

RELATIVE ROLES OF DESIGN FOR RE-X METHODS, RENEWABLE ENERGY, AND INDUSTRIAL SYMBIOSIS IN THE TRANSITION OF THE CHEMICALS AND MATERIALS INDUSTRY TO A SUSTAINABLE CIRCULAR ECONOMY

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Abstract

Approaches and frameworks such as Design for Re-X, Circular Economy, and Industrial Symbiosis are expected to help transform industry and its products to meet challenges posed by changes in resource availability and prices, economic policies, and environmental changes. Guiding the development and adoption of appropriate technologies and approaches requires methods and software tools for choosing the sequence of changes that is best at addressing the trade-offs between economic and environmental goals. This talk will describe a framework for modeling the current industry and emerging technologies and identifying the most promising combination of technologies and their life cycles for meeting various economic and environmental goals. It will specifically focus on the role that Design for Re-X technologies such as recycling, reuse, remanufacturing, and recovery, Renewable Energy, and Industrial Symbiosis could play in the transition to net-zero greenhouse gas emissions. This framework relies on an open-access model of the chemicals and materials industry, which contains about 150 currently used processes and 220 emerging technologies. This materials flow analysis model also includes data about emissions, energy use, and costs, and it may be integrated with life cycle inventory data. For emerging technologies, their technology readiness level provides information about the time period in which the technology may become available for commercial use. Multiobjective optimization is used to determine cost-effective pathways for transforming the selected industry or product to meet environmental goals such as net-zero emissions in the short-, medium-, and long-term. Marginal abatement cost curves help identify alternatives that could provide win-win solutions and the magnitude of their role in reaching net zero. Application to the chemicals (plastics, solvents, fertilizers, fuels, etc.) and materials (iron and steel, cement, pulp and paper, glass, aluminum, etc.) industry helps identify the importance of Design for Re-X technologies (remanufacturing, recycling, reuse, etc.), industrial symbiosis, and renewable energy. The integrated chemicals and materials industry model also conveys the importance of technologies that cut across multiple sectors such as use of plastic waste and carbon dioxide from the chemical industry in steel and cement industries. The ability of this framework to guide the transition to products with net-zero emissions will be illustrated by application to products such as carbon fiber reinforced plastics and polyester textiles. A user-friendly software will also be introduced.

1. Introduction and Motivation

1.1 Background and Problem Context

Global industrial systems are undergoing a profound period of transition as they confront converging pressures on resources, markets, and the environment. Rapidly increasing resource scarcity, volatile commodity prices, tightening climate policies, and accelerating ecological degradation are reshaping how materials and energy must be produced and consumed. These challenges have intensified interest in frameworks that seek to decouple economic prosperity from environmental harm, particularly the Circular Economy, Design for Re-X, and Industrial Symbiosis. Although each of these approaches is conceptually distinct, they share a common ambition: to extract greater value from raw materials, products, and wastes by extending the useful life of resources and reducing dependence on virgin feedstocks. Circular Economy emphasizes retaining products and materials within economic circulation for as long as possible. Industrial Symbiosis focuses on retaining wastes within circulation by enabling cross-sector exchanges of by-products, heat, and intermediates. Design for Re-X provides the practical engineering principles required to operationalize both concepts through strategies such as reuse, remanufacturing, repair, recycling, and recovery. Together, these approaches represent a shift toward a more resilient industrial ecosystem that seeks not only to reduce environmental impacts but also to unlock untapped value embedded in material flows.

1.2 Why Industry Transformation Is Difficult

Despite its promise, transforming the chemicals and materials industry toward a more circular and low-carbon paradigm remains exceptionally difficult. These sectors operate through complex and deeply interconnected supply chains in which chemicals, materials, and fuels are mutually dependent, making unilateral interventions ineffective or even counterproductive. Many of the technologies needed to achieve large-scale resource efficiency or deep decarbonization remain at low levels of technological maturity, introducing uncertainty in cost, performance, and scalability. Industrial actors must also navigate difficult trade-offs among cost, emissions, energy demand, and resource consumption, with improvements in one dimension often leading to compromises in another. As a result, achieving progress requires coordinated action across multiple sectors, careful sequencing of technological pathways, and robust tools that can capture the full scope of interactions across industrial systems.

1.3 Gaps in Current Modeling Approaches

Existing modeling approaches frequently fall short of capturing the complexity of industry-wide transformation. Most tools focus on single sectors or isolated technologies, neglecting the multi-sectoral coupling that defines the real behavior of industrial systems. Conventional marginal abatement cost curves are typically constructed under the assumption that interventions operate independently, which obscures the systemic interactions that shape costs and emissions in practice. Similarly, many models treat circularity and symbiosis as abstract concepts rather than representing them as explicit technological pathways with quantifiable material exchanges and environmental effects. This lack of integrated, cross-sectoral modeling capabilities limits the ability of researchers and policymakers to identify strategies that are both feasible and synergistic, and it constrains understanding of how circular solutions interact with emerging low-carbon technologies.

1.4 Motivation for This Work

There is a growing need for analytical frameworks and software tools that can quantify the trade-offs inherent in industrial transitions and identify where circularity, symbiosis, and renewable integration provide the greatest leverage. This study is motivated by the need to move beyond siloed assessments and toward a systems-level understanding of how Re-X strategies, cross-sector exchanges, and low-carbon technologies collectively shape industrial pathways to net-zero emissions. The CMI model addresses this gap by providing an open-access, rigorously formulated decision-support framework that integrates material flow analysis with multiobjective optimization. It enables simultaneous evaluation of cost, emissions, resource use, and technological feasibility while representing circularity and symbiosis as explicit, operational pathways. By doing so, it supports a more realistic and

opportunity-oriented perspective on industrial transformation, one that highlights how innovation can unlock additional value from materials and wastes while reducing environmental impacts. This work therefore contributes not only to the academic understanding of industrial sustainability but also to the practical design of low-carbon, and circular industrial ecosystems.

2. Review of Related Work

Research on the Circular Economy and Design for Re X has highlighted the role of reuse, remanufacturing, recycling, and other different R strategies in reducing dependence on primary resources and extending material value across multiple products such as textiles [1], electronics [2] and automobiles [3]. Although these strategies are conceptually mature, their practical implementation in chemical and material industries is far more complex because of strict performance requirements, heterogeneous feedstocks, and highly globalized supply chains [4, 5]. These difficulties suggest that circularity in heavy industrial systems must be understood not only as a set of individual interventions but as a coordinated transformation embedded within broader industrial networks. Building on this perspective, the literature on industrial symbiosis shows how cross-sector exchanges can strengthen circular resource flows and help overcome some of the limitations faced by individual facilities. Examples such as the conversion of plastic waste into inputs for steel and cement production [6] demonstrate that shared infrastructure and resource exchange can create synergies that are difficult to achieve within isolated production systems. However, most documented symbiosis networks remain confined to specific locations or industrial parks, which limits their generalizability [7]. This reinforces the need to link circularity frameworks with system level models capable of representing how symbiotic exchanges emerge and interact across sectors. A natural extension of this idea appears in the literature on multiobjective optimization and marginal abatement cost analysis, where researchers examine how economic and environmental objectives can be balanced in complex industrial transitions [8]. While these tools offer important insights, traditional marginal abatement curves often assume that mitigation options act independently, thereby overlooking the technology interactions and sector couplings emphasized in both circularity and symbiosis research. As a result, the literature calls for interaction-aware abatement cost curves that better capture the complexity of industrial systems [9]. This need for integrated analysis creates a conceptual bridge between optimization frameworks and the circular industrial strategies discussed earlier. The broader literature on analytical tools and databases forms the backbone of these modeling efforts. Resources such as EXIOBASE [10], along with LCA databases like Ecoinvent [11] and GaBi [12], provide the core inventories used in most industrial assessments. Yet these datasets often lack the technological detail needed to represent Re-X strategies, industrial symbiosis, or low-TRL options. Proprietary sources, such as IHS Markit [13] and Carbon Minds [14], expand coverage but remain closed and non-open access, limiting transparency and reproducibility. These gaps highlight the need for flexible, integrated, and openly accessible modeling platforms that can capture the circularity, symbiosis, and decarbonization dynamics emphasized in recent literature.

3. Technology Approach

3.1 Overview of the Open-Access Chemicals and Materials Industry (CMI) Model

The Chemicals & Materials Industry (CMI) model [15,16] developed in this work is a comprehensive, open-access systems modeling framework designed to represent the full industrial ecosystem across chemicals, polymers, fuels, and advanced materials. It integrates material flow analysis, optimization, technology readiness levels, and circularity pathways to evaluate net-zero and resource-efficient transition strategies. The model captures more than 150 conventional processes, over 220 emerging low-carbon technologies, and detailed recycling and carbon-transformation routes, enabling rigorous and transparent assessment of both system-wide transitions and product-specific decarbonization strategies. All emissions reported in this study are evaluated on a cradle-to-grave basis and include upstream production of electricity, hydrogen, and feedstocks, consistent with the life-cycle inventories

embedded in the CMI framework. Refer to the table 1 for a detailed overview of the core structure, components, and use cases of the CMI framework.

Table 1: Description of CMI Model

Overall Purpose of the CMI Model	An open-access, matrix-based systems model representing the full chemicals and materials ecosystem from feedstocks to end-products. It enables system-wide optimization of emissions, cost, resource use, and technology transitions across interconnected industrial sectors.
Core Structure (MFA + Optimization)	Built on an MFA backbone integrated with cost, emissions, and TRL data. Interconnected matrices define process coefficients, resource demands, product outputs, and environmental exchanges, ensuring mass and energy balance.
Conventional Industrial Processes (150+)	Represents major high-TRL processes, including SMR, catalytic cracking, methanol and ammonia synthesis, and polymer routes (PET, PE, PP), as well as all key intermediates such as ethylene, aromatics, EG, and TPA.
Emerging Technologies (220+)	Includes electrified routes (e-Haber–Bosch, e-steam cracking), advanced catalytic processes (OMC), biobased pathways (PLA, ethanol-to-ethylene/butadiene), and novel low-carbon synthesis routes.
Circularity & Re-X Pathways	Captures mechanical and chemical recycling, pyrolysis, methanolysis, depolymerization, and open-/closed-loop industrial symbiosis (e.g., steel and glass recycling, cross-sector waste valorization).
Carbon Transformation / CCU	Represents CO ₂ -to-chemicals pathways such as CO ₂ →ethanol, →ethylene, →methanol, enabling analysis of carbon circularity and synthetic feedstocks.
Integration of TRL Data	TRL-filtered deployment (TRL ≥9, ≥7, ≥5, ≥3) ensures realistic near-, mid-, and long-term technology adoption in transition scenarios.
Optimization Capabilities	Supports cost and emissions minimization, ϵ -constraint multi-objective tradeoffs, and systemic MACC generation that captures technology interactions and resource coupling.
Resource & Environmental Limits	Embeds constraints on biomass availability, renewable electricity, CCS/CCU capacities, and sectoral demand fulfillment to avoid burden-shifting.
Use Cases – System-Level	Analysis of net-zero pathways, circularity strategies, TRL-based transition roadmaps, carbon pricing impacts, and global industrial symbiosis potentials.
Use Cases – Product-Level	Can be downscaled to specific value chains e.g., carbon fiber reinforced plastics (CFRP), polyester textiles, PET bottles, PE films enabling high-resolution product-level net-zero assessments.
Net-Zero Product Transitions	Demonstrates how electrification, circularity, CCU, and renewable energy combine to achieve net-zero or net-negative emissions for selected products (e.g., CFRP, polyester fibers).
User-Friendly Software Tool	Includes a simplified interface allowing non-experts (industry, policymakers, researchers) to run scenarios, adjust assumptions, and visualize material and carbon flows without coding knowledge.

3.2 Representation of Pathways

The model evaluates circularity and decarbonization through a set of broader aggregated pathways, as summarized in Table 2, where recycling and reuse are combined as Re-X, remanufacturing and recovery are grouped under symbiosis, and renewables and rethinking are treated as distinct levers. These aggregated categories provide a system level view of how upstream circularity, cross sector exchanges, low carbon energy, and process redesign interact to influence overall cost and emissions outcomes. To understand the specific mechanisms driving these aggregated results, we also disaggregate each category within the model to examine the individual contribution of reuse, recycling, remanufacturing, recovery, renewables, CO₂ reutilization, and rethinking based interventions. At the disaggregated level, reuse is implemented through multi cycle loops that reduce the need for new production,

while remanufacturing and recovery are modeled as forms of industrial symbiosis in which material residues, by products, and partially degraded components flow across sectors to restore functional value. Recycling includes both mechanical and chemical pathways that highlight trade offs between cost, quality, and energy use, and recovery captures residual value extraction through pyrolysis, gasification, and similar processes. Renewable energy substitution replaces fossil based heat and electricity, CO₂ reutilization converts captured carbon into new chemicals and materials, and rethinking introduces electrified and biobased process routes that enhance compatibility with circular and low carbon systems. Viewed together, this aggregated to disaggregated structure allows the model to identify not only the system level benefits of combined pathways but also the individual technological contributions that shape the feasibility and performance of industrial decarbonization strategies.

Table 2: Summary of Re-X and symbiosis scenario descriptions used in the analysis.

Scenarios	Description
Reuse (Re-X)	Examines the circulation of plastics through multiple use cycles to reduce demand for virgin production.
Renewables	Evaluates the substitution of fossil-based energy with renewable electricity across industrial processes.
Recycling (Re-X)	Includes both mechanical and chemical closed-loop recycling routes that return materials to high-quality feedstocks.
Remanufacturing and Recovery (Symbiosis)	Represents open-loop pathways where waste streams are converted into inputs for other industrial sectors, reflecting cross-sector resource flows.
Reutilize (Symbiosis)	Explores the conversion of emitted CO ₂ into chemicals and fuels through emerging carbon-transformation technologies.
Rethink	Captures the adoption of biobased and electrified production routes that replace conventional fossil-based processes.

3.3 Multiobjective Optimization Formulation

To evaluate trade-offs across technological choices and circularity interventions, the model employs a multiobjective optimization framework that jointly minimizes total system cost and greenhouse gas emissions. The problem is primarily solved using the ϵ -constraint method, in which emissions are progressively restricted to generate a Pareto frontier, while an alternative weighted-sum formulation is used for sensitivity checks. The optimization problem is implemented in Julia and solved using the Gurobi optimizer.

The core optimization problem is summarized as:

$$\text{Min: } G[\text{CO}_2], \text{ Cost} \quad (1)$$

$$\text{s.t. } As \geq f \quad (2)$$

$$G = Bs \quad (3)$$

$$\text{Cost} = Cs \quad (4)$$

$$s \geq 0 \quad (5)$$

$$G[\text{CO}_2] \leq \epsilon \quad (6)$$

Here, s represents non-negative scaling variables that determine the adoption level of individual technologies and pathways. Matrix A represents the technology matrix which encodes material balance relationships across the chemicals and materials system, ensuring that final demand f is satisfied. Matrix B is the intervention matrix which

maps technology activity levels to greenhouse gas emissions, while vector C represents corresponding system costs. The ϵ -constraint $G_{CO_2} \leq \epsilon$ enforces progressively tighter emissions limits to trace the cost–emissions Pareto frontier.

Both formulations yield a set of Pareto-optimal transition pathways that reveal how the chemicals and materials industry evolves as environmental ambition increases. The resulting solutions identify the optimal mix of technologies, the allocation of material flows across Re-X and symbiosis pathways, and the structural shifts in production portfolios that emerge when cost and emissions are jointly considered. This formulation enables the model to capture system-level interactions and trade-offs that are often obscured in single-objective or technology-isolated analyses.

3.4 Systemic Marginal Abatement Cost Curves (MACCs)

The analysis focuses on scenarios built from different combinations of Re-X strategies and industrial pathways, rather than individual technologies. These scenario groups encompass life-extension measures, renewable energy transitions, material-cycling options, carbon-integrated symbiosis routes, and fully integrated circular configurations. Together, they represent the range of plausible transition routes within a circular and low-carbon industrial system. Marginal abatement cost curves are then constructed by selecting scenario configurations along the Pareto frontier and mapping their incremental costs against the corresponding emissions reductions relative to the Business As Usual Case. Unlike conventional MACCs, which treat interventions as independent and additive, the curves developed here incorporate interaction effects that shape real industrial systems, for instance, how recycling outcomes depend on electricity carbon intensity, how carbon utilization depends on upstream process emissions, or how symbiotic exchanges influence marginal costs across multiple processes. By embedding these interdependencies, the resulting MACCs provide a more grounded and system-aware view of abatement opportunities, better reflecting the coupled decisions and cross-sector linkages that characterize the chemicals and materials industries.

4. Discussion

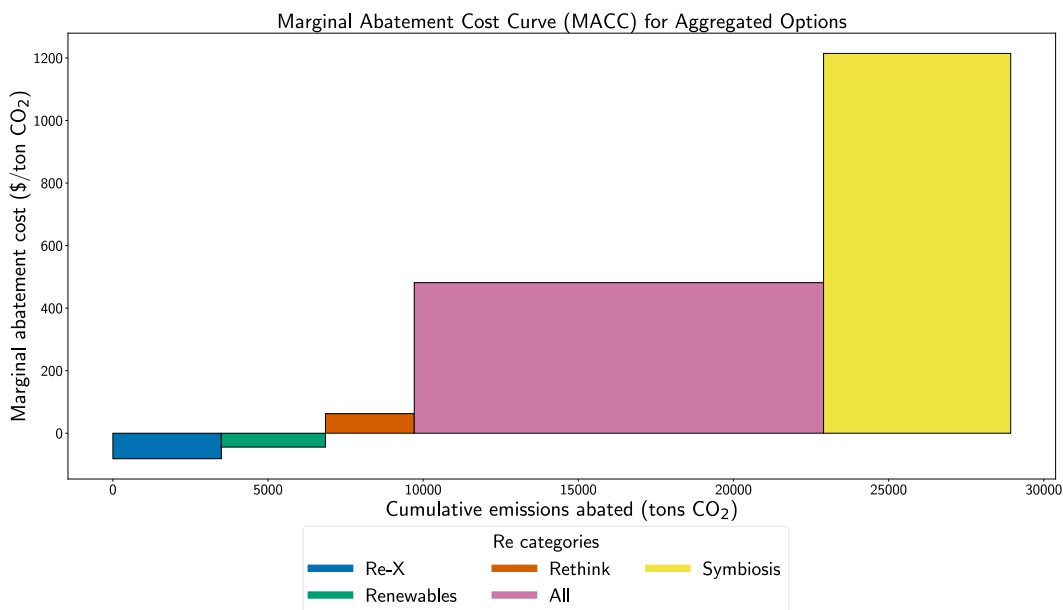


Figure 1: Marginal Abatement Cost Curve for Aggregated strategies

The marginal abatement assessment in Figure 1 reveals distinct cost and mitigation profiles across the four intervention categories and the fully integrated case. Re-X strategies deliver cost-negative abatement at approximately \$ 82 per ton while avoiding about 3,495 tons of CO₂, reflecting the influence of mature circularity measures such as glass and steel recycling and the use of scrap-based electric arc furnaces for steel production. Renewable energy substitution also produces net savings of roughly \$ 44 per ton and reduces emissions by more than 3,356 tons, driven primarily by penetration of wind power and limited contributions from bioelectricity. In contrast, the symbiosis category achieves the largest stand-alone mitigation at more than 6,030 tons, but at a substantially higher marginal cost of around \$ 1,214 per ton. This reflects the energy and infrastructure intensities of cross-sector pathways such as the pyrolysis of plastics to syngas, partial substitution of blast-furnace slag in cement, and the catalytic conversion of CO₂ into methanol, ethanol, propanol, methane, or gasoline. Rethinking offers a moderate mitigation potential of about 2,861 tons with a marginal cost of \$ 62 per ton, capturing a diverse set of redesign and process-innovation routes including methanol-to-aromatics, oxidative methane coupling, biobased polymers such as PLA, PBS, VOH, and PHB, and ethanol-to-ethylene or ethylene oxide pathways. When all strategies are combined, the system achieves its highest total mitigation at roughly 13,191 tons, though at an intermediate marginal cost of about \$ 481 per ton. This integrated outcome reflects the simultaneous deployment of wind, hydro, and solar electricity, green hydrogen, CO₂-to-syngas electrolysis, pyrolysis-based material recovery, electrified Haber–Bosch synthesis, ethanol-to-ethylene and ethanol-to-butadiene pathways, BECCS, hydrogen-based DRI–EAF steelmaking, electric-kiln cement, direct air capture, CO₂ storage, and advanced waste-to-steel routes such as polyamide-based recovery. While the aggregated analysis highlights their collective performance, it does not reveal the relative importance of individual technologies within each category or how specific interventions interact across the system. To address this, we now turn to the disaggregated representation of these pathways and examine their behavior through detailed trade-off analysis and marginal abatement cost curves.

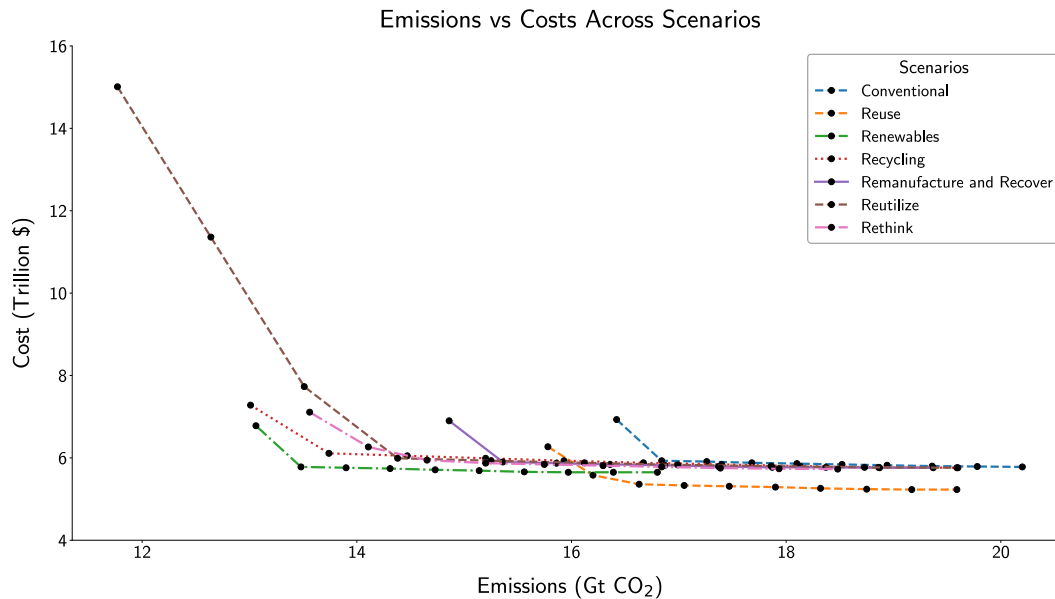


Fig 2: Pareto Curves depicting different strategies for the Chemicals and Materials industry

The cost–emission patterns across the scenarios in Figure 2 show that each intervention moves the industrial system in a distinct direction. The conventional case offers very little flexibility, with emissions remaining high and costs changing only marginally, indicating that a business-as-usual configuration cannot deliver meaningful decarbonization. Reuse improves system performance by lowering both emissions and costs, reflecting the value of keeping materials in circulation and reducing demand for new production. Renewables shift the system further toward low-emission outcomes, illustrating the pivotal role of clean electricity in enabling deep reductions across multiple sectors. Recycling produces comparable emission improvements but at generally higher system costs,

driven by the energy and processing requirements of mechanical and chemical recycling at scale. Remanufacturing and recovery show similar patterns, offering moderate reductions supported by cross-sector use of secondary materials. Reutilizing CO₂ emerges as the pathway with the strongest potential to reduce emissions but requires substantially higher initial investments, which gradually decline as carbon-conversion technologies mature. Rethink provides steady improvements by incorporating electrified and biobased process routes that enhance overall system compatibility with low-carbon configurations. Taken together, these results show that circularity strategies, clean energy deployment, and process redesign provide the most cost-effective early gains, whereas CO₂ conversion and advanced recycling become increasingly important for achieving deeper reductions as supporting technologies mature. The costs of these later-stage options are expected to decline as innovation progresses and deployment scales, making them more viable components of long-term decarbonization. Building on these insights, we now turn to the marginal abatement cost curve to examine how these pathways perform incrementally and how their relative value shifts across the broader mitigation landscape.

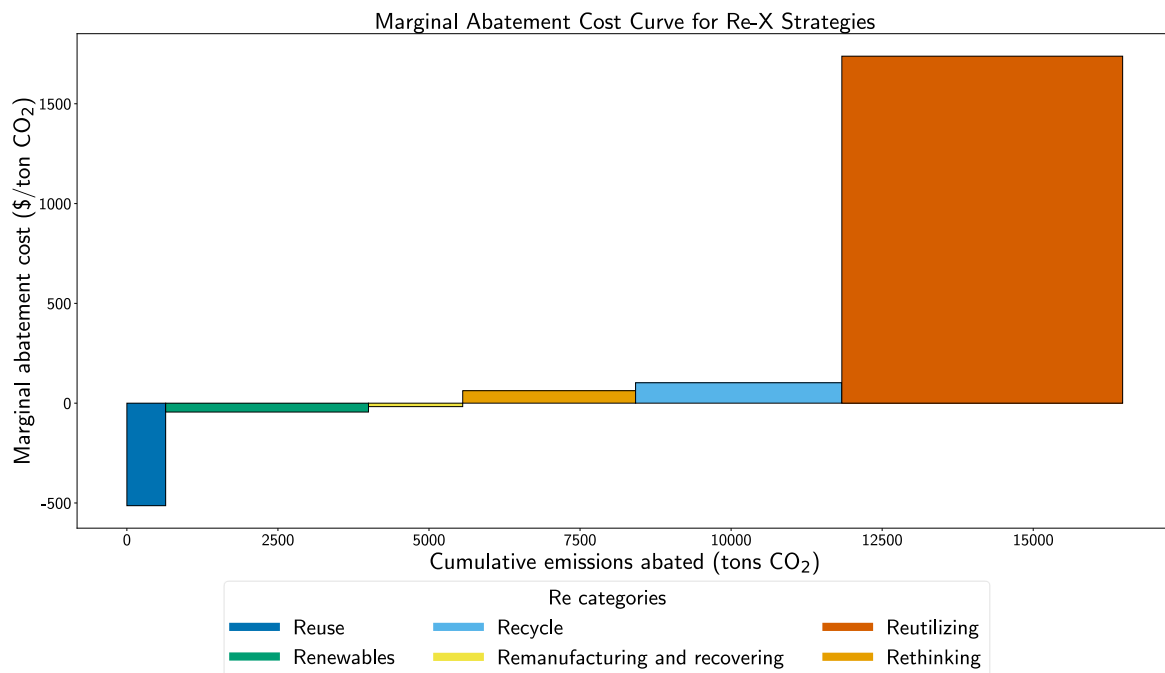


Figure 3: Marginal Abatement Cost Curve for different strategies

The marginal abatement cost assessment in Figure 3 reveals substantial variation in the economic and environmental performance of different strategies. Reuse exhibits the most favorable outcome, generating a cost reduction of approximately \$ 514 per ton of CO₂ abated while avoiding more than 640 tons of emissions. Renewables also deliver strong benefits, achieving a moderate cost savings of approximately \$ 44 per ton and reducing more than 3,300 tons of emissions, highlighting the role of clean energy substitution as a foundational lever for decarbonization. Remanufacturing and recovery contribute a smaller yet meaningful benefit by reducing costs by approximately \$ 17 per ton and abating more than 1,500 tons. Rethinking through the deployment of biobased feedstocks and electrified process routes additionally costs by roughly \$ 62 per ton while mitigating over 2800 tons of emissions. In contrast, mechanical and chemical recycling impose additional system costs of roughly \$ 102 per ton even though they collectively reduce more than 3400 tons of emissions, a result that aligns with their higher energy and purification requirements. Reutilizing, which includes advanced CO₂ capture or conversion pathways, presents the highest marginal cost burden, at more than \$1,700 per ton, despite achieving the largest emissions reduction of approximately 4,600 tons. Taken together, these results emphasize that not all circularity pathways contribute

equally to net-zero transitions. Strategies that prioritize material preservation, such as reuse, remanufacturing, and recovery, alongside process-redesign measures captured under rethinking, consistently deliver both economic and environmental benefits. These pathways reduce upstream demand, lower energy requirements, and avoid the steep cost penalties associated with more technologically complex interventions. In contrast, end-of-pipe or energy-intensive approaches such as advanced chemical recycling, extensive cross-sector symbiosis, or CO₂ conversion require significant system support, including abundant clean electricity, hydrogen availability, and large-scale infrastructure. As a result, they are best deployed as complementary measures that enable deeper decarbonization once lower-cost opportunities have been exhausted. Nevertheless, these higher-cost options remain essential for achieving the final reductions in emissions, particularly in hard-to-abate sectors. Importantly, as technological maturity increases and innovation progresses, the costs of energy-intensive and carbon-transforming pathways are expected to decline, making them progressively more viable components of future circular and low-carbon industrial systems.

5. Conclusions & Recommendations

This study shows that decarbonizing the chemicals and materials industry requires a coordinated portfolio of measures rather than reliance on any single pathway. The aggregated analysis demonstrates that reuse, renewables, and process redesign deliver the most cost-effective mitigation, driven by technologies such as glass and steel recycling, scrap-based electric arc furnaces, and the expansion of wind electricity. Recycling and remanufacturing provide additional reductions but depend heavily on enabling technologies including pyrolysis, methanolysis, and high-quality sorting systems, highlighting the importance of clean electricity and material-compatible design. Symbiosis and CO₂ reutilization offer the largest absolute abatement through options such as CO₂-to-methanol, CO₂-to-ethylene, plastic-to-syngas pyrolysis, and slag substitution in cement, although these come with higher marginal costs and infrastructure needs. The disaggregated MAC curves further reveal the growing importance of electrified process technologies such as electrified Haber–Bosch, oxidative methane coupling, and ethanol-to-ethylene routes as the system moves toward deeper reductions. Taken together, the results indicate that a credible industrial transition must combine early gains from circularity and renewables with strategic investment in electrification, carbon-conversion technologies, and cross-sector symbiosis to achieve meaningful progress toward net-zero emissions.

6. Acknowledgements

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