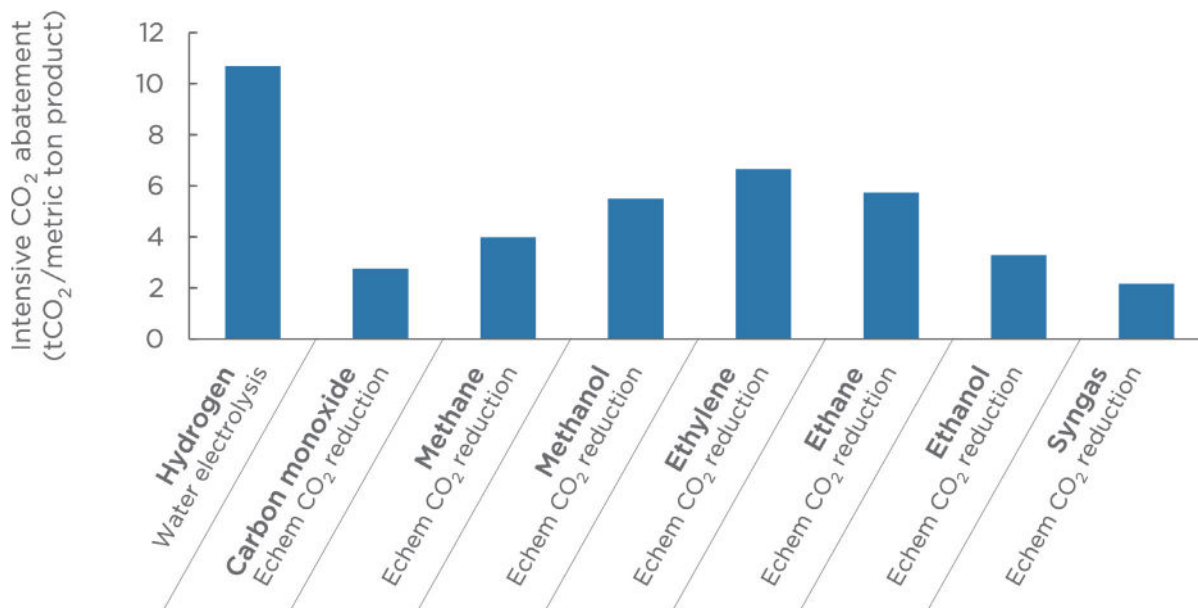
a.



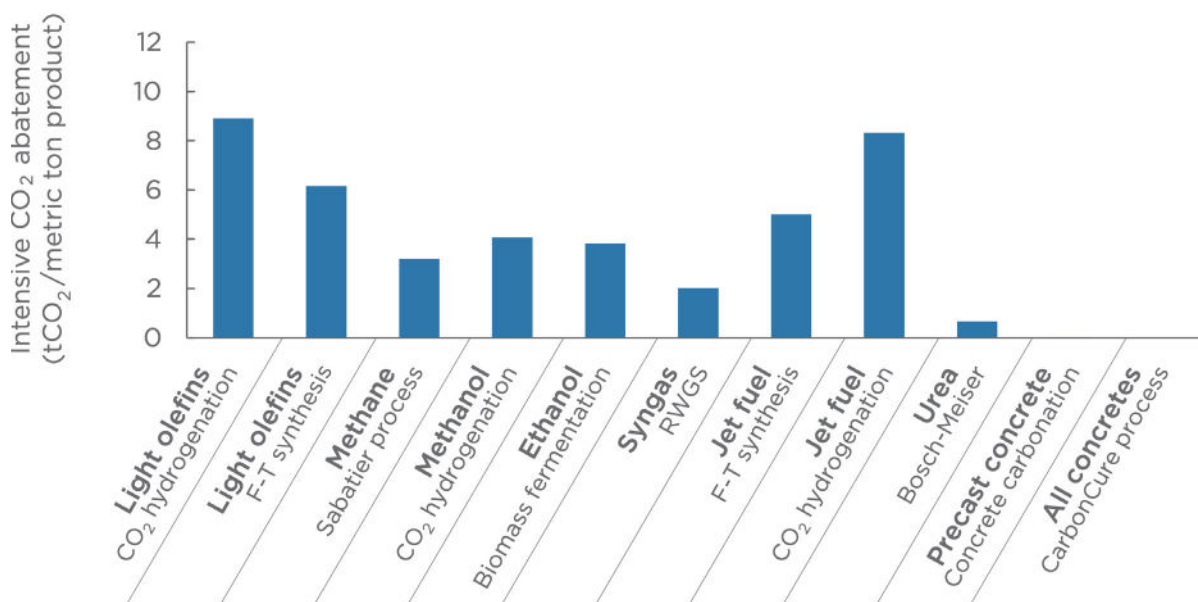
b.



c.



d.



We estimated the sum carbon abatement potential for these CO₂ recycling pathways together by adding the abatement potentials of each pathway, excluding the outlier methane pathways and redundant products as described in the methodology. **The combined carbon abatement potential of the included pathways is 6.8 gigatonnes of CO₂ per year (GtCO₂/yr), or 16 percent of the 2019 global CO₂ emissions of 43.1 GtCO₂.¹⁹** Adding in the abatement potential



contribution from Sabatier process methane production, the more viable of the two methane pathways, the maximum abatement potential is 16 GtCO₂/yr.

The intensive carbon abatement gives the tons of CO₂ abated per ton of product made through each pathway based on the aforementioned life cycle emissions assessment (Figure 4c and 4d). Importantly, all pathways evaluated have a positive carbon abatement value under our assumption that the pathways use low-carbon inputs, indicating that using a CO₂ recycling pathway to displace conventional production would indeed reduce CO₂ emissions. Many pathways have carbon abatement values between 2 and 9 tCO₂/metric ton of product, demonstrating an appreciable amount of carbon abatement for each unit of CO₂ recycling production. The two concrete pathways have particularly low intensive carbon abatements. This is because, during CO₂ curing of concrete, CO₂ is incorporated at a relatively low weight percent into solely the cement component of concrete, and cement only accounts for an estimated 12.5 percent of the total mass of concrete.²⁰ However, the very large global demand for concrete leads to appreciable global carbon abatement potentials for concrete pathways. Urea also has a relatively low intensive carbon abatement, partly because urea has a low gravimetric carbon content, meaning a small amount of CO₂ is consumed in the urea-producing reaction. Ethylene and jet fuel pathways have large intensive carbon abatements due to the high carbon content of these products. Hydrogen, on the other hand, has a large carbon abatement because the conventional pathway it displaces, steam methane reforming, has high emissions of roughly 12 tCO₂/metric ton H₂.

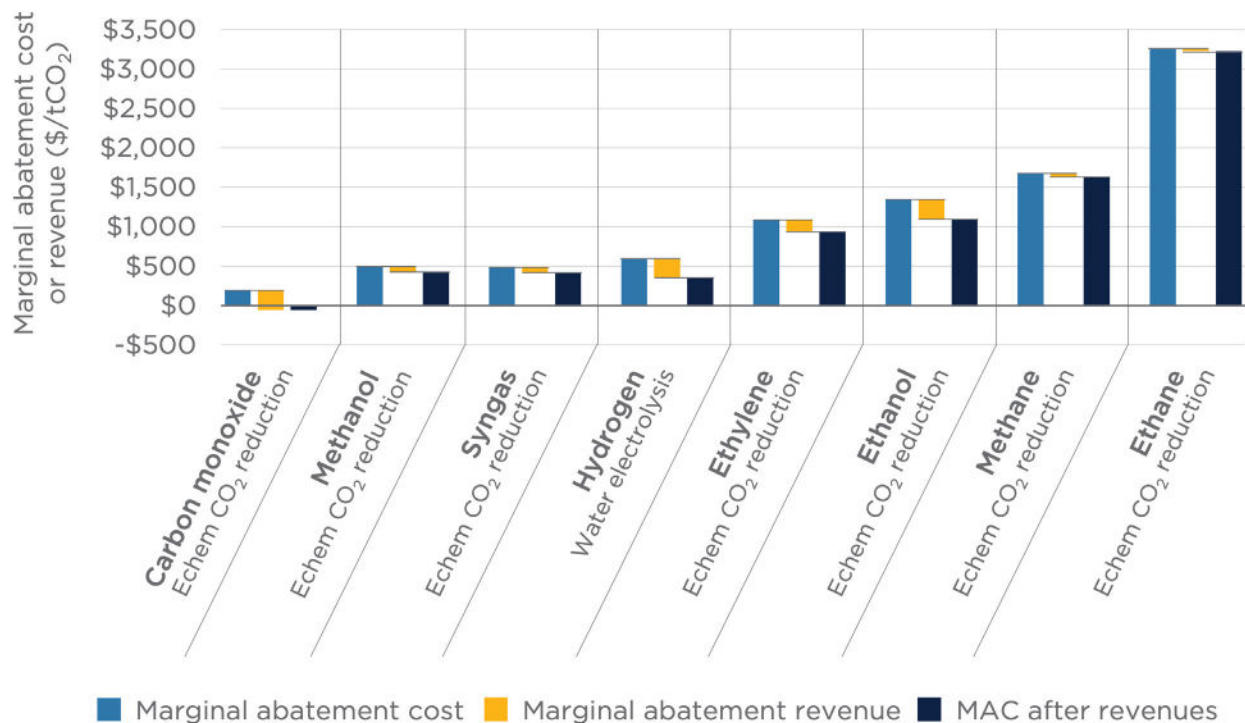
Marginal Abatement Cost and Revenue

To assess the economics of carbon abatement, the marginal cost of reducing carbon emissions, or marginal abatement cost (MAC), provides an initial economic metric for evaluating these pathways. The MAC gives the cost of each pathway in dollars per metric ton of CO₂ abated and was calculated by dividing ECOP by intensive carbon abatement. Since the products of these pathways will be sold for revenue, we also calculated the revenue generated per metric ton of CO₂ abated by recycling pathways, termed the marginal abatement revenue (MAR). The marginal abatement revenue was then subtracted from MAC to obtain the MAC after revenues. These three values are displayed in Figure 5 as a waterfall chart, in which MAC is shown as the initial value from which MAR is subtracted to yield MAC after revenues for each pathway.

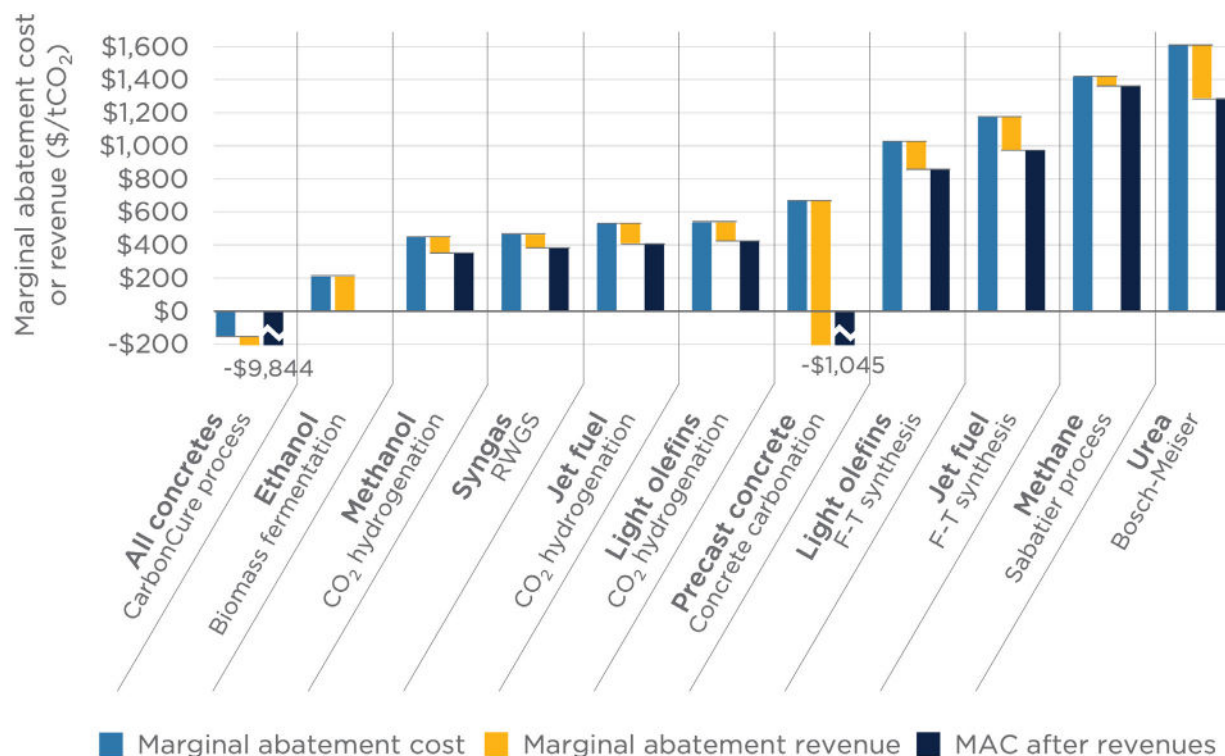


Figure 5: Marginal abatement cost and revenue, and MAC after revenues for a) electrochemical and b) thermochemical CO₂ recycling pathways. Marginal abatement cost minus marginal abatement revenue gives MAC after revenues.

a.



b.



MAC estimates lie in the vicinity of \$200–\$700/tCO₂ for many of the pathways analyzed, with electrochemical pathways having generally higher MACs than thermochemical pathways. The MAC for electrochemical ethane production is the highest due to the pathway's high ECOP. The MAC values for most pathways are greater than those of many other common carbon abatement levers, including renewable electricity and efficiency measures.²¹ However, these CO₂ recycling pathways fulfill a need for emissions reductions in hard-to-abate sectors like transportation that other levers on a MAC curve cannot readily satisfy. For this reason, it may be favorable to implement certain CO₂ recycling pathways concurrently with other measures that have a lower MAC.

For most pathways, the MAR is less than the MAC, resulting in a net cost after revenues, which is represented as a positive value for MAC after revenues. **However, for electrochemical CO production and the two concrete production pathways, the MAC after revenues is negative, indicating that a net profit can be made while abating emissions through these pathways.**

Effective Carbon Price and Gross Subsidies

The value of MAC after revenues can also be taken to roughly represent the effective carbon price necessary for a pathway to reach market parity. We assume that an effective carbon price would be translated fully into an increase in the product selling price. In this



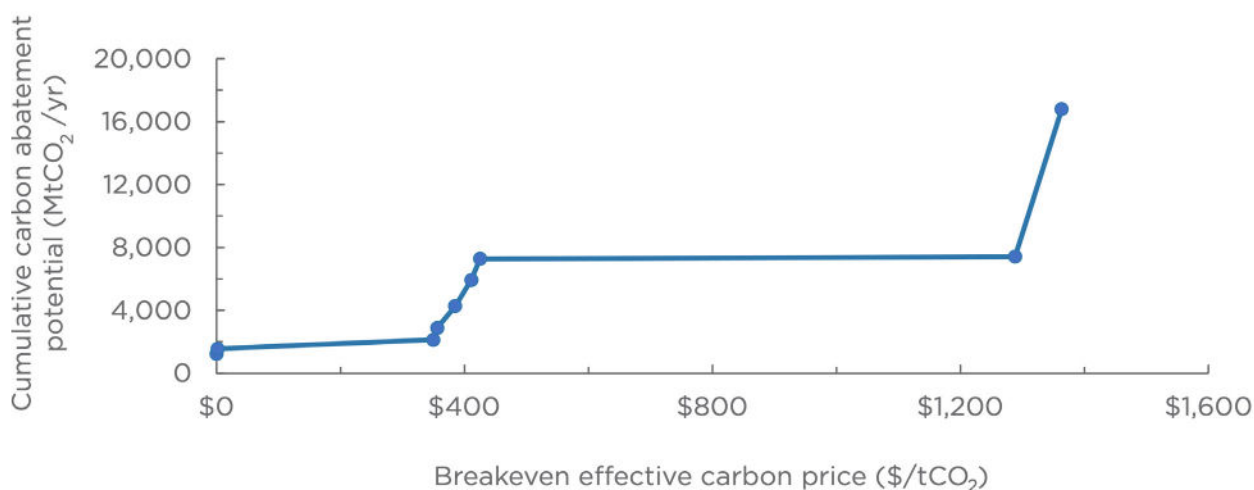
case, applying an effective carbon price equal to the value of MAC after revenues for a CO₂ recycling pathway would result in the pathway's MAC being equal to its MAR (in other words, its ECOP being equal to the selling price), achieving market parity for the pathway.

Using this assumption, we calculated the cumulative carbon abatement potential of pathways that have reached market parity as a function of effective carbon price (Figure 6a). We excluded repeated pathways with higher breakeven carbon prices as described in the methodology. **With no carbon price, 1.6 GtCO₂/yr of cumulative abatement potential is available at market parity** since electrochemical CO production, ethanol from lignocellulosic biomass, and the two concrete production pathways have ECOPs lower than product selling price. As the effective carbon price increases, the cumulative carbon abatement potential increases rapidly between \$350/tCO₂ and \$425/tCO₂ as more pathways reach market parity until **cumulative carbon abatement potential reaches 7.3 GtCO₂/yr at an effective carbon price of \$425/tCO₂**. This sum is different from the previously cited abatement sum because we did not exclude electrochemical CO production from Figure 6a, as it has a much lower breakeven carbon price than syngas and the resolution between the two is important to illustrate. The cumulative potential jumps to 16.8 GtCO₂/yr with the addition of Sabatier process methane production at an effective carbon price of \$1,363/tCO₂.

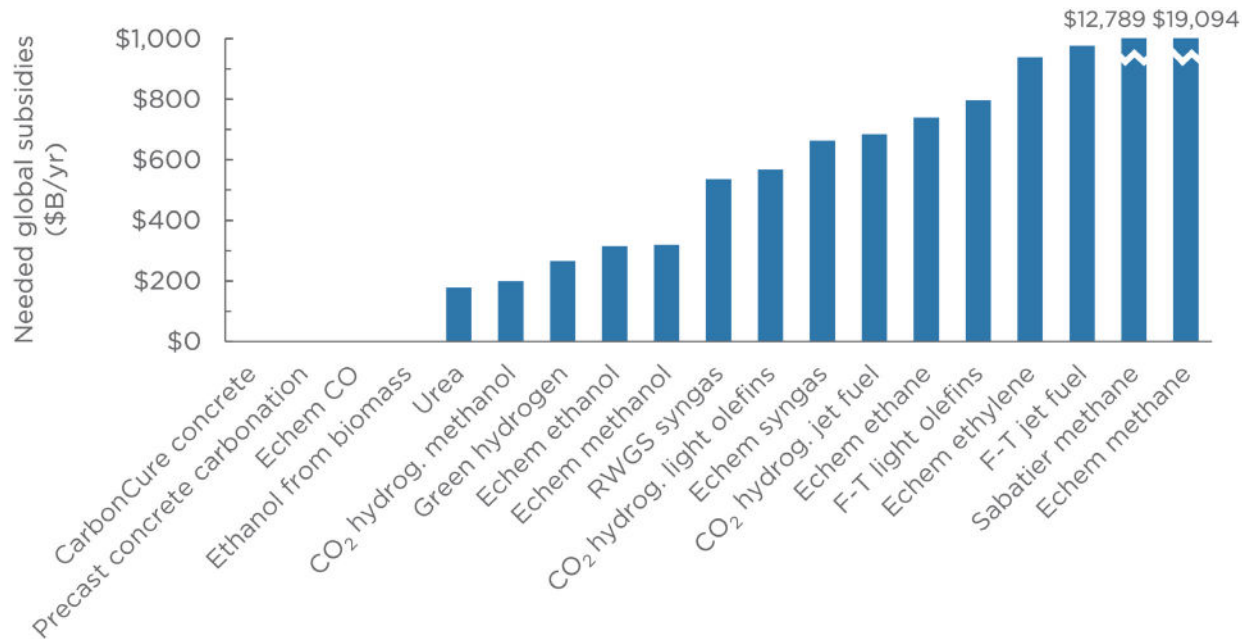
In a similar vein, we determined the gross value of subsidies needed, absent a carbon price, to bridge the gap between ECOP and product selling price for CO₂ recycling pathways at the full scale of current global markets (Figure 6b). The needed subsidies vary widely between pathways but are in the range of hundreds of billions of dollars per year. For comparison, global fossil fuel subsidies were \$318 billion in 2019.²²

Figure 6: a) Cumulative carbon abatement potential from CO₂ recycling pathways that have reached market parity as a function of effective carbon price. b) Needed subsidies to bridge the current gap between ECOP and selling price, absent a carbon price, for CO₂ recycling pathways at global scale.

a.



b.



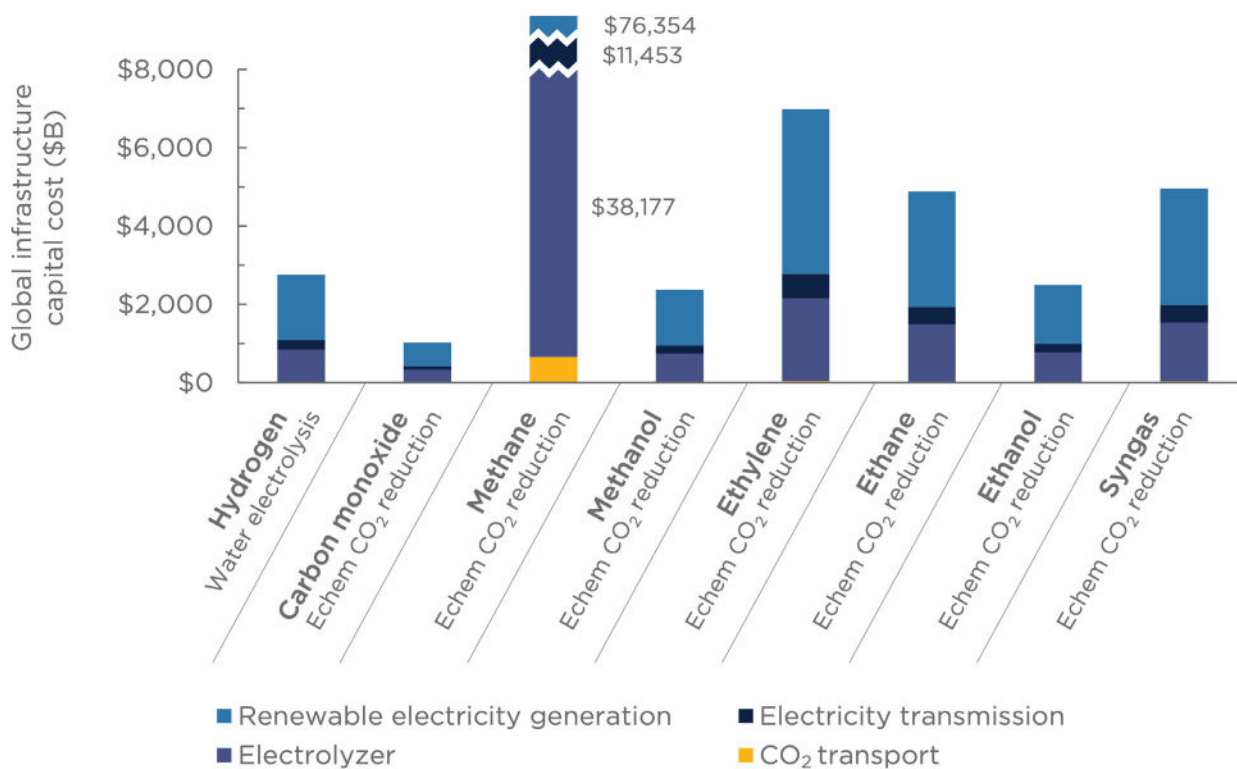
Critical Infrastructure Needs

For CO₂ recycling to reach a global scale and contribute substantially toward reaching net-zero emissions, these pathways will need to draw on tremendous expansions of low-carbon electricity, CO₂ transport, and electrolyzer infrastructure. Figure 7 shows the breakdown of the critical infrastructure capital cost and gigawatt capacity required to supply a product's current global demand entirely using a given CO₂ recycling pathway. All critical infrastructure requirements for methane production pathways are large outliers due to the enormous scale of global methane demand. **The total infrastructure capital cost for CO₂ recycling at global scale, summed across all pathways excluding methane production and duplicate products, is \$27.5 trillion.** This estimate is based on today's capital costs for all forms of critical infrastructure, and as these capital costs are dropping rapidly (particularly for renewable generation capacity and electrolyzers),²³ the total infrastructure cost is expected to decrease significantly before CO₂ recycling reaches large scale.

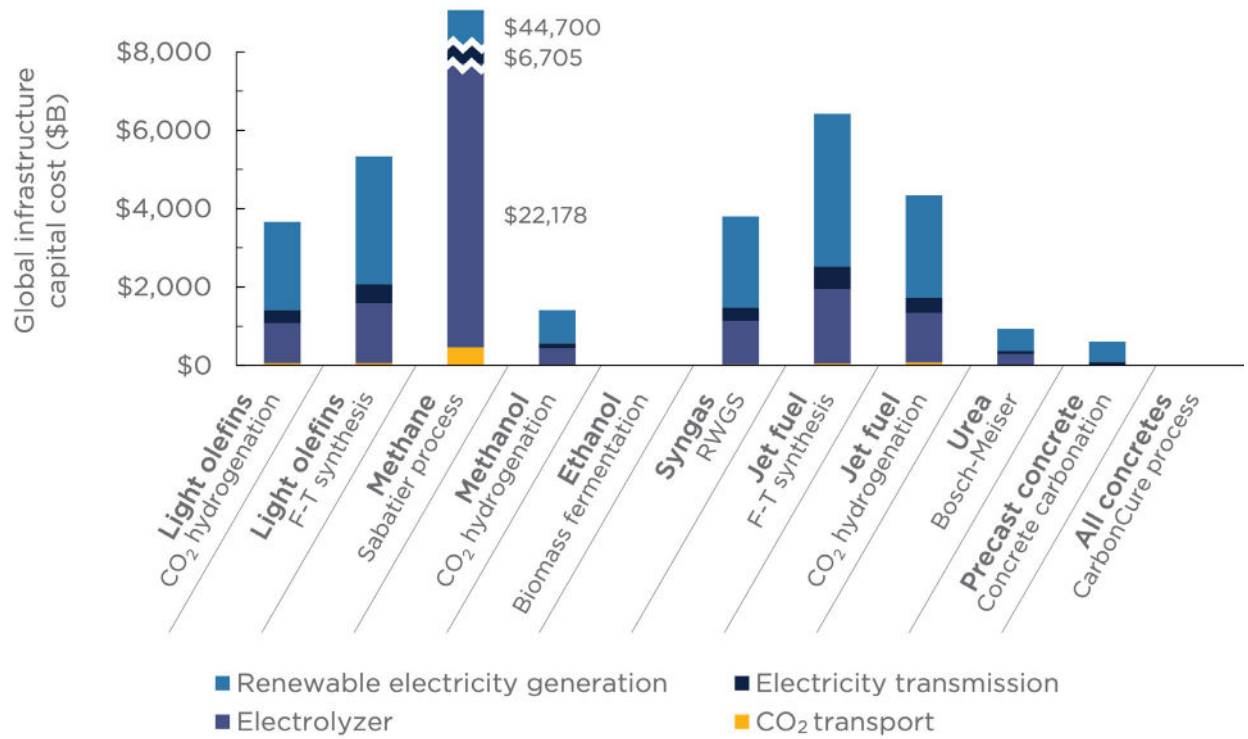


Figure 7: Global critical infrastructure capital cost for a) electrochemical and b) thermochemical CO₂ recycling pathways. Global nameplate electrical capacity needs for c) electrochemical and d) thermochemical pathways.

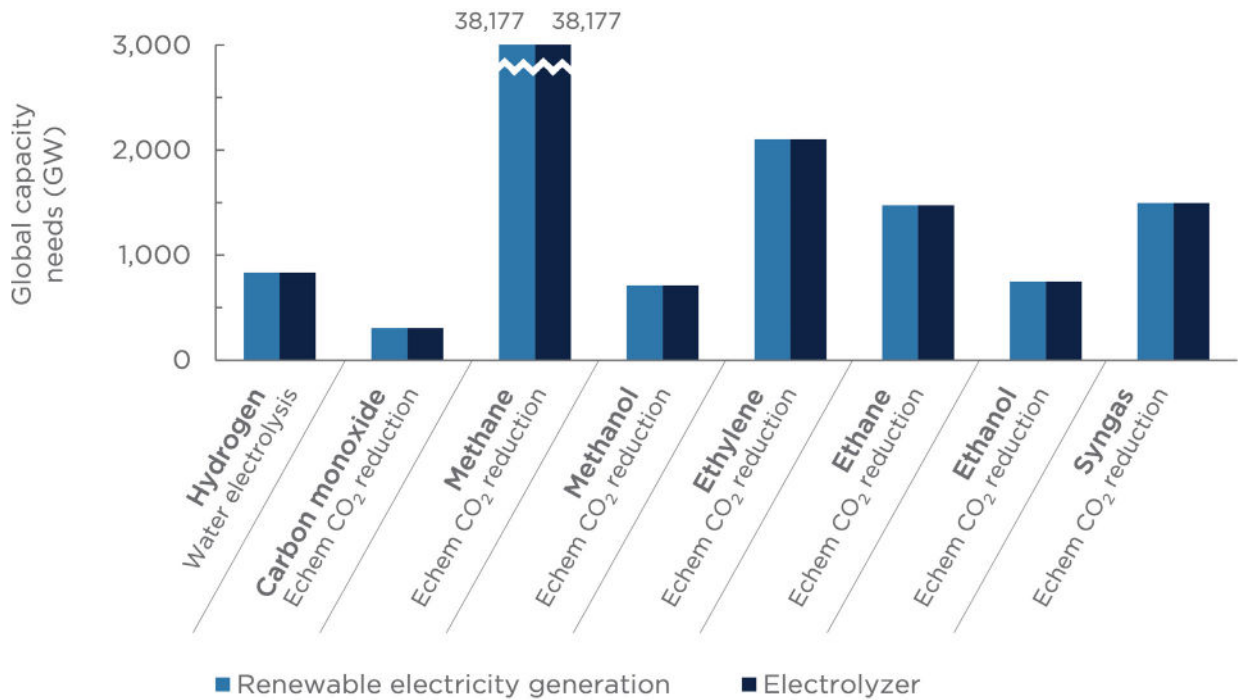
a.



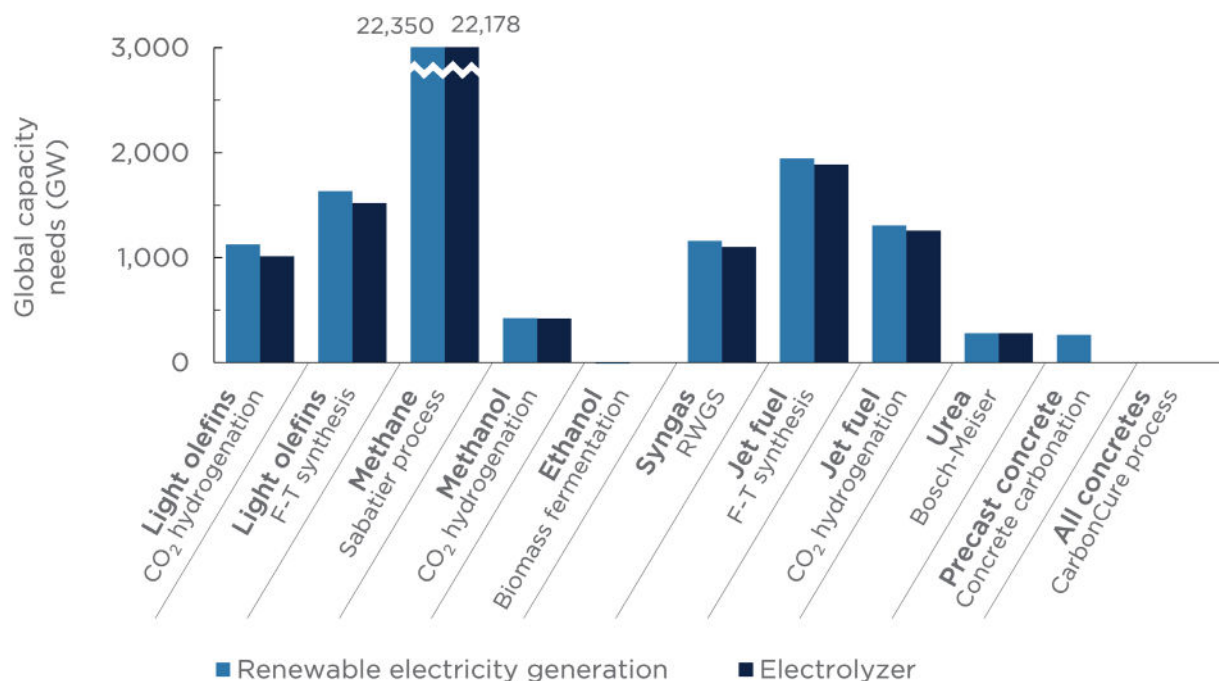
b.



c.



d.



The critical infrastructure capital costs are dominated by new renewable electricity generation capacity

due to the high electricity consumption of CO₂ recycling pathways. The thermochemical pathways notably require similar quantities of renewable electricity investment to electrochemical pathways due to our assumption that the thermochemical feedstocks are produced electrochemically. The required renewables generation capital cost is trillions of dollars globally for each pathway, with a total renewables cost across pathways of \$16.8 trillion. This total cost is based on a current average renewables capital cost of \$2,000/kW across utility-scale solar, onshore wind, and offshore wind power and assumes complete displacement of current products with recycled products. With projected decreases in renewable power capital costs,²⁴ an average capital cost of \$1,300/kW is reasonable to expect in 2030, which would require a total renewable generation capital cost of \$10.9 trillion.

The electrochemical CO₂ reduction pathways will require CO₂ electrolyzer infrastructure, while the thermochemical pathways will largely require water electrolyzer build-out to supply their green hydrogen consumption. These electrolyzers represent the second largest critical infrastructure expense, though their capital cost is likely to decrease rapidly with broader deployment of this nascent technology. Transmission lines to deliver renewable electricity are a smaller but notable capital cost, ranging in the hundreds of billions of dollars for each pathway.

To estimate the capital cost of the CO₂ transport network needed to supply CO₂ for recycling markets, we used a CO₂ pipeline capital cost of \$42/tCO₂/yr capacity, which was obtained from a model of a 20 MtCO₂/yr network with a 500 km central spine.²⁵ This provides a minimal cost estimate, as smaller diameter or longer pipelines would cost more.²⁶ Overall,



the electrochemical and thermochemical pathways show no systematic differences in CO₂ transport infrastructure costs, which are driven by the global volumes of the process and the ratio of CO₂ consumed to product generated in the reaction. The pathways directly consume a combined 5.3 GtCO₂/yr that must be delivered by CO₂ transport infrastructure. Most pathways require on the order of \$50 billion of CO₂ transport infrastructure, while electrochemical and thermochemical methane pathways would require hundreds of billions of dollars of CO₂ transport infrastructure due to the large market for methane. ***These CO₂ transport capital costs are nearly negligible compared to the large capital costs of the other forms of critical infrastructure.*** The total CO₂ transport infrastructure capital cost of all pathways, excluding methane production and repeated products, is \$222 billion, which is comparable to the combined annual revenues of the four largest chemical firms globally.²⁷

In terms of the needed gigawatt capacity of renewable generation and electrolyzers, ***most pathways require between 200 and 2,000 GW of both renewable generation capacity and electrolyzers*** (Figure 7c and 7d). In total, excluding methane production and duplicate products, the pathways would collectively require 8,400 GW of new renewable capacity. Due to a global methane demand far exceeding the demand of all other processes, Sabatier process methane production alone would require 22,400 GW of renewable capacity. By comparison, the global installed renewable electricity capacity, including hydropower, was 2,500 GW at the end of 2019.²⁸ The installed capacity of wind power and solar PV is projected to grow at a rate of ≈180 GW/year through 2025, and this new capacity must serve other important needs for low-carbon energy, including electrification and displacement of fossil power generation.²⁹ Similarly, the total required electrolyzer capacity calculated using the same method is 8,000 GW. For context, the announced water electrolyzer projects that are expected to go online in 2021–2023 account for only 2.7 GW of capacity.³⁰ Without rapid and profound acceleration of both renewables and electrolyzer deployment, the demand of global-scale CO₂ recycling will remain unmet.

Global Electricity and Hydrogen Consumption

To illustrate the volume of inputs that CO₂ recycling at global scale will demand from this critical infrastructure, Figure 8 shows the electricity and hydrogen consumption of CO₂ recycling pathways at full market scale. ***Most CO₂ recycling pathways at global scale would require 1,100 to 9,200 TWh/yr of low-carbon electricity*** (Figure 8a and 8b). The sum across all pathways, excluding methane and duplicate products as described in the methodology, is 36,700 TWh/yr. Since the world consumes approximately 26,000 TWh/yr of electricity today,³¹ this represents a monumental amount of electricity demand, which must be supplied entirely by low-carbon sources! At the same time, the global technical potential for electricity generation from solar and wind sources is hundreds of thousands of TWh/yr for each,³² indicating that the required scale of renewable resource is available many times over if economics and other constraints allow.

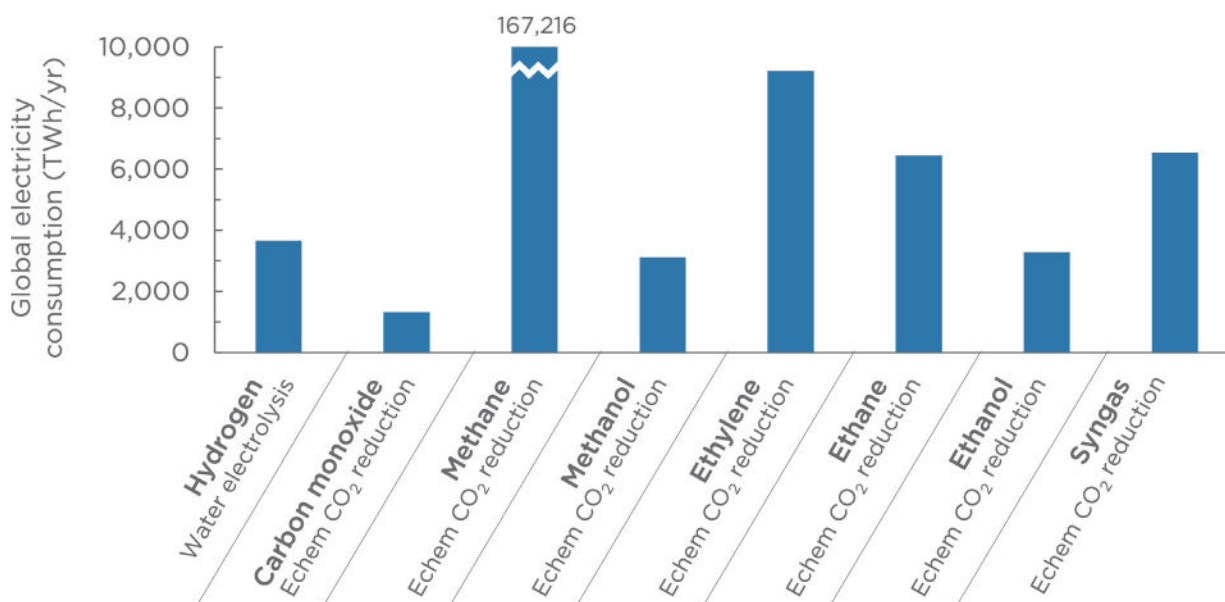
The global feedstock hydrogen consumption of thermochemical CO₂ recycling pathways is 30–100 Mt/yr for each pathway (Figure 8c), comparable to the current global hydrogen consumption of 70 Mt/yr.³³ Similar to electricity, this hydrogen demand must be supplied by low-carbon sources for CO₂ recycling to abate emissions. With low-carbon hydrogen



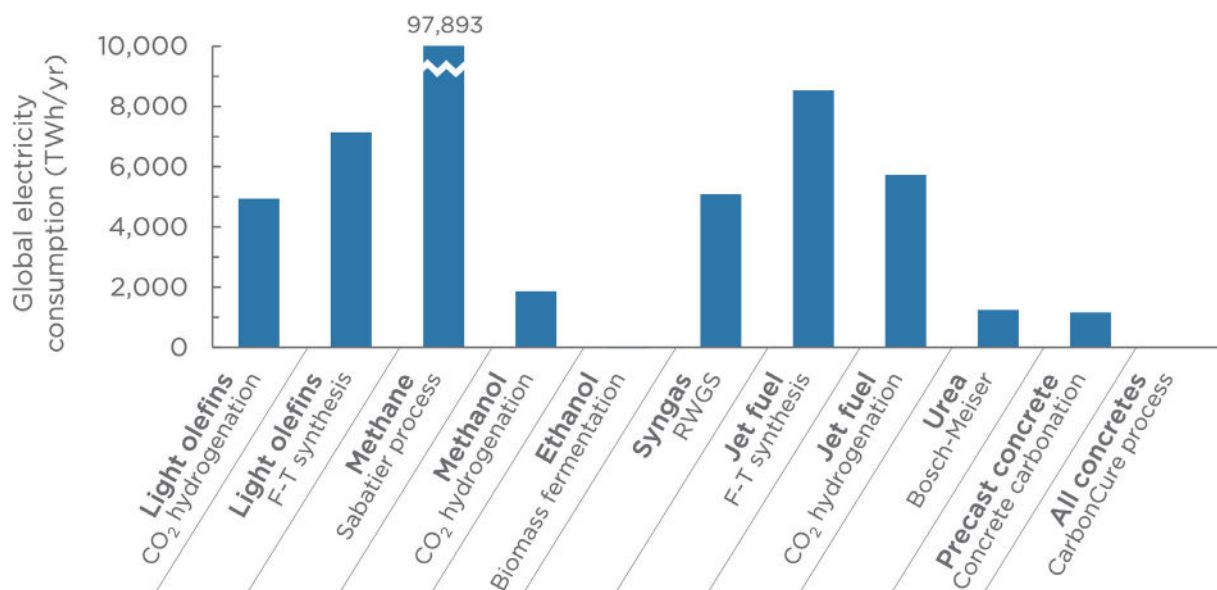
production reaching 8 Mt/yr in 2030 in the IEA's Sustainable Development Scenario,³⁴ accelerating growth of low-carbon hydrogen will be needed to scale CO₂ recycling.

Figure 8: Global electricity consumption of a) electrochemical and b) thermochemical CO₂ recycling pathways. c) Global hydrogen consumption of thermochemical CO₂ recycling pathways. Values represent CO₂ recycling pathways scaled to the current global demand for their product.

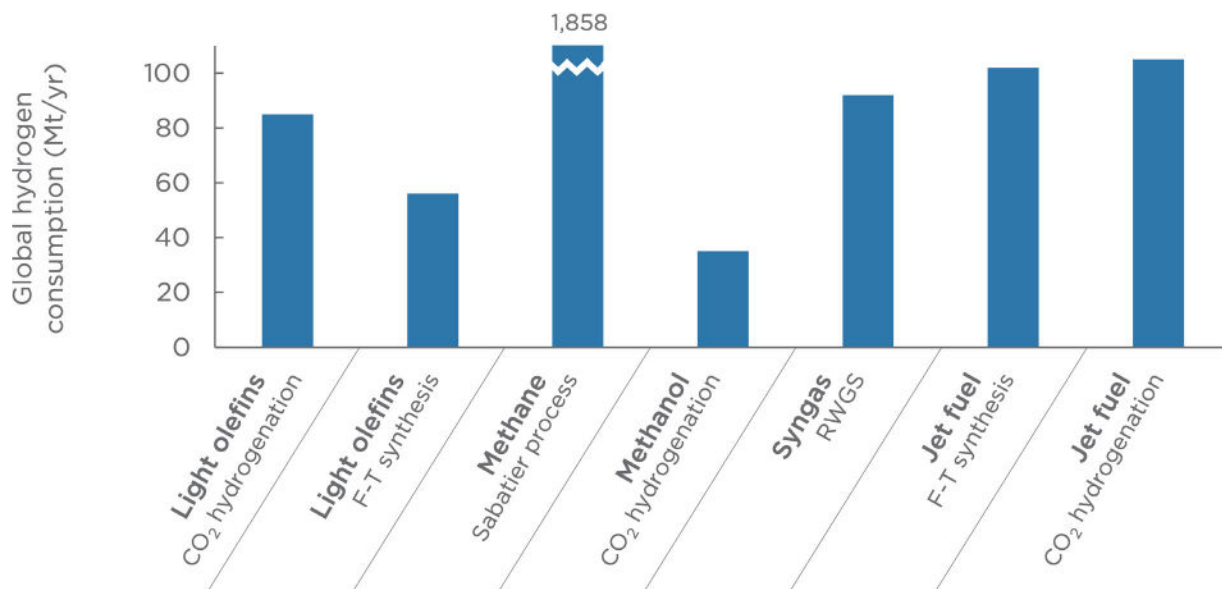
a.



b.



c.



DISCUSSION

Our results lay the groundwork for a large-scale CO₂ recycling deployment strategy. ***The analysis finds that four pathways have an ECOP lower than the selling price and may therefore currently be profitable: electrochemical CO production, ethanol production from lignocellulosic biomass, precast concrete carbonation, and the CarbonCure concrete process.*** This highlights opportunities for planning, investment, and policy actions. The ethanol from lignocellulosic biomass pathway is already commercial. Electrochemical CO production is not, though a large portion of CO is produced and consumed as syngas (CO + H₂). Although there is a commercial CO market today, it is small and difficult to enter, limiting opportunities to scale. To accelerate commercialization of low-cost electrochemical CO production, produced CO could be mixed with low-carbon H₂ and sold as low-carbon syngas. This would provide a market for electrochemical CO production while reducing emissions associated with conventional syngas formation from natural gas.

Reducing the Estimated Cost of Production of CO₂ Recycling Pathways

The remaining CO₂ recycling pathways have an ECOP above the selling price, making them unprofitable today. If the gap between ECOP and selling price is small enough to be bridged by subsidies designed to bring down ECOP, this can result in subsidy-supported profitability. Alternatively, as the result of carbon pricing or other market forces, the product selling price might increase to meet a higher ECOP. This price increase may reflect increased need for CO₂ recycling in the future or demand for low-carbon products leading to a higher willingness to pay. Importantly, our ECOP calculations were designed to give globally representative production costs, and in certain locations or conditions, ECOP may be significantly closer to the current selling price.

Of course, price parity is not the sole criterion for adoption by companies and markets, and the net present value of existing assets, security of supply chains, ease of integration, and many other criteria are important in corporate decision making. However, most pathways assessed could cost substantially more to produce than today's market-available alternatives, indicating a need for cost reduction and market-aligning policies.

Innovations in CO₂ recycling technologies, particularly for catalysts, are likely to be the most effective way to reduce the ECOP of CO₂ recycling pathways. Since direct electricity consumption is the largest contributor to ECOP for all electrochemical processes, improvements in electrical energy conversion efficiency are critical to reducing cost and can be achieved by lowering the required overpotentials on electrocatalysts for electrochemical CO₂ reduction and water electrolysis. For both thermochemical and electrochemical pathways, product selectivity dramatically affects cost by influencing the required volume of material and energy inputs. By reducing the resource intensity of production, higher efficiencies and selectivities will also lessen the critical infrastructure needs to support CO₂ recycling. Improved selectivities would also alleviate the need for intensive separations processes to isolate the desired product from byproducts, whose costs are not considered in



this study. Since many of these technologies are relatively nascent, there are wide margins for improvement in catalyst performance that could yield significant cost reductions.

Improving selectivity will require developing a new generation of catalysts tailored to specific products and tuning reactor conditions for the desired product distribution. These two technical opportunities strongly recommend a targeted innovation agenda focused on developing thermo- and electrocatalysts with improved activity and selectivity, thereby reducing total power requirements and the need for separation and processing of products.

An alternative response to selectivity limitations is the commercialization of coproduced valuable molecules from the same reactor. CO₂ recycling pathways often produce a wide range of hydrocarbons, alcohols, and oxygenates, all of which have market value. The conventional approach (applied in this study) is to design a CO₂ recycling facility to produce one product with ≈30–70 percent selectivity and to discard the byproducts. This essentially wastes both the energy and feedstocks used to create these marketable byproducts. If facilities could instead be designed to simultaneously produce multiple products for sale, selectivity constraints could be repurposed as an asset. The cost of product separations could present a challenge to such an approach. In this context, one strategy is to coproduce easily separable products, such as a liquid and a gas, to avoid energy- and cost-intensive separation steps. For instance, carbon monoxide is often produced in large quantities as a byproduct of electrochemical and thermochemical direct CO₂ conversion processes.³⁵ Instead, gaseous CO could be separated and sold as a coproduct of liquid products such as methanol or jet fuel.

An additional challenge of coproduction could be that the generation ratios of coproducts is mismatched to market demand, an issue that could become acute at large scale. Pathways with viable coproduction ratios should be identified for coproduction during planning. In addition, the selectivity of CO₂ recycling catalysts could be tuned so that product ratios align closer with market demand. By making full use of the energy and feedstock inputs to the reactor, effective coproduction would allow us to meet global demand for CO₂ recycling products with lower critical infrastructure needs and lower ECOP for each product.

A second strategy to decrease ECOP is lowering the costs of the key inputs and feedstocks for CO₂ recycling pathways. These include the costs of electricity for the electrochemical processes and hydrogen or syngas for many thermochemical pathways. This cost reduction challenge is deepened by the requirement that the inputs have a low- to zero-carbon intensity to ensure a net emissions reduction through CO₂ recycling. For this reason, low-carbon/ renewable electricity, green hydrogen, and low-carbon syngas are the ideal forms of these inputs. As assumed in this study, feedstocks for thermochemical processes including hydrogen and syngas can potentially be made with electrochemical pathways, creating a hybrid process that has been found to be favorable for emissions reductions.³⁶

Reducing the cost of low-carbon hydrogen production would be key to making thermochemical pathways less costly. For green H₂ production by water electrolysis, cost reductions will be most sensitive to improvements in electrical energy conversion efficiency. Efficiency gains can be made by enhancing electrocatalyst activity to lower the required overpotential for water electrolysis. The aforementioned renewable electricity price reductions would also lower electricity input costs for the process, which make up the majority of ECOP



for green H₂. While the green H₂ production cost is highly sensitive to product selectivity, there are no major competing reactions in water electrolysis, with the notable exception of seawater electrolysis in limited contexts.³⁷ Selectivities of nearly 100 percent for water electrolysis have been consistently achieved,³⁸ so improving catalyst selectivity in green H₂ production should not be a focus.

An additional option is to use blue H₂ instead of green H₂, which is produced through steam methane reforming with carbon capture, making it a low-emissions hydrogen source. Costing around \$1.5/kg–\$3/kg,³⁹ blue H₂ is currently less expensive than green H₂ (estimated to cost \$6.3/kg in this study), which could make it a useful near-term alternative input to CO₂ recycling processes. However, blue H₂ requires continued supply of natural gas, which entails substantial upstream/midstream methane leakage, CO₂ emissions, and other detriments,⁴⁰ so green H₂ would be the ideal hydrogen source in the longer term. In contrast, lowering the cost of CO₂ is not a priority due to its relatively small effect on estimated cost of production.

Lowering renewable electricity costs can have a large impact on ECOP, but it represents a secondary measure for reducing ECOP and should be pursued accordingly. Innovation for renewable energy technologies would be helpful for decreasing renewable electricity costs. However, innovation funding to reduce ECOP is likely to be more effective through improving the performance of CO₂ recycling catalysts, which are relatively underdeveloped and have larger margins for improvement than renewable electricity technologies. Additionally, improving catalyst selectivity and activity would reduce the energy intensity of CO₂ recycling and thus bring down the large renewable energy infrastructure demands of these pathways.

Though lowering the price of renewable electricity should be a secondary priority from an ECOP reduction perspective, accelerated deployment of renewable energy capacity will be critical to meet the demanding low-carbon electricity consumption of global-scale CO₂ recycling processes. This renewables deployment will have an additional benefit of lowering electricity costs through learning-by-doing, although deep cost reductions through this approach will be difficult to achieve due to the enormous global deployment required to achieve doublings of installed renewable capacity.

Improvements in the capital cost and capacity factor—which determine total CAPEX from an intensive and extensive standpoint, respectively—will not be as effective in reducing ECOP compared to the measures already discussed. However, as efficiencies and selectivities improve and the cost of inputs goes down, variable costs will become a smaller portion of total cost and ECOP will become increasingly sensitive to CAPEX. This shift will signal an important milestone for CO₂ recycling pathways, where efforts to reduce capital cost will become crucial and policy levers such as capital cost loan programs will become financially salient. Importantly, Figure 1 demonstrates that many pathway ECOPs would remain higher than the selling price even if the costs of electricity and hydrogen went to zero. ***Although variable costs dominate ECOP currently and should be the main focus for cost reductions at the outset, concurrently lowering CAPEX and fixed O&M cannot be neglected if cost parity is to be achieved in the longer term.***

Our analysis finds it exceedingly difficult and often impossible to achieve profitability for a pathway by improving only one of the techno-economic inputs alone. Decreasing ECOP



sufficiently requires cost reductions across the board, from improvements in technological performance to cheaper feedstocks. This calls for redoubled efforts across sectors. It also suggests a coordinated approach involving both innovation investment and market-aligning policies.

Carbon Abatement

Our findings demonstrate that replacing conventional pathways with CO₂ recycling could significantly abate emissions. Excluding methane pathways, completely producing the products investigated using CO₂ recycling would abate 6.8 GtCO₂/yr. On an intensive basis, most pathways abate 2–11 tCO₂ per metric ton of product when replacing conventional production, representing substantial abatement for each unit of CO₂ recycling production. **However, these carbon abatement potentials are heavily contingent on our assumption that the CO₂ recycling pathways consume renewable electricity and low-carbon feedstocks.** If these pathways instead consume fossil-based grid electricity and feedstocks generated using conventional petrochemical processes like SMR-derived H₂, CO₂ recycling is likely to emit more CO₂ than the current production methods.⁴¹ Therefore, it is critically important that CO₂ recycling pathways use low-carbon inputs to ensure that deploying these pathways does not ultimately increase emissions. In this context, developing the critical infrastructure to generate and deliver these low-carbon inputs at low cost is a priority.

The MAC and breakeven effective carbon price of most pathways are relatively high, in the hundreds of dollars per tCO₂. We note that these estimates do not incorporate the costs or savings of displacing conventional production, such as the avoided fuel costs of operating a chemical plant at reduced capacity due to partial displacement by a CO₂ recycling pathway. If displacing conventional production results in net savings, the MAC and breakeven effective carbon price would be lower.

Critical Infrastructure Needs

Our analysis demonstrates that CO₂ recycling at scale will require large quantities of new infrastructure for renewable electricity generation, electricity transmission, electrolyzer capacity, and CO₂ transport. We estimate this infrastructure will cost trillions of dollars in capital investment for each pathway at global scale. These findings indicate that, in addition to reducing the cost of production for CO₂ recycling pathways, building these supportive infrastructures at an aggressive pace and scale will be key to enabling CO₂ recycling.

In order to maximize emissions abatement, CO₂ recycling must be supplied with low-carbon electricity. Due to the high electricity demand of each CO₂ recycling pathway, new low-carbon electricity generation capacity constitutes the large majority of critical infrastructure capital costs for CO₂ recycling. Since CO₂ recycling will join a range of growing demands for clean electricity in a sustainable energy future, including electrified transport and heating, it is likely that even more low-carbon generation, mostly renewable generation, will be required to meet the needs of CO₂ recycling along with these other demands. This makes accelerated deployment of low-carbon/renewable electricity capacity crucial to enabling CO₂ recycling at scale.

A build-out of long-range electricity transmission lines will likely be needed to deliver



renewable electricity to CO₂ recycling centers far from renewable energy resources. Our estimates show that new transmission infrastructure for CO₂ recycling globally would account for a small portion of the overall critical infrastructure capital investment needs but would still require hundreds of billions of dollars in capital investment. In this analysis, we attribute new transmission costs entirely to new renewable generation installations at a transmission capital cost of \$300 per kW of renewable capacity.⁴² However, the transmission cost may ultimately be lower since the new transmission lines will probably be shared by multiple sources and not all renewable projects will require entirely new transmission build-out.

The second most capital-intensive type of critical infrastructure for most pathways is electrolyzer capacity. CO₂ electrolyzers will be needed to perform electrochemical CO₂ reduction for the electrochemical pathways, and water electrolyzers will supply green hydrogen for the thermochemical pathways. The capital investment needed for electrolyzers can be expected to drop substantially in coming years through innovation and rapid doublings of installed capacity.

CO₂ transport pipelines appear to be the least expensive form of critical infrastructure, with most pathways requiring less than \$50 billion in CO₂ transport capital costs. These CO₂ transport pipelines will be needed to deliver feedstock CO₂ from its source, either a DAC or point-source carbon capture facility, to its end use in a CO₂ recycling pathway. Our CO₂ transport costs represent minimal cost estimates, since the CO₂ transport networks modeled are very high capacity and smaller pipelines would require more capital. Nevertheless, for most pathways CO₂ transport accounts for less than 3 percent of the total infrastructure cost, suggesting that CO₂ transport will likely remain the least expensive piece of critical infrastructure even with higher cost estimates.

As an important caveat, these estimates of critical infrastructure capital cost do not consider the additional difficulties of building the infrastructure. In many nations, especially OECD countries, new energy infrastructure is contentious and is not guaranteed on the basis of cost competitiveness alone.

Greater efficiencies in infrastructure build-out can be found by “piggybacking” on existing industrial and chemical infrastructure. For instance, oil and gas pipelines can potentially be repurposed to transport hydrogen or CO₂ feedstocks to the CO₂ recycling plant. The thermochemical CO₂ recycling pathways in particular will use many of the same process units conventionally used in chemical plants, which could be repurposed for CO₂ recycling processes. Some CO₂ recycling pathways would even directly use existing infrastructure. For example, both CO₂ recycling urea production and the CarbonCure concrete process simply require an external CO₂ input stream retrofit to a conventional urea or concrete plant.

Market Size

One important feature to these CO₂ recycling pathways is that their products represent existing markets on the order of 100 Mt/yr globally. ***Although current cost barriers are substantial, the market for these fuels, chemicals, and materials already exists and is robust,*** as these products are essential to our global society. For this reason, CO₂ recycling products have a low risk of saturating existing markets in early deployment or driving down



selling prices. The reliable demand and largely stable prices for the products provide a high degree of near-term certainty that should encourage actors making entry into a nascent CO₂ recycling industry.

Since our analysis of carbon abatement potential, infrastructure needs, global electricity/hydrogen consumption, and needed subsidies assume CO₂ recycling pathways will supply current global demand for their products, these estimates represent a maximum scale case. The true size of these extensive metrics is likely to be lower than our estimates, particularly in the nearer term. Additionally, as the per-unit capital cost of renewable capacity and electrolyzers continue to drop rapidly, the total infrastructure cost at the time CO₂ recycling reaches global scale will likely be significantly lower. Nevertheless, these estimates help bound the possibility space for the scale of CO₂ recycling.



POLICY RECOMMENDATIONS

Our findings indicate that, while CO₂ recycling is a potentially pivotal carbon abatement tool, a measured approach must be taken to improving the techno-economics of and deployment of CO₂ recycling pathways. Policies to support CO₂ recycling pathways should prioritize the pathways with the most promise for reaching commercial maturity to avoid expending limited resources on pathways that have limited prospects of becoming techno-economically viable in the foreseeable future. For these prioritized pathways, policymakers should seek to both create demand for CO₂ recycling products and to bring down the costs of CO₂ recycling pathways.

Prioritizing Pathways

For prioritizing certain CO₂ recycling pathways, our analysis suggests pathways that are closest to market and might benefit most from policy to help support market entry. We define these as pathways with an ECOP to selling price ratio of less than five. Under this definition, ***the following pathways should be prioritized for early market entry: green hydrogen production, electrochemical CO production, CO₂ hydrogenation to light olefins, CO₂ hydrogenation to methanol, CO₂ hydrogenation to jet fuel, ethanol production from lignocellulosic biomass, CO₂ recycling urea production, precast concrete carbonation curing, and the CarbonCure concrete process.*** Because these CO₂ recycling processes are relatively close to reaching market parity (or are profitable today), demand pull policies such as public procurement could prove cost effective at bringing these pathways to scale quickly, achieving substantial emissions reductions. ***In addition, these pathways, along with pathways that have ECOP to selling price ratios from 5 to 7.5, remain excellent candidates for investment in innovation and technical development.***

Though many of the remaining pathways have large carbon abatement potentials, pursuing these less promising pathways could hinder the progress of CO₂ recycling, and policy support on these pathways would be ineffective, absent a breakthrough innovation. These pathways, namely electrochemical methane and ethane production and Sabatier process methane production, would require meeting a highly demanding set of techno-economic targets to reach market parity. The greater than 25:1 ECOP to selling price ratios for these processes present a difficult gap to bridge through subsidies, and demand-side policies like portfolio standards could force producers to adopt exceedingly expensive production processes and pass on undue price increases to consumers. ***Large subsidies or innovation spending for processes that are unlikely to become profitable could be better spent supporting more viable CO₂ recycling pathways.*** As a result, methane and ethane markets may require ongoing supplies of conventional natural gas even as measures to minimize natural gas demand and emissions continue in parallel. Given the high ECOP to selling price ratios, it may prove necessary to balance these emissions with CO₂ removal practice elsewhere.⁴³

Pursuing the more promising pathways first could have spillover benefits for the less promising pathways. Under a targeted innovation agenda, technological advances for the prioritized CO₂ recycling pathways could be applied broadly. For instance, a breakthrough



in our understanding of how to tailor the selectivity of electrochemical CO₂ reduction catalysts for C-C coupling may provide insights for targeting a range of C₂₊ products through electrochemical CO₂ reduction. Additionally, the renewable energy and CO₂ transport infrastructure deployed for scaling near-term CO₂ recycling pathways could be leveraged by all remaining pathways later on. With these spillover benefits, it may become more viable in the medium to long term to pursue currently unfavorable pathways and unlock the sizable carbon abatement potential associated with them. This logic may also apply to the deployment of CO₂ recycling pathways for low-volume, high-market price products that are outside the scope of this study. These pathways include some listed in our broad summary of CO₂ recycling pathways in Table A5.

Policies for Cost Reductions and Market Deployment

In addition to identifying the most promising CO₂ recycling pathways, our findings highlight how policies can most effectively reduce the ECOP of these pathways. ***The primary lever we propose for lowering ECOP is technological innovation policy focused on improving the activity and selectivity of CO₂ recycling catalysts.*** Innovation policy has been found to be an important contributor and accelerant of cost reduction and performance increase.⁴⁴ Because the efficiency and yield of CO₂ recycling pathways were found to have a large influence on ECOP in our sensitivity analysis, a targeted RD&D program to enhance catalytic activity and product selectivity of electro- and thermocatalysts would improve the efficiency and yield of CO₂ recycling pathways, respectively, unlocking cost reductions. Since many of these technologies, particularly electrochemical CO₂ reduction, are relatively nascent, an innovation program could achieve substantial improvements in catalyst performance and drive deep cost reductions. The costs of renewable electricity, green H₂, and/or low-carbon syngas inputs to the pathways also have a high impact on ECOP, and innovation in renewable electricity technologies as well as catalysts to produce green H₂ and low-carbon syngas will be key to lowering these input costs. Finally, production pathways for these three inputs would see deployment-related cost reductions if scaled rapidly to supply the growing CO₂ recycling pathways that depend on them.

In tandem with cost reductions of CO₂ recycling pathways, policies should include market-aligning measures for the pathways ready for early market entry, to lower barriers to entry and create demand. However, the differential between ECOP and selling prices suggests care and consideration in prioritizing market-aligning policies. Some pathways, such as methane production or electrochemical methanol production, are so expensive that even large expenditures might prove unable to stimulate market adoption today. In contrast, supporting the purchase and market adoption of products that are relatively close to market prices would create supply chains for some products, provide contracting experience and quality standards, and accelerate cost reduction for enabling technology for the other products and pathways.

Regarding specific policies, incentives for CO₂-based products could narrow the cost gap between a CO₂ recycling pathway and existing market alternatives, as was done with tax credits and feed-in tariffs for renewable power. A comparable policy strategy could include production tax credits for CO₂ recycled products. Similarly, mandates could serve to create early market pull and establish supply chains and methodologies for standards. For example,



governments could require that a certain percentage of a product under direct procurement is supplied by CO₂ recycling pathways (i.e., “buy clean” requirements). This strategy has proven important to many clean energy technologies, notably in biofuel procurement mandates in defense-related applications. This was tried successfully in California’s Buy Clean Act,⁴⁵ which included structural steel and rebar but did not include CO₂ recycled materials. New York State is considering a clean concrete legislation that would provide modest price support for novel low-carbon cement formulations.⁴⁶ Importantly, the development, testing, and codification of standards and life cycle methodologies from early procurements provided an important basis for future regulation and drove investment in qualification and performance enhancement. In addition, prize competitions or milestone payments for CO₂ recycling technologies upon reaching certain stages of maturity can be effective at creating early markets for these pathways and spur further innovation as technologies transition from the RD&D stage toward market deployment.⁴⁷

Critical Infrastructure Build-out

Innovation and market policy alone will not deliver CO₂ recycled products to markets due to infrastructure limits. The analysis shows that critical electrical and CO₂ transmission infrastructure investments are required to serve manufacturers and supplies. In most markets, governments provide critical funds or critical authorization of rate base to build and maintain critical energy infrastructure. Infrastructure policies should include funding for construction, permitting and regulatory support, public outreach and engagement, and, in rare cases, condemnation or exercise of eminent domain—this should apply to both transmission and renewable generation infrastructure. Similar policy measures are important components of the Biden “Build Back Better” policy drive, Canada’s Hydrogen Roadmap, and the EU’s Green Deal plan.⁴⁸



CONCLUSION

CO₂ recycling pathways show real promise for displacing existing fossil-intensive production pathways of high volume products. If implemented on a global scale, these CO₂ recycling pathways (excluding costly methane) could collectively result in up to 6.8 GtCO₂/yr of carbon abatement, although the pathways that are currently profitable account for 1.6 GtCO₂/yr of abatement potential. The estimated cost of production (ECOP) varies significantly between pathways but is typically significantly higher (2.5–7.5 times more expensive) than the product selling price. A few key pathways may prove the most attractive for early market entry due to their ECOP to selling price ratios of less than five, and many others are suitable for further RD&D.

To provide relevant climate and economic benefits through commercial markets, ECOP reductions of key CO₂ recycling pathways are essential and urgently needed. A variety of cost reduction levers can and should be used to achieve profitability, including improving a pathway's electrical efficiency and selectivity, as well as reducing the costs of key inputs such as renewable electricity, green H₂, electrochemically produced CO, and low-carbon syngas inputs. Well-crafted innovation policy combined with market-alignment policies can contribute substantially to all these approaches. On a global scale, CO₂ recycling pathways would require major investment in critical infrastructure. Enormous growth of both renewable electricity (generation and transmission), electrolyzer capacity, and CO₂ transport networks are critical pathways for global deployment.



APPENDIX

Appendix Tables

Table A1: Technical inputs and assumptions for CO₂ recycling pathways. Definitions of figures of merit given in Appendix.

Product	Process	Global demand (Mt product/yr)	Gravimetric energy density (kWh/kg)	Echem electrical energy efficiency	Thermochem plant electrical energy efficiency	Hydrogen selectivity	Carbon selectivity	Faradaic efficiency	Conversion	References
Electrochemical pathways										
Hydrogen	Water electrolysis	70	39.4	0.75	--	--	0	1.0	1.0	49
Carbon monoxide	Electrochemical CO ₂ reduction	320	2.3	0.55	--	--	1.0	1.0	1.0	50
Methane	Electrochemical CO ₂ reduction	2,920	15.2	0.53	--	--	0.57	0.56	0.90	51
Methanol	Electrochemical CO ₂ reduction	140	6.4	0.54	--	--	0.42	0.59	0.90	52
Ethylene	Electrochemical CO ₂ reduction	150	13.9	0.48	--	--	0.51	0.52	0.90	53
Ethane	Electrochemical CO ₂ reduction	40	14.4	0.41	--	--	0.30	0.24	0.90	54
Ethanol	Electrochemical CO ₂ reduction	87	8.3	0.45	--	--	0.65	0.54	0.90	55
Syngas	Electrochemical CO ₂ reduction	691	3.9	0.51	--	--	0.72	0.76	1.0	56

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Product	Process	Global demand (Mt product/yr)	Gravimetric energy density (kWh/kg)	Echem electrical energy efficiency	Thermochem plant electrical energy efficiency	Hydrogen selectivity	Carbon selectivity	Faradaic efficiency	Conversion	References
Thermochemical pathways										
Light olefins incl. ethylene	CO ₂ hydrogenation	150	13.9	--	0.75	0.68	0.36	--	0.90	57
Light olefins incl. ethylene	F-T synthesis	150	13.9	--	0.75	0.64	0.34	--	0.90	58
Methane	Sabatier process	2,920	15.2	--	0.75	0.79	0.72	--	1.0	59
Methanol	CO ₂ hydrogenation	140	6.4	--	0.75	0.75	0.75	--	0.90	60
Ethanol	Biomass fermentation	87	8.3	--	0.75	--	1.0	--	0.76	61
Syngas	RWGS	691	3.9	--	0.75	1	0.90	--	1.0	62
Jet fuel	F-T synthesis	200	11.9	--	0.75	0.58	0.56	--	0.90	63
Jet fuel	CO ₂ hydrogenation	200	11.9	--	0.75	0.56	0.35	--	0.90	64
Urea	Bosch-Meiser	208	2.9	--	0.75	0.72	1.0	--	0.88	65
Precast concrete	Concrete carbonation	5,974	--	--	0.75	--	--	--	--	66
All concretes	CarbonCure process	33,000	--	--	0.75	--	--	--	--	67



Table A2: Plant assumptions for CO₂ recycling pathways

Product	Process	Capacity factor	Electrolyzer capital cost (\$/kW)	Plant capital cost (\$/ton/yr-capacity)	Equipment lifetime (yr)
Electrochemical pathways					
Hydrogen	Water electrolysis	0.5	1,000	--	15
Carbon monoxide	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Methane	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Methanol	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Ethylene	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Ethane	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Ethanol	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Syngas	Electrochemical CO ₂ reduction	0.5	1,000	--	30
Thermochemical pathways					
Light olefins incl. ethylene	CO ₂ hydrogenation	0.9	--	2,741	30
Light olefins incl. ethylene	F-T synthesis	0.9	--	2,447	30
Methane	Sabatier process	0.9	--	2,111	30
Methanol	CO ₂ hydrogenation	0.9	--	777	30
Ethanol	Biomass fermentation	0.9	--	2,226	30
Syngas	RWGS	0.9	--	84	30
Jet fuel	F-T synthesis	0.9	--	3,969	30
Jet fuel	CO ₂ hydrogenation	0.9	--	3,320	30
Urea	Bosch-Meiser	0.9	--	819	30
Precast concrete	Concrete carbonation	0.9	--	--	30
All concretes	CarbonCure process	0.9	--	--	30



Table A3: Financial assumptions for CO₂ recycling pathways

Parameter	Value
Renewable electricity price (\$/kWh)	0.095
Green hydrogen feedstock price (\$/tH ₂)	6,302
CO ₂ feedstock price (\$/tCO ₂)	50
CO feedstock price (\$/tCO) ⁶⁸	546
Green ammonia feedstock price (\$/tNH ₃)	1,573
Lignocellulosic biomass feedstock price (\$/dry ton)	65
CO ₂ transport pipeline network capital cost (\$/tCO ₂ /yr capacity) ⁶⁹	42
Transmission capital cost (\$/kW renewable generation capacity) ⁷⁰	300
Renewable electricity carbon intensity (gCO ₂ /kWh) ⁷¹	25
Weighted average cost of capital (WACC)	5%
Fixed O&M percentage of capex electrolyzer	4%
Fixed O&M percentage of capex thermochemical plant	10%
Capacity factor of renewable mix used to determine GW capacity needs	50%



Table A4: Summary of key results from techno-economic analysis of CO₂ recycling pathways

Product	Process	Product selling price (\$/metric ton)	Estimated cost of production (\$/metric ton product)	ECOP/selling price ratio	Carbon abatement potential (MtCO ₂ /yr)	Intensive CO ₂ abatement (tCO ₂ /metric ton product)	Marginal abatement cost (\$/tCO ₂)	Critical infrastructure capital cost (\$B)
Electrochemical pathways								
Hydrogen	Water electrolysis	2,500	6,302	2.5	749	10.7	589	2,757
Carbon monoxide	Electrochemical CO ₂ reduction	700	546	0.8	882	2.8	198	1,023
Methane	Electrochemical CO ₂ reduction	175	6,714	38.4	11,659	4.0	1,681	126,635
Methanol	Electrochemical CO ₂ reduction	400	2,689	6.7	768	5.5	490	2,372
Ethylene	Electrochemical CO ₂ reduction	1,000	7,258	7.3	997	6.7	1,091	6,984
Ethane	Electrochemical CO ₂ reduction	196	18,705	95.4	230	5.7	3,260	4,881
Ethanol	Electrochemical CO ₂ reduction	800	4,416	5.5	286	3.3	1,341	2,488
Syngas	Electrochemical CO ₂ reduction	158	1,116	7.1	1,501	2.2	491	4,961
Thermochemical pathways								
Light olefins incl. ethylene	CO ₂ hydrogenation	1,000	4,789	4.8	1,337	8.9	537	3,661
Light olefins incl. ethylene	F-T synthesis	1,000	6,311	6.3	925	6.2	1,024	5,337
Methane	Sabatier process	175	4,555	26.0	9,384	3.2	1,417	74,048
Methanol	CO ₂ hydrogenation	400	1,824	4.6	570	4.1	448	1,411
Ethanol	Biomass fermentation	800	809	1.0	333	3.8	211	0
Syngas	RWGS	158	934	5.9	1,393	2.0	464	3,797
Jet fuel	F-T synthesis	1,000	5,885	5.9	1,003	5.0	1,174	6,417
Jet fuel	CO ₂ hydrogenation	1,000	4,423	4.4	1,664	8.3	532	4,339
Urea	Bosch-Meiser	215	1,071	5.0	138	0.7	1,611	936
Precast concrete	Concrete carbonation	100	70	0.7	174	0.03	672	612
All concretes	CarbonCure process	100	49	0.5	170	0.01	-156	0



Overview of Selected CO₂ Recycling Pathways

The CO₂ recycling pathways analyzed in this study are listed in Table 1. Each pathway is defined by the pairing of a chemical process (e.g., CO₂ hydrogenation) and its desired product (e.g., methanol). Several of the chemical processes can be adapted to target various products, and in these cases, we evaluate each process-product pairing as a distinct pathway.

Eight of the pathways are electrochemical, meaning the driving force for the reactions comes from electricity. They include the following pathways:

- *Water electrolysis to produce hydrogen:* In water electrolysis, electricity is used to split water molecules into hydrogen (H₂) and oxygen (O₂). Though not strictly a CO₂ recycling pathway, the generated H₂ is a key input for many thermochemical CO₂ recycling pathways.
- *Electrochemical CO₂ reduction to produce carbon monoxide, methane, ethylene, or ethanol:* The electrochemical CO₂ reduction pathways entail reacting CO₂ and water in a CO₂-saturated aqueous solution to produce a wide range of carbon-based or hydrocarbon products.⁷² By tailoring the selectivity of the electrocatalyst, the reaction can be directed to produce different molecules as the major product.
- *Electrochemical CO₂ reduction to produce methanol:* Methanol is produced with low selectivities in typical electrochemical CO₂ reduction in aqueous electrolyte, but several studies have achieved significantly higher methanol selectivities by conducting electrochemical CO₂ reduction in an electrolyte consisting of a mixture of water and an ionic liquid such as [Bmim]BF₄.⁷³ We model our electrochemical CO₂ reduction to methanol pathway based on these ionic liquid electrolyte studies. The need to use an ionic liquid electrolyte may present additional challenges to scale that are not considered here.
- *Electrochemical CO₂ reduction to produce ethane:* We model electrochemical CO₂ reduction to ethane based on catalysis studies that use PdCl₂ in the aqueous electrolyte to enhance performance. The need to use this additive, which is consumed in the reaction process, may entail additional challenges to scale that are not considered here.
- *Electrochemical CO₂ reduction to produce syngas:* A common byproduct of electrochemical CO₂ reduction is H₂ generated through the hydrogen evolution side reaction. In the electrochemical syngas pathway, electrochemical CO₂ reduction is used to create carbon monoxide (CO) with H₂ as a byproduct to yield syngas, a mixture of CO and H₂. We design this pathway to produce syngas with a CO/H₂ mole ratio of 0.8.

The remaining nine pathways are thermochemical pathways for which the driving force is thermal, though often the majority of the energy input for these processes comes from feedstock hydrogen as discussed in the results section. The thermochemical pathways are:

- *Fischer-Tropsch (F-T) synthesis to produce light olefins or jet fuel:* F-T synthesis involves the reaction of syngas (CO and H₂) to form various hydrocarbons with adjustable



product selectivity.⁷⁴ We model the F-T pathways as using separately generated green hydrogen from renewables-powered electrolysis as the feedstock H₂ source and using feedstock CO generated from renewables-powered electrochemical CO₂ reduction. The “light olefins” product mixture includes ethylene, propylene, and butylene.

- *CO₂ hydrogenation to produce light olefins, methanol, or jet fuel:* In CO₂ hydrogenation, CO₂ and H₂ are reacted to form various hydrocarbons, and catalyst selectivity can be used to tailor the product mix.⁷⁵ In this paper, we do not distinguish between hydrogenation mechanisms, such as the methanol reaction involving a methanol intermediate or F-T based CO₂ hydrogenation, in which CO₂ is reduced to CO in situ before reacting with H₂ through the F-T process.⁷⁶ We assume CO₂ hydrogenation pathways use green hydrogen feedstock.
- *Sabatier process to produce methane:* The Sabatier process, also known as CO₂ methanation, combines CO₂ and H₂ (assumed to be green H₂ in this study) to form methane thermochemically.⁷⁷
- *Reverse water-gas shift (RWGS) reaction to produce syngas:* The RWGS reaction is a reversible process by which CO₂ and H₂ (assumed to be green H₂) are converted to CO and H₂O.⁷⁸ The RWGS reaction is typically taken only partially to completion in order to yield syngas.
- *Bosch-Meiser process to produce urea:* The Bosch-Meiser process is a large-scale industrial pathway that reacts ammonia and CO₂ to produce urea.⁷⁹ Conventionally, the feedstock ammonia is often produced onsite by combining steam methane reforming (SMR)-derived hydrogen with nitrogen (N₂) in the Haber-Bosch process. The CO₂ produced from SMR is then combined with the produced ammonia to create urea through Bosch-Meiser.⁸⁰ This study uses an alternative CO₂ recycling Bosch-Meiser process in which green ammonia is produced using green hydrogen and N₂ through the Haber-Bosch process, and externally sourced feedstock CO₂ is then reacted with this green ammonia to produce urea.
- *Lignocellulosic biomass fermentation to produce ethanol:* Ethanol production from lignocellulosic biomass, perhaps more specifically categorized as a biochemical process, involves the breakdown of lignin and polysaccharides into simple sugars, which are then fermented to produce ethanol.⁸¹ Feedstock lignocellulosic biomass can be sourced from agricultural residues such as corn stover, forestry residue, and other wastes and nonfood crops.

The remaining two pathways are different CO₂ recycling-based modifications to a single step in conventional concrete production. We model the concrete pathways by assuming that the pathways are identical to conventional concrete production with identical costs and emissions except for the single modified step.

- *Precast concrete carbonation curing:* In precast concrete carbonation curing, newly formed precast concrete is exposed to CO₂-enriched air in a closed container for 4–48 hours, allowing CO₂ to be taken up into the concrete in the form of calcium



carbonates and calcium silicates.⁸² The carbonation process improves the strength and durability of the concrete and replaces the conventional steam curing step in precast concrete production.

- *CarbonCure process for all concrete types:* In addition to the carbonation curing process, we also evaluate a similar pathway developed by CarbonCure Technologies, a start-up company. The CarbonCure process injects CO₂ into precast, ready-mix, or masonry concrete during the mixing stage, similarly incorporating the CO₂ into the concrete as minerals.⁸³ Since this process has different costs and CO₂ uptake than the precast concrete carbonation curing pathway and is also applicable to forms of concrete other than precast, we evaluate the CarbonCure process as a separate pathway.

Detailed Methodology

Our assumptions and calculations are described in detail below. All ton units are in metric tons.

Figures of Merit

In our calculations we use several related but distinct figures of merit to describe the performance of CO₂ recycling catalysts. These figures of merit are defined here:

- *Carbon selectivity* is defined as the percentage of input moles of carbon that go toward the desired product. This is used to calculate the CO₂ consumption of electrochemical and thermochemical pathways as well as the CO consumption of Fischer-Tropsch pathways.

Several figures of merit apply exclusively to thermochemical pathways:

- *Hydrogen selectivity* is the percentage of input moles of H₂ in a thermochemical process that is converted to the desired product. This is used to calculate the hydrogen consumption of thermochemical pathways.
- *Thermochemical plant electrical efficiency* is the percentage of input electricity that is converted to usable forms of energy by thermochemical plant equipment. Thus, the energy efficiency value for thermochemical pathways applies only to the direct electricity consumption of the plant, which is a very small portion of total energy input to the thermochemical process.

Other figures of merit apply exclusively to electrochemical pathways:

- *Electrochemical electrical efficiency* is calculated as the ideal cell voltage for the desired reaction divided by the real cell voltage for that reaction. Disregarding current that goes to undesired reactions, this metric represents the percentage of input electrical energy that is converted into chemical energy in the desired product. This metric is used along with faradaic efficiency to calculate the total electricity consumption of electrochemical pathways.
- *Faradaic efficiency* gives the percentage of overall input electrical current that goes toward the desired product in an electrochemical pathway. This metric represents a



form of selectivity of the pathway. It is used along with electrical efficiency to calculate total electricity consumption.

When evaluating the effect of selectivity in our cost sensitivity analysis, we varied the faradaic efficiency, carbon selectivity, and hydrogen selectivity simultaneously for each pathway and described the resulting percent change in ECOP with the umbrella term of “selectivity” for the sake of simplicity. When the general terms “product selectivity” or “selectivity” are used throughout the report, they are referring to faradaic efficiency, carbon selectivity, and hydrogen selectivity collectively.

Estimated Cost of Production (ECOP) and Sensitivity Analysis

The estimated cost of production (ECOP, in \$/metric ton product) for each pathway was composed of the following cost estimates: feedstock cost (low-carbon hydrogen, CO, biomass, CO₂, and/or ammonia feedstock), electricity cost, CAPEX, and fixed operation and maintenance (O&M) cost. The input value assumptions for the calculations are summarized in Table A1, A2 and A3. The calculation methodology differed slightly between the electrochemical and thermochemical processes.

To determine the per-unit chemical feedstock consumption of electrochemical and thermochemical pathways (in tons of feedstock consumed per ton of product), we divided the feedstock consumption ratio from the reaction’s stoichiometry by the appropriate selectivity metric of the pathway. Dividing by product selectivity accounts for the additional feedstock that is consumed to produce reaction byproducts. To find the H₂ consumption, we used the hydrogen selectivity, which gives the percentage of input hydrogen that goes to the desired product. This allows us to exclude CO₂ conversion to CO in many thermochemical pathways, which does not consume H₂.

To calculate CO₂ consumption through this method, we used the carbon selectivity of the pathway—the selectivity to the desired product among all carbon-containing products. We multiplied carbon selectivity by the CO₂ conversion (the percent of feedstock CO₂ that is reacted) to obtain the carbon yield, and divided the stoichiometric consumption ratio by carbon yield. This allowed us to exclude the hydrogen evolution side reaction in electrochemical CO₂ reduction, which does not consume CO₂. This method accounts for the consumption of CO₂ to produce the desired product and byproducts, as well as the unconverted CO₂ that remains and is assumed to be wasted. The carbon selectivity and hydrogen selectivity used in our calculation are listed in Table A1.

For the electrochemical pathways, the electricity cost (\$/metric ton product) was determined by multiplying the electricity price (\$/kWh) by the gravimetric energy density of the product (kWh/metric ton) and dividing by both the electrical efficiency and the faradaic efficiency. The feedstock costs were calculated by multiplying the \$/ton feedstock purchase price by the per-unit feedstock consumption of the pathway. The CAPEX (\$/metric ton product) was calculated by dividing the required energy input including efficiency and selectivity losses (kWh/metric ton product) by the lifetime hours of operation as determined by the capacity factor and equipment lifetime, which was then multiplied by the intensive capital cost (\$/kW). The capital cost was multiplied by 1.05 to reflect a weighted average cost of capital (WACC)



of 5 percent. The annual fixed O&M cost (\$/yr) was estimated as 10 percent of the total capital investment for thermochemical plants and 4 percent of total capital costs for electrolyzers, so fixed O&M cost (\$/metric ton product) was calculated by taking this percentage of the capital cost (\$/metric ton product) and multiplying by the equipment lifetime (years). The ECOP was found by summing the cost components in \$/metric ton product: electricity cost, feedstock costs, CAPEX, and fixed O&M cost.

For each thermochemical pathway, we selected a techno-economic analysis (TEA) from the literature that designed a full plant in a chemical process simulator such as Aspen Plus to execute the pathway. The literature TEAs used, along with all other sources for input values, are cited in Table A1. From the mass and energy balances in the stream summary of each analysis, we extracted values for the direct electricity consumption of plant equipment (kWh/metric ton product) and plant capital cost (\$/metric ton/yr of capacity). Using these values, the feedstock cost (\$/metric ton product) was calculated by multiplying feedstock consumption (ton feedstock/ton product) by the feedstock price (\$/metric ton feedstock). For most pathways, the feedstocks were hydrogen and CO₂. The feedstock price used was equivalent to our calculated ECOP for the electrochemical pathway that produces the feedstock (e.g., water electrolysis to produce feedstock H₂). The CAPEX (\$/metric ton product) was determined by dividing total capital cost (\$/metric ton/yr of capacity) by the capacity factor and then dividing by the equipment lifetime (years). Direct electricity costs were calculated by multiplying the direct electricity consumption (kWh/ton product) by the electricity price (\$/kWh). Fixed O&M costs (\$/metric ton product) were calculated in a manner identical to the electrochemical pathway methodology. The ECOP was calculated by summing the electricity cost, feedstock costs, CAPEX, and O&M cost. We did not include in our calculations the cost of process heat for thermochemical pathways. CO₂ recycling pathways require relatively low operating temperatures of 200–350 °C,⁸⁴ compared to temperatures well above 1,000 °C needed for steelmaking or concrete production, for which process heat becomes a predominant cost.⁸⁵ As such, process heat accounts for a minor portion of CO₂ recycling production costs⁸⁶ and can be reasonably neglected.

For thermochemical pathways, we make a distinction between direct electricity consumption and overall electricity consumption. Direct electricity consumption is the amount of electricity consumed by plant equipment during operation. This value is used to calculate the direct electricity costs as part of ECOP. The overall electricity consumption includes direct electricity consumption plus the electricity consumed to produce the chemical feedstocks for the pathway, such as green hydrogen. The amount of electricity consumed to produce feedstocks is calculated by multiplying the feedstock consumption of a thermochemical pathway (ton feedstock/ton product) by the previously calculated electricity consumption of the electrochemical pathway that produces that feedstock (kWh/ton feedstock). Overall electricity consumption is significantly larger than direct electricity consumption and is used for calculating carbon abatement and infrastructure needs as detailed in subsequent sections.

We determined the sensitivity of ECOP to each variable techno-economic input by individually increasing and decreasing each input value by 20 percent in our model, with all else equal, and noting the resulting percent change in ECOP. When calculating the sensitivity of ECOP to selectivity, we varied the faradaic efficiency, carbon selectivity, and hydrogen



selectivity up or down 20 percent simultaneously.

Carbon Abatement Metrics and Effect of Subsidies

The intensive carbon abatement (tCO₂ abated/metric ton product) of each pathway was defined as the net decrease in CO₂ emissions that would result from displacing a conventional production process with a CO₂ recycling pathway that produces the same product. Since a CO₂ recycling product and its corresponding conventional product are functionally identical, we assume that the emissions associated with the combustion or use of the products (gate to grave emissions) are equivalent. Under this assumption, the change in emissions from displacing conventional processes with CO₂ recycling arises entirely within the cradle to gate life cycle scope. Thus, carbon abatement was calculated through a cradle to gate life cycle assessment of emissions. The intensive carbon abatement of each pathway (tCO₂ abated/ton product) was calculated by adding the per-unit CO₂ consumption of the pathway (tCO₂ consumed/ton product) to the counterfactual cradle to gate CO₂ emissions of producing the product using a conventional pathway (tCO₂ emitted/ton product) and subtracting the emissions of the CO₂ recycling pathway associated with carbon capture, renewable electricity generation, process heat, and reaction byproduct CO₂. The intensive carbon abatement was then multiplied by the global demand for the product (Mt/yr) to obtain the global carbon abatement potential of the pathway (MtCO₂/yr).

The per-unit CO₂ consumption of each pathway is identical to the per-unit CO₂ consumption metric described in the ECOP calculation. The counterfactual emissions of the conventional pathway represent the gross emissions reduction of displacing conventional production processes. These counterfactual emissions values were found using the ecoinvent version 3 life cycle inventory database⁸⁷ and literature studies cited in Table A1. We assumed that the process of point-source carbon capture created CO₂ emissions equivalent to 10 percent of the amount of CO₂ captured. Thus, we included emissions equivalent to 10 percent of the per-unit CO₂ consumption of the pathway in the abatement calculation. We also incorporated life cycle emissions from renewable electricity generation of 25 gCO₂/kWh⁸⁸ by multiplying this value by the overall electricity consumption of the pathway (kWh/metric ton product). The emissions associated with process heat were found by assuming process heat is provided by natural gas-derived steam and calculating the emissions associated with providing the required heat load from literature TEAs using this steam.⁸⁹ The byproduct CO₂ generation was found for the Fischer-Tropsch pathways by converting the molar CO to CO₂ selectivity (obtained from literature catalysis studies) to a mass ratio of CO₂ to desired product using the selectivity to desired product and the molar mass of each species. For the ethanol from lignocellulosic biomass pathway, we did not incorporate emissions associated with land-use change.

Additionally, the marginal carbon abatement cost (MAC) for each pathway was obtained by dividing ECOP (\$/metric ton product) by the intensive CO₂ abatement (tCO₂/ton product). The marginal abatement revenue was found by dividing the product selling price (\$/metric ton product) by the CO₂ abatement (tCO₂/ton product). The MAC after revenues was calculated by subtracting MAR from MAC.

The MAC after revenues for each pathway was taken as the effective carbon price needed for the pathway to reach market parity, where costs equal revenues. We used this framing to find



the cumulative carbon abatement potential that has reached market parity as a function of effective carbon price. At each effective carbon price value, the carbon abatement potential of all pathways with a MAC after revenues less than or equal to the effective carbon price were summed together. In the case of repeated products, we excluded the cost with the higher MAC after revenues. We included both concrete production pathways since they apply to different types of concrete. Electrochemical carbon monoxide production was included along with one syngas pathway because of these two pathways' very different MAC after revenues values. Separately, we calculated the gross subsidies needed to close the cost-price gap for each pathway by multiplying the difference between selling price and ECOP by the global demand for the product.

Global Critical Infrastructure Needs and Resource Consumption

To estimate the annual electricity consumption (TWh/yr) of each pathway at global scale, the overall electricity consumption of the pathway (TWh/ton product) was multiplied by the global demand for the product (Mt product/yr). For thermochemical pathways, the overall electricity consumption included the electricity needed to produce the pathway's feedstocks electrochemically. Since the vast majority of conventional chemical production and industrial energy use does not come from electricity⁹⁰ and current electricity mixes are mostly fossil-based, we assume that the conventional processes being displaced by CO₂ recycling use no renewable electricity. Therefore, all renewable electricity consumption from deploying CO₂ recycling has full additionality. The global electricity consumption was then divided by the hours per year of operation based on a 50 percent capacity factor to obtain the capacity of renewable electricity (GW) required to power the pathway at global scale. The required electrolyzer capacity (GW) was similarly found using a 50 percent capacity factor along with the global electricity consumption for electrochemical pathways and the global electricity consumption minus the direct electricity consumption for the thermochemical pathways. The 50 percent capacity factor was chosen to represent a combination of wind and solar with complementary output profiles.⁹¹ These GW capacity values were converted to global capital costs (\$B) using the electrolyzer capital costs (\$/kW) listed in Table A2 and using a \$2,000/kW capital cost for renewable energy, representative of an even mix of solar and wind power at today's costs.⁹²

To estimate the transmission infrastructure capital cost associated with the required global renewable electricity capacity, we multiplied the GW renewable capacities by a \$300/kW transmission line capital cost.⁹³ This transmission capital cost is based on a review of existing renewable energy projects and models and assumes transmission costs are fully allocated to the associated renewable installation. If certain renewable generation projects do not require new transmission infrastructure or the use of new transmission infrastructure is shared between various actors, our estimated costs would be lower. Transmission capital costs vary widely, as reported in the cited study, so \$300/kW was chosen as a representative value.

For estimates of CO₂ transport pipeline capital costs, the global CO₂ consumption of each pathway (tCO₂/yr) was first determined by multiplying the intensive CO₂ consumption of the pathway (tCO₂/ton product) by the global volume of product demand (ton product/yr). Then, the global CO₂ consumption was multiplied by a CO₂ transport pipeline capital cost



of \$42/tCO₂/yr of capacity to obtain the global CO₂ transport capital cost (\$B). This capital cost was drawn from a previously analyzed CO₂ transport network with 20 MtCO₂/yr capacity consisting of a 500 km spine pipeline and two 10 km distribution pipelines on each end.⁹⁴ In this model, the 500 km pipeline has a diameter of 32" and the 10 km distribution pipelines have a diameter of 20". This provides a minimal cost estimate of CO₂ transport costs, as lower capacity, smaller diameter pipelines would cost more.

The global hydrogen consumption of the hydrogen-consuming thermochemical pathways was determined using the per-unit H₂ consumption of the pathway (tH₂/ton product), which was found with the same method used for all per-unit feedstock consumption values. We multiplied the per-unit H₂ consumption by the global demand for the product (Mt/yr) to obtain the global hydrogen consumption (MtH₂/yr).

Inputs and Assumptions

We designed both the electrochemical and thermochemical CO₂ recycling pathways to consume low-carbon electricity, here modeled as renewable energy, and assumed the H₂, CO, and/or ammonia consumed as a reactant in thermochemical pathways are supplied by onsite electrochemical processes powered by renewable energy. All numerical assumptions are detailed in Table A1, A2, and A3.

We assume the feedstock CO₂ is sourced from carbon capture at point-source emitters and delivered to the CO₂ recycling plant via a CO₂ pipeline network at a total cost of \$50 per metric ton of CO₂ (tCO₂).⁹⁵ While lower carbon capture costs may be available in certain contexts, these lower costs will not be accessible on average for the global scope and scale of this study. For the thermochemical pathways that consume electrochemically generated feedstocks, we use our own calculated ECOP of the electrochemical feedstock production pathway (e.g., water electrolysis for feedstock green H₂) as the feedstock price.

Though similar studies often assume renewable electricity prices based on the levelized cost of energy (LCOE) for renewable generators or average power purchase agreement (PPA) prices for renewables, these methods do not reflect the duty cycles of industrial use, contributions of network costs (costs of transmission and distribution), and electricity taxes to the end-use industrial electricity price paid by producers. While producers may have access to PPA-range renewable electricity prices at certain times, in limited contexts, and with low capacity factors, these low prices will not be available on average for the global production scale evaluated in this study. Therefore, for our estimate of the renewable electricity price paid for global-scale CO₂ recycling processes, we must incorporate the duty cycle requirements and contributions of network costs and taxes beyond renewable PPA prices.

To estimate the renewable electricity price used in this study, we take renewable power PPA prices in a region to be equivalent to the wholesale price of renewable electricity, and calculate the corresponding industrial price of renewable electricity by increasing the PPA price to reflect the additional contributions of network costs and taxes to industrial prices. Wholesale electricity prices account for 10–70 percent of industrial electricity prices in different countries.⁹⁶ We assume that renewable PPA prices on average account for the same percentage of the final renewable electricity industrial price in a particular country.



To estimate the renewable electricity price used in this study, we assume that CO₂ recycling producers have access to industrial electricity markets, and that wholesale electricity prices represent 50 percent of the price of industrial electricity on a global basis. We use an average global renewables PPA value of 4.75 ¢/kWh⁹⁷ and divide it by 0.5 to obtain an industrial electricity price for renewables of 9.5 ¢/kWh. In keeping with this framing, we assume a capacity factor of 50 percent for electrochemical pathways supplied by renewable electricity, which was chosen to represent a combination of wind and solar with complementary output profiles.⁹⁸ Since thermochemical pathways have very small direct electricity consumption, we assume a higher capacity factor of 90 percent.

An obvious condition from this cost framing is that the true costs of recycling CO₂ will vary substantially across regions and jurisdictions and that some locations may provide high-capacity electricity at much lower costs. These sensitivities and ranges will be published separately.

In our techno-economic analysis, we choose values for faradaic efficiency, carbon selectivity, and hydrogen selectivity that are 20 percent lower than those of the highest performance catalysts reported in the literature. This 20 percent decrease from the highest performance values was applied to reflect that many of the cited catalysis studies at the bench scale do not demonstrate industrially relevant production rates (measured as current density or space-time yield), and industrial demonstrations of these pathways today would not achieve bench-scale performance.

Faradaic efficiency values were found directly reported in the literature. For thermochemical pathways, carbon selectivities on a molar basis were directly reported in the literature. For each electrochemical pathway, the carbon selectivity was found by converting the faradaic efficiencies to a molar basis. First, we listed out the faradaic efficiency toward each product/byproduct as reported in the cited catalysis study, excluding the hydrogen evolution reaction, which does not involve carbon atoms. Then, each faradaic efficiency was divided by the moles of electrons consumed per mole of CO₂ consumed in the associated reaction. Finally, the resulting quotient for the desired product was divided by the sum of all quotients to obtain the carbon selectivity. For the hydrogen selectivity of thermochemical pathways, we directly used the hydrocarbon selectivity values directly reported in the literature, which give the molar carbon selectivity toward the desired product among all hydrocarbon products (excluding non-hydrocarbon byproducts such as CO). The hydrocarbon selectivity is a close approximation of hydrogen selectivity because, as dictated by the stoichiometry, all side reactions in CO₂ hydrogenation consume between three and four moles of H₂ per mole of CO₂ consumed, and F-T consumes between two and three moles H₂ per mole of CO.⁹⁹ This narrow range of H₂ to carbon consumption ratios means that a conversion from hydrocarbon selectivity to hydrogen selectivity would result in a very similar value. All faradaic efficiency, carbon selectivity, and hydrogen selectivity values obtained or derived from the literature were decreased by 20 percent to obtain the values used in this study, as described in the previous paragraph.

To estimate the electrical energy efficiency of the electrochemical pathways, we divided the ideal cell voltage by the real cell voltage indicated in the studies cited in Table A1. The ideal cell voltage is the difference between the reversible potentials of the electrochemical CO₂



reduction half-reaction and its paired oxygen evolution reaction. When the real cell voltage was not directly reported by a study, we used the cathode potential used for electrochemical CO₂ reduction in the study and assumed an oxygen evolution reaction overpotential of 400 mV.¹⁰⁰ We found the difference between the study's cathode potential and the assumed oxygen evolution reaction potential to obtain the real cell voltage. For the thermochemical pathways, we assumed a plant equipment electrical efficiency of 75 percent, which applied only for our calculation of direct electricity consumption for thermochemical pathways. Our efficiency and selectivity assumptions along with the associated references are summarized in Table A1.

The conversion values listed in Table A1 give the molar percentage of feedstock CO₂ or CO that is ultimately consumed in the reactor. We assume high conversions of 90–100 percent. Though single-pass conversions have not been demonstrated at these levels, we assert these conversion values based on the assumption of using recycle streams with multiple passes to increase overall conversion.

We assumed an electrolyzer capital cost of \$1,000/kW for water electrolysis.¹⁰¹ For electrochemical CO₂ reduction pathways, since these technologies have not reached commercial scale and CO₂ electrolyzer capital cost data is therefore not available, we modeled the electrolyzer based on water electrolyzers with a capital cost of \$1,000/kW. For thermochemical pathways, we obtain capital cost estimates from plant simulations in the literature (Table A2). The annual fixed O&M costs were estimated as a small percentage of the total capital cost (Table A3).

Table A5: Extended list of CO₂ recycling pathways from initial literature review

Product	Process	Inputs	Global demand (Mt/yr)
Fuels			
Methanol	Electrochemical CO ₂ reduction	CO ₂ , H ₂	140
Methanol	Methanol from syngas	CO, H ₂ (up to 30% CO ₂)	140
Methanol	CO ₂ hydrogenation	CO ₂ , H ₂	140
Ethanol	Electrochemical CO ₂ or CO reduction	CO ₂ , H ₂ O	87
Ethanol	Biomass fermentation	Lignocellulosic biomass	87
Propanol	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	1
Methane	Electrochemical CO ₂ or CO reduction	CO ₂ , H ₂ O	2,920
Methane	Sabatier process	CO ₂ , H ₂	2,920
Methane	F-T synthesis	CO, H ₂	2,920
Methane	Anaerobic digestion	Biomass, microbes	2,920
Ethane	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	40
Jet fuel	F-T synthesis	CO, H ₂	200

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Product	Process	Inputs	Global demand (Mt/yr)
Fuels (continued)			
Jet fuel	CO ₂ hydrogenation	CO ₂ , H ₂	200
Sustainable aviation fuels	Waste to fuels	Waste oils, fats, biomass	100
Hydrogen	Water electrolysis	H ₂ O	70
Hydrogen	Steam methane reforming (with CCS)	Methane	70
Carbon monoxide	Reverse water gas shift reaction	CO ₂ , H ₂	320
Carbon monoxide	Thermal decomposition	CO ₂	320
Carbon monoxide	Electrochemical CO ₂ reduction	CO ₂	320
Syngas	Reverse water gas shift reaction	CO ₂ , H ₂	691
Syngas	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	691
Methyl formate	CO ₂ hydrogenation	CO ₂ , H ₂	1
Dimethyl ether	Methanol dehydration	MeOH	10
Dimethyl ether	Tri-reforming	CH ₄ , CO ₂ , H ₂ O	10
Biofuels	Microalgae	algae, CO ₂	132
Chemicals			
Urea	Bosch-Meiser process	NH ₃ , CO ₂	208
Carbamates	--	CO ₂ , amines or alcohols	~5 Mt/yr pesticide consumption
Carboxylic acids	Carboxylation	C-H bonds, carbon nucleophiles, unsaturated organic compounds	45
Acrylic and methacrylic acids	CO ₂ insertion into C-H bond	CO ₂ , ethylene/propylene	10
Acrylates (acrylic acid derivatives)	--	CO ₂ , alkenes	3
FDCA (furan-2,5-dicarboxylic acid)	Carbonate-promoted carboxylation	CO ₂ , furoic acid	0.5
Formic acid	BASF formic acid process	CO, H ₂ O	1
Formic acid	CO ₂ hydrogenation	CO ₂ , H ₂	1
Formic acid	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	1
Oxalic acid	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	0.5
Acetic acid	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	19
Acetic acid	Carbonylation of methanol	CO, MeOH	19

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Product	Process	Inputs	Global demand (Mt/yr)
Chemicals (continued)			
Acetic acid	Carboxylation of methane	CO ₂ , CH ₄	19
Acetaldehyde	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	2
Organic linear carbonates	Alcoholysis of urea or CO ₂	CO ₂ or urea, alcohols	9 Mt/yr for all carbonates
Ethene (ethylene) carbonate	Cycloaddition of CO ₂ to epoxides	CO ₂ , ethene epoxide (aka ethylene oxide)	--
Cyclic carbonates	Cycloaddition of CO ₂ to epoxides	CO ₂ , epoxides	9 Mt/yr for all carbonates
Polycarbonates	Epoxide/CO ₂ copolymerization	CO ₂ , epoxides	7
Polyurethanes	Copolymerization	CO ₂ , aziridines/azetidines	20
Polyethylene	Addition polymerization	Ethylene, H ₂	80-100
Polypropylene	Addition polymerization	Propylene	60
Polycarbamates	Copolymerization	CO ₂ , aziridines	--
Oxetanes	Copolymerization	CO ₂ , aziridines	--
Ethylene	Electrochemical CO ₂ or CO reduction	CO ₂ , H ₂ O	150
Ethylene	CO ₂ hydrogenation	CO ₂ , H ₂	150
Ethylene glycol	Electrochemical CO ₂ reduction	CO ₂ , H ₂ O	35
Ethylene glycol	Oxidative coupling of CO with oxamides intermediate	CO, H ₂	35
Epoxides	Electrochemical epoxidation using water as O source	Alkenes, H ₂ O	35
Ethylene oxide	Oxidation of ethylene	Ethylene, O ₂	30
Carbon black	CO ₂ methanation + pyrolysis	CO ₂ , H ₂	10
Materials			
Cement	Cement curing	CO ₂ , cement	4,000
Concrete	Concrete curing	CO ₂ , concrete	33,000
Inorganic carbonates, aggregate	Mineral carbonation	CO ₂ , alkaline solids e.g. from iron and steel slags	315-420
Graphite	Electrochemical CO ₂ reduction	CO ₂	1.5
Carbon fiber	Electrochemical CO ₂ reduction	CO ₂	0.15
Carbon nanotubes	Molten carbonate electrolysis w CO ₂	CO ₂ , Li ₂ CO ₃	0.005 Mt/yr, but rapidly growing



NOTES

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