ACS Sustainable Chemistry & Engineering

pubs.acs.org/journal/ascecg

Research Article

Recycled Polymers As a Feedstock for Chemical Manufacturing Supply Chains in the United States: A Network Analysis for Polyethylene Pyrolysis

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Cite This: *ACS Sustainable Chem. Eng.* 2023, 11, 9394−9402

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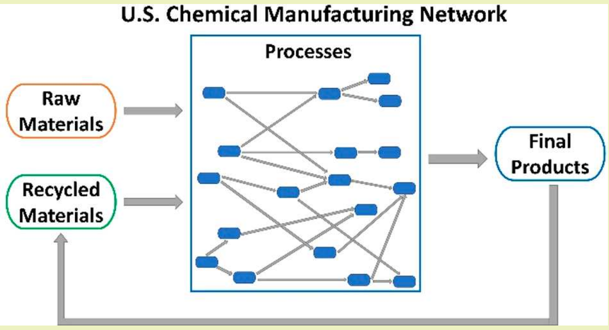


ABSTRACT: For chemical recycling of plastic wastes to be viable, chemical products generated in recycling need to find markets. A network model of the U.S. chemical manufacturing industry was used to assess at what cost points, and the extent to which, chemical products from thermal pyrolysis of polyethylene might find markets in the current U.S. chemical manufacturing industry. Network modeling determined the cost points at which the simulated industry network utilized the thermal pyrolysis products and which processes were displaced by the supply of recycled materials. The characteristic feature of the simulations is the large number of processes in the chemical manufacturing network that are impacted by the availability of a relatively small number of products from polyethylene recycling. In the case of polyethylene recycling, the capital cost requirements for expanding capacity to effectively utilize the recycled materials is greater than the capital required for the pyrolysis process. This suggests that identifying scenarios where recycled materials can be utilized in processes that have excess capacity will be a critical consideration in techno-economic analyses of recycling plastics.

KEYWORDS: *Petrochemicals, Chemical recycling, Plastic recycling, Network model*

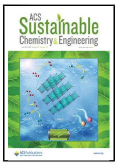
■ INTRODUCTION

Global production of plastics has been growing rapidly since 1950, reaching more than 400 million metric tons (Mt) in 2015.[1] Plastics have been extensively used in packaging, consumer products, construction, and transportation applications, however, most plastics are single use and recycling is limited. The U.S. Environmental Protection Agency (EPA) reports that 36 Mt of plastic waste was generated in the United States in 2018, and about 9% of plastic waste was recycled, with 76% going to landfills.[2]

Much of the current plastics recycling in the United States involves mechanical reprocessing of the polymers, with relatively limited chemical recycling. For chemical recycling of plastic wastes to be viable, chemical products generated in the recycling need to find markets. A number of analyses of plastic waste management and recycling have been reported. These analyses have examined topics such as the optimization of waste plastic reverse logistics[3] and the economic viability of waste recycling infrastructures.[4] Chemical manufacturing in the United States is a highly networked system, however, few analyses have been performed that examine the impact of plastic recycling on the entire chemical manufacturing network. This work will use network models of the chemical manufacturing industry to assess at what cost points, and the extent to which, chemical products from depolymerization of plastic waste might find markets in the current U.S. chemical manufacturing industry. The pyrolysis of polyethylene (PE) will be used to demonstrate the methodology.

Polyethylene production represents about 25% of the total production of plastics in the U.S. and, therefore, represents a logical target for recycling. Multiple processes have been proposed for the recycling of polyethylene, including both thermal and catalytic pyrolysis. Pyrolysis is the process of thermally degrading polymer molecules with intense heat and in the absence of oxygen.[5] Thermal pyrolysis is usually performed at temperatures in excess of 500 °C.[5] The three major products from thermal pyrolysis of polyethylene are oil, gas, and char. The products of pyrolysis depend on temperature, pressure, residence time, reactor configurations, and other process parameters.[6,7] Reddy et al.[8] reviewed the influence of process parameters on product distribution for thermal pyrolysis of polyethylene and report that gas products generally contain H_2, CH_4, C_2H_4, C_2H_6, C_3H_6, and C_3H_8, while liquid products generally consist of alkanes, alkenes and aromatic hydrocarbons,

Received: February 18, 2023
Revised: May 13, 2023
Published: June 14, 2023



https://doi.org/10.1021/acssuschemeng.3c00990

with the exact composition and yields depending on process conditions.[9,10] Thermal pyrolysis under other conditions, or catalytic pyrolysis, can lead to different reaction mechanisms and product compositions.[11−13] There are also various reactor configurations for plastic pyrolysis, including fixed beds, fluidized beds, and rotary kilns.[14] This work will investigate the potential use of the products of thermal pyrolysis of polyethylene in chemical manufacturing.

A network model of the U.S. chemical manufacturing industry, developed by DeRosa et al.,[15] will be adapted to assess the potential use of these products of chemical recycling. The model tracks material and energy flows in a complex network of feedstocks, processes, intermediates, and final products. Feedstocks are converted into intermediate chemicals via various processes to obtain final end products. The same intermediates and final end products can be produced by different technologies. For example, ethylene can be produced from ethane by steam cracking of either ethane or naphtha, with naphtha cracking leading to greater yields of byproducts than ethane cracking. The model developed by DeRosa et al.[15] consisted of 873 chemical processes that produce 283 different chemicals to represent the U.S. chemical manufacturing industry. The process data was obtained from the IHS 2012 Process Economic Program Yearbook. In the original model formulation, natural gas, natural gas liquids (NGLs), and crude oil were the primary raw materials, and a linear programming model with supply, demand, and mass balance constraints was used to minimize the total production cost. In this work, waste polyethylene (PE) will be assumed to be available as a raw material, and a thermal pyrolysis process will be assumed to be available to convert these waste plastics into chemicals. The impact of the plastic recycling process on the use of processes in the network will be examined as a function of the costs of the waste plastics and the pyrolysis process. Key issues to be addressed by the work are the cost points at which the simulated industry network utilizes the recycling technology, and which processes are displaced by the supply of recycled materials. The results from the network model provide insight into how, and to what extent, chemical recycling of plastics might be adopted by the current chemical manufacturing infrastructure in the United States.

METHODS

Polymer Recycling Processes. The products from thermal pyrolysis of PE can be classified as gas, oil, and char.[8−10] In this work, it is assumed that thermal pyrolysis of PE yields 80% gas product and 20% oil and char. Product composition from a simplified PE pyrolysis is shown in Table 1. For this work it will be assumed that ethane, ethylene, propane, and propylene from pyrolysis will be used as feedstock chemicals for manufacturing. Char is assumed to be used as a fuel to provide heat for the reactor for thermal pyrolysis. Methane, hydrogen, and oil are assumed to be used for energy recovery and result in energy credits. The details of stoichiometry of the reaction, heat requirement for pyrolysis, and energy recovered from the products are described in the SI (Tables S1−S3).

Table 1. Product Composition and Supply from Thermal Pyrolysis of Waste PE[a]

product from pyrolysis	wt percentage (%)	annual supply (Mt/year)
ethylene	35	1.77
ethane	5	0.26
propylene	24	1.18
propane	1	0.07
oil and char	20	1.00
hydrogen	1	0.07
methane	13	0.66

[a] The composition is simplified based on various experimental results.[8−10]

Base Case Model Development. The development of the original network model of the chemical manufacturing industry is described by DeRosa et al.[15] Demand of final end products and the cost of processes are retained in this work. The current model includes 851 processes and 885 materials. To characterize the markets for the pyrolysis products of polyethylene (ethane, propane, ethylene, and propylene), several additional model modifications were required:

- A new raw material of waste PE was assumed to be available at zero cost. A new thermal pyrolysis process for PE was added to the network model. The stoichiometry for the added process is described in Table S1 in the SI.
- The supply of waste PE was assumed to be 5 Mt/year. If the approximately 40 million tons per year of plastic waste in the United States is 25% polyethylene, then 5 million tons per year represents half of US polyethylene waste. The maximum available annual supplies of raw materials to the modified network model are listed in Table 2.

Table 2. Annual Supply Constraints of Primary Raw Materials for the Network Model in Base Case

raw material	annual supply (Mt/year)
natural gas	138
NGLs	28
crude oil	762
coal	39
lignite	3
PE waste	5

- To account for the different grades of propylene (refinery grade, chemical grade and polymer grade) used in the model, interconversion processes for the various grades of propylene were added. PE pyrolysis was assumed to yield refinery grade propylene and the added processes enabled the conversion of refinery grade propylene into chemical and polymer grade propylene. In the base case analyses, the costs of interconversion among propylene grades were assumed to be zero.
- Processes for ethylene, polypropylene and olefins productions that are no longer in industrial use were removed. Processes from methane to gasoline and diesel production, which are not in widespread use in the United States, were removed.
- Cost for three refinery processes for NG, NGLs and crude oil are represented by raw material costs based on market price of year 2012 (NG \$0.09/lb,[16] NGLs \$0.22/lb,[17] and crude oil \$0.31/lb[18]). No cost interconversion among gasoline, kerosene, diesel, light naphtha, and naphtha are allowed, so that crude oil refining satisfies both industrial demand (such as naphtha) and fuel demand (such as diesel and gasoline) without strict constraint across these light hydrocarbons. This assumption is consistent with refiners adapting the operation of their processes to yield products in ratios demanded by markets.

Natural gas, NGLs, and crude oil are among the primary raw materials in the model. They provide important feedstocks including methane, ethane, propane, butane, and naphtha. For natural gas, the supply in the model was assumed to be equal to industrial natural gas consumption in the United States, which was 7226 billion cubic feet in 2012.[19] Using density of 0.042 lb/cubic foot,[20] the supply was 300×10^9 lb in 2012. The distribution of components in natural gas was assumed to be 93.07% methane, 3.21% ethane, and 0.59% propane (higher hydrocarbons and nonhydrocarbons are ignored in the mass balance).[21]

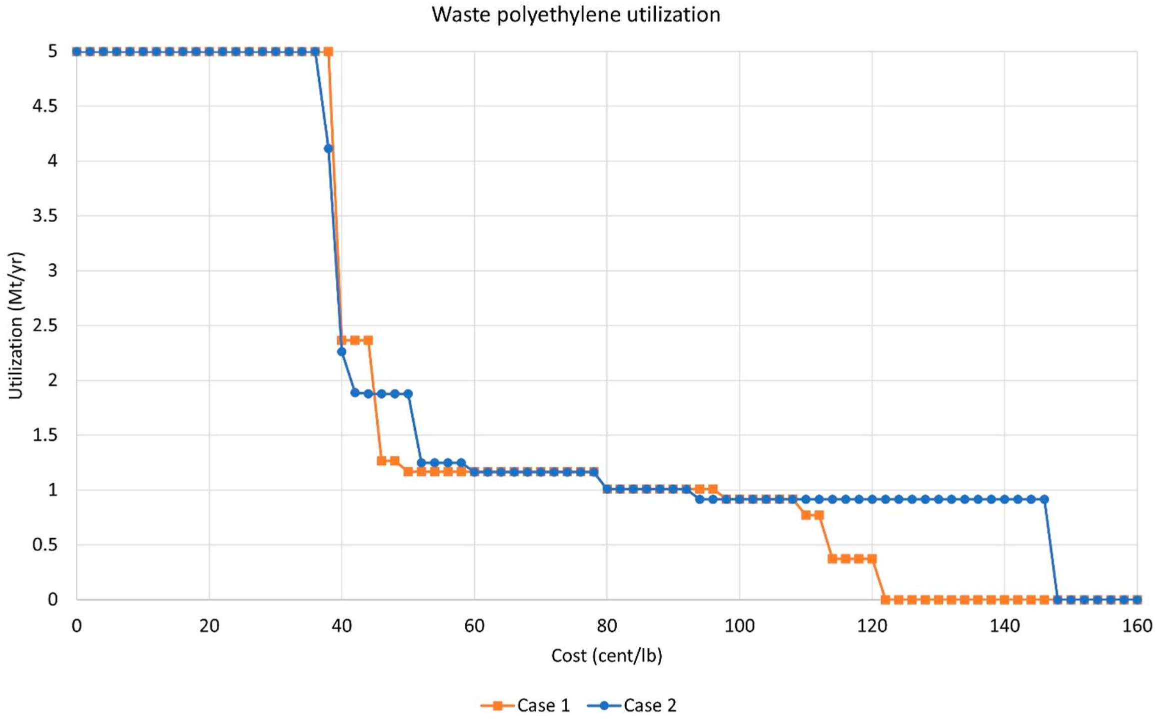


Figure 1. Utilization of waste PE by the network model at different recycling cost in Case 1 (orange square) and Case 2 (blue circle).

The supply of NGLs is assumed to be 20% of that of natural gas, as they are extracted as byproducts in the production of natural gas.[22] The composition of NGLs is based on 2012 production data from EIA[23] and shown in Table S4 in the SI.

For crude oil, the supply in the model is assumed to be the same as the total refinery input level. This includes use of refinery products as feedstock for chemical manufacturing and as fuel and other final end products. Total crude oil refinery input for all U.S. refineries in 2012 was 5489516000 barrels,[24] with a weighted average API gravity of 31.0.[25] This API gravity gives a density of 7.267 lb/gal which leads to 1675 × 10^9 lb crude oil supply in 2012. The crude yield is approximated for 2012 using EIA refinery yield data.[26]

The supply of coal is based on industrial use in 2012, which was 85.6 × 10^9 lb.[27] Lignite comprises 7% of U.S. coal production by weight.[28] The supply of lignite is assumed to be 6 × 10^9 lb. In addition to the constrained raw materials supplied in Table 2, the model utilizes a series of raw materials, such as minerals, solvents, initiators, and catalysts, without supply constraints. About 90% of these materials were inorganic materials such as phosphate rock and sulfur dioxide. The use of organic materials without supply constraints is about 7 Mt/yr, which is less than 5% of the use of primary raw materials in the base case.

Demands are specified by final end products. There are 141 final end products in the demand list. Total demands across all final end products are 748 × 10^9 lb. The detailed demand data are described by DeRosa et al.[15]

Model Statement. The objective of the model is the minimization of total cost for chemical manufacturing (eq 1)

$$\text{min total cost} = \sum_j C_j X_j \tag{1}$$

where C_j is the cost of process j in cent/pound of primary product, X_j is annual production level of process j in pounds/year. The model has the following supply and demand constraints (eqs 2−4):

$$-\sum_j a_{i,j} X_j \le S_i \quad \text{for} \quad i \in \{\text{primary raw materials}\} \tag{2}$$

$$\sum_j a_{i,j} X_j \ge 0 \quad \text{for} \quad i \in \{\text{intermediate materials}\} \tag{3}$$

$$\sum_j a_{i,j} X_j \ge D_i \quad \text{for} \quad i \in \{\text{final end products}\} \tag{4}$$

where $a_{i,j}$ is the input−output coefficient for material i in process j, S_i is the annual supply of material i, D_i is the annual demand of material i. There are a total of 851 variables and 401 constraints. The problem was modeled using General Algebraic Modeling System (GAMS). BDMLP solver is used to find optimal values for production levels that meet the total demand of all final products with the constraints of supply and minimizing total production cost.

Process Cost Determination. Production cost of each process was determined per pound, generally per pound of a primary product (e.g., per pound of ethylene, for steam cracking of ethane to form ethylene). The cost is the sum of operating and variable costs (eq 5). Operating cost is estimated from IHS 2012 Process Economics Program Yearbook, including maintenance, operation, labor, overhead, taxes and depreciation over a 10-year period. These costs are all directly reported in the IHS 2012 Process Economics Program Yearbook. Variable cost includes raw material cost, byproduct credit (by sale) and utility cost. The price of utilities and all raw materials, byproducts, and primary products are used as reported in the IHS yearbook, except for the costs of petroleum, natural gas, and NGLs, which were based on commodity prices in 2012.[16−18]

$$\begin{aligned}\text{production cost} &= \text{operating cost} + \text{raw material cost} + \text{utility cost} \\ &\quad - \text{byproduct credit}\end{aligned} \tag{5}$$

The costs of the PE pyrolysis process were based on processing per pound of recycled polymer. The total costs were varied from 0 to 160 cents per pound of recycled polymer. For the process cost of PE pyrolysis, a byproduct credit is included. The byproduct credit is a reduction in process cost due to energy recovery from hydrogen, methane, and oil products. The details of calculation of byproduct credit can be found in the SI. The byproduct credit is 2 cents per lb of waste PE.

Base Case Supply Availability. Two different cases, with different NGLs availability were simulated. In Case 1, as described above, supply of NGLs alone does not meet the demands of light alkanes (C2−C4) in the model. In Case 2, supply of natural gas and NGLs is increased so that the availability of these feedstocks could be used to satisfy all light

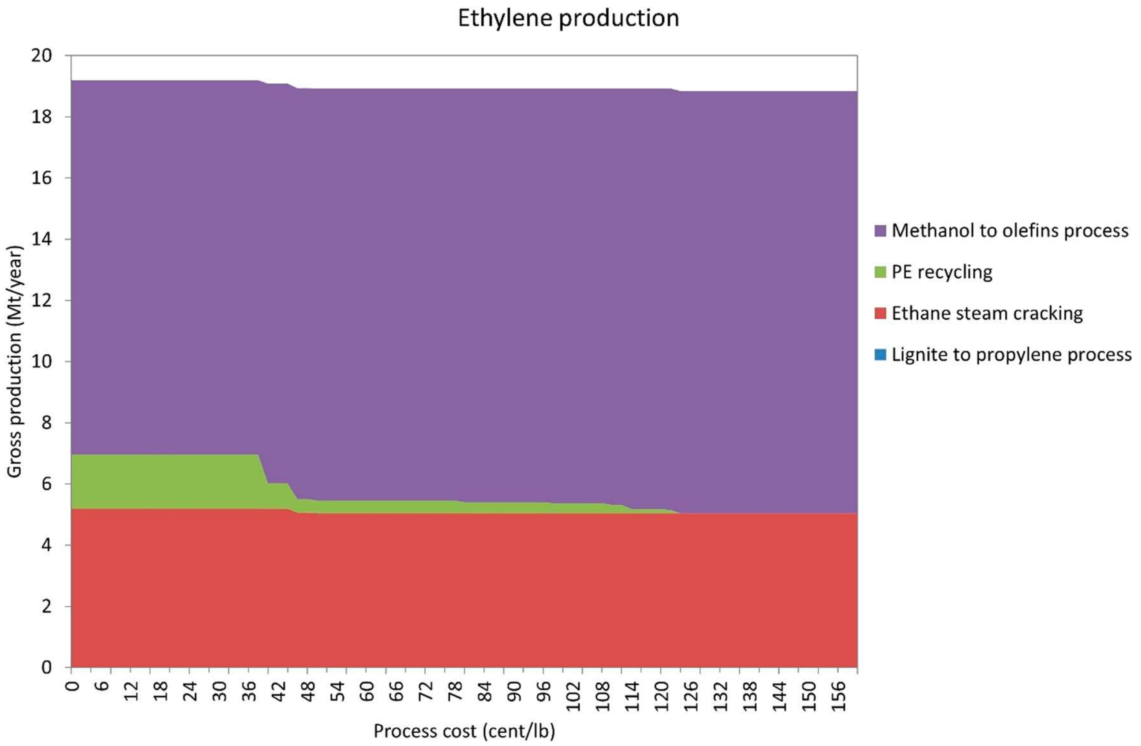


Figure 2. Gross production of ethylene by different processes vs process cost of recycling PE in case 1.

alkane demands. The maximum supply of natural gas (483 Mt/yr) and NGLs is 3.5 times larger than that in Case 1. The supply of NGLs (97 Mt/yr) is still assumed to be 20% of natural gas. Other inputs are kept the same as in Case 1.

■ RESULTS AND DISCUSSION

Waste PE Utilization. Figure 1 shows the amount of waste PE utilized via the recycling process in the network model for Cases 1 and 2. In Case 1 (orange squares in Figure 1), the network model does not utilize any waste PE when the process cost is at or above 122 cents/lb. When the cost decreases below 122 cents/lb, the recycling process starts to be adopted and 0.4 Mt/year of waste PE is used. The "process cost" of PE recycling referred to here is the cost point at which the recycling process gets adopted by the system. If the adoption cost is greater than the costs associated with acquiring the waste PE and operating the process, then the recycling could be done profitably. As the process adoption cost further decreases to 114 cents/lb, an additional 0.4 Mt/year of waste PE is utilized by the system. The use of waste PE increases to 1.3 Mt/year with several steps as the process cost further decreases to 48 cents/lb. When the cost is lower than 46 cents/lb, the utilization of waste PE starts to increase sharply. The system utilizes all the available waste PE (5 Mt/year) when the cost is below 38 cents/lb.

In Case 2 (more supply of natural gas and NGLs), utilization of PE recycling starts at a higher cost (right-shifted) beginning when the cost decreases to 146 cents/lb. In Case 2, with excess supply of natural gas and NGLs, ethane cracking is the initial process displaced by PE recycling, while in Case 1, methane to olefins processes are the processes initially displaced. More detailed mappings of these changes are provided in the sections that follow. In Case 2, there is a sharp increase in the utilization of waste PE starting at 52 cents/lb and Case 2 reaches full utilization (5 Mt/year) when the cost decreases to 36 cents/lb, which is similar to the cost point for full utilization in Case 1.

Ethylene Production. The gross production of ethylene from different processes in Case 1 is shown in Figure 2. When waste PE is not utilized, ethylene is mainly produced by methanol-to-olefins (MTO) processes and ethane cracking. PE recycling displaces production of ethylene from MTO processes by 1.59 Mt/year, as shown in Table 3.

Table 3. Comparison of Production of Ethylene from Different Processes in Case 1

	production when PE recycling cost is 100 cents/lb, Mt/yr	production when PE cost recycling is 0, Mt/yr	change, Mt/yr
ethane cracking	5.04	5.20	+0.16
MTO	13.88	12.29	−1.59
waste PE	0	1.77	+1.77

The changes in ethylene production lead to a complex cascade of additional changes in the chemical manufacturing network because the changes in the use of MTO processes lead to changes in production of byproducts. These complex transformations can be mapped using the framework shown in Figure 3. The detailed description of the visualization procedure and meaning of the nodes and edges can be found in the SI. In Figure 3, raw materials for chemical manufacturing (natural gas, NGLs, crude oil, lignite, and coal) are shown as nodes that have circles with red borders. Raw materials that have no supply constraints, such as minerals, solvents, initiators, and catalysts, are shown as nodes that have circles with orange borders. Products are shown as nodes that have circles with green borders. Intermediates are shown as nodes in the middle of the diagram. Raw materials, intermediates and products are connected by lines representing processes that transform raw materials and intermediates into products with the thickness of the lines representing the extent

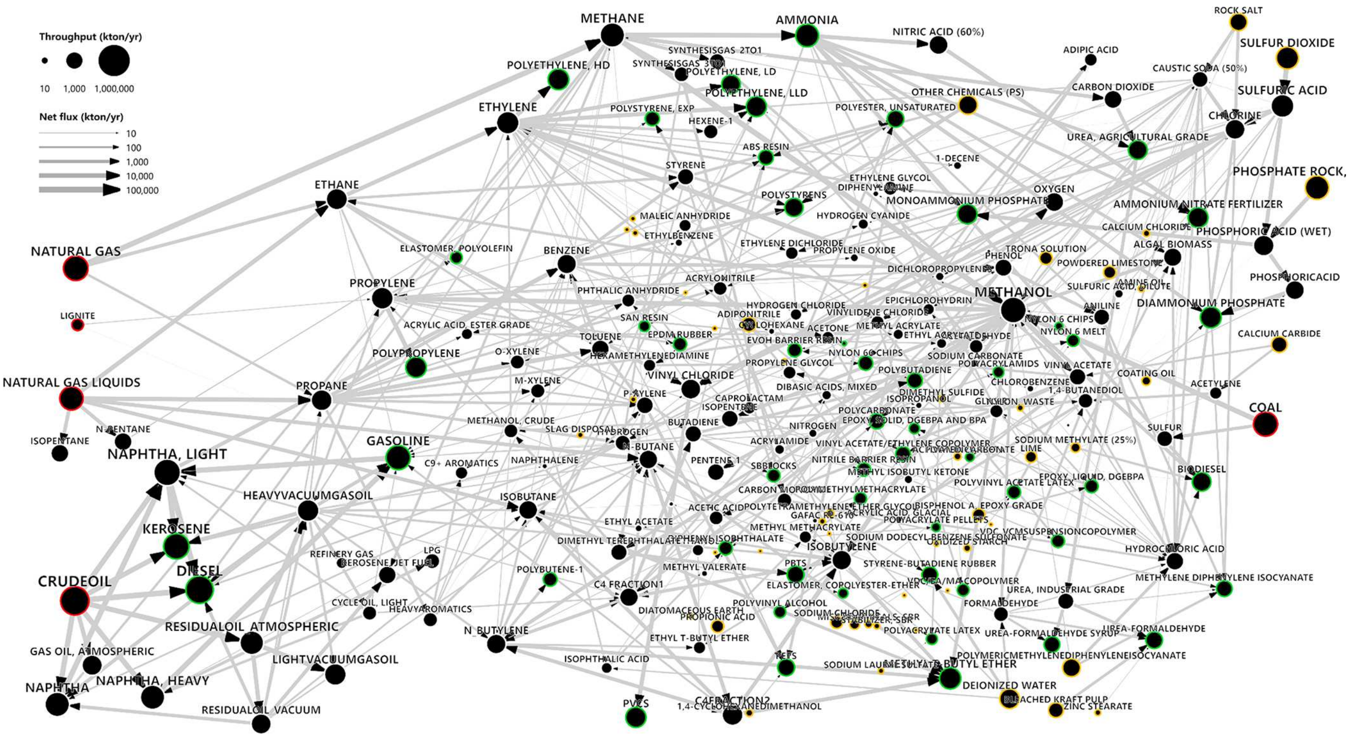


Figure 3. Network of chemical manufacturing in base case 1 (recycling PE not introduced).

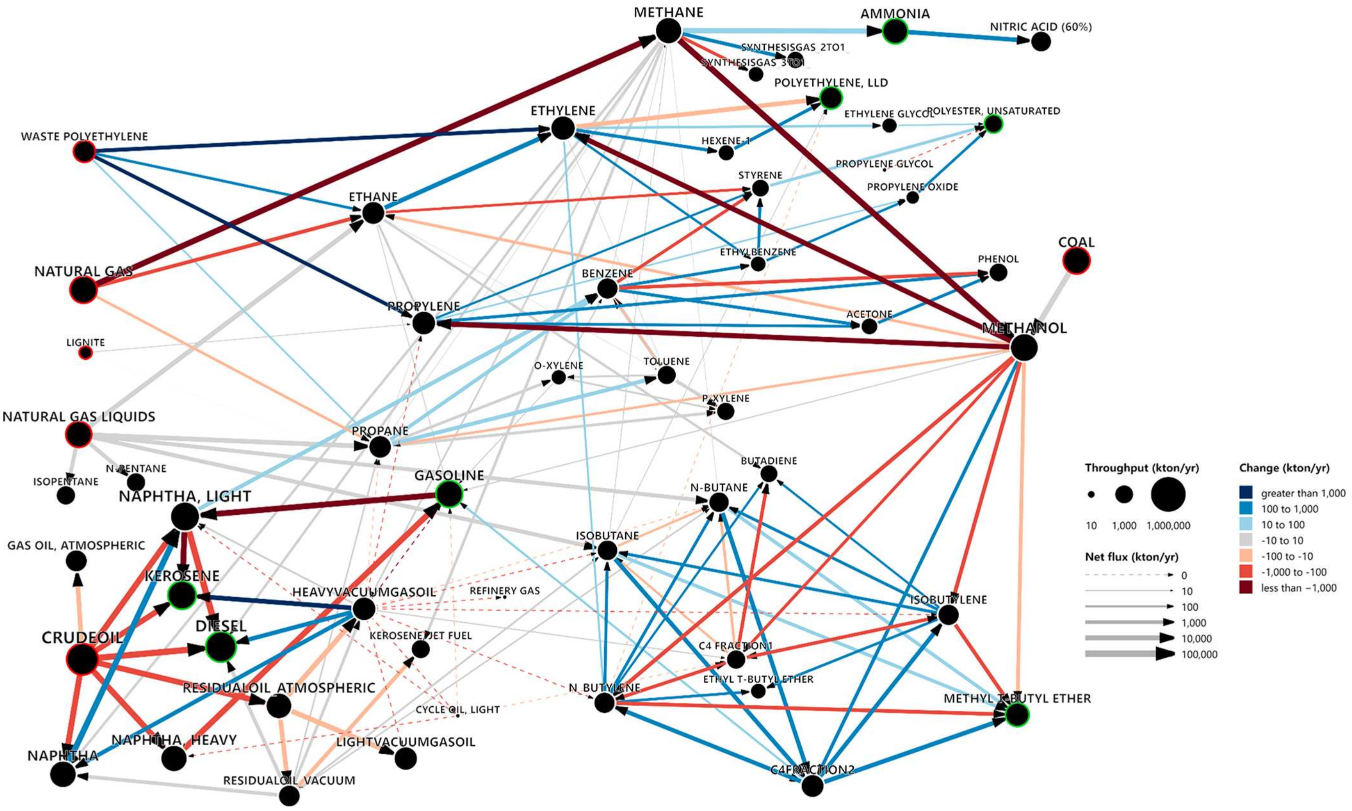


Figure 4. Network of chemical manufacturing: changes between no use of waste PE and 5 Mt/year of waste PE use. Only processes that have changes in flow are shown in the figure. The magnitude of the change in flow is shown by different colors and the line width indicates the flow at 5 Mt/year of waste PE use. Dashed lines indicate the processes that are no longer used at 5 Mt/year of waste PE use.

of use of the process. Figure 3 represents process utilization for all the processes in Case 1.

Figure 4 shows the effect of adding a supply of waste polyethylene (upper left of diagram) to raw material supplies. Figure 4 shows the differences between the flows with no plastics recycling and the flows with plastics recycling at zero cost (all 5 Mt of available waste PE is used). Only lines representing processes with changes in flow are shown and the thicknesses of the lines indicate the magnitude of the process use with full utilization of waste PE. Dashed lines indicate the processes that are no longer used with plastics recycling at zero cost. The colors of the lines indicate the magnitude of the change. The changes shown in Figure 4 result from the fact that the ethylene and propylene resulting from PE recycling displace MTO processes. The decrease in use of methanol leads to the decrease in use of methane from natural gas. The displaced MTO process also leads to a change in the sources of C4 products, which, in turn, leads to a change in refinery product slates. For example, production of methyl *tert*-butyl ether switches to a route that uses mainly isobutane and *n*-butane instead of isobutylene and *n*-butylene and the changes in product distributions then propagate throughout the manufacturing network.

Figure 4 maps the changes between no use of waste PE and 5 Mt/year of waste PE use. The process changes that occur at intermediate levels of waste PE use (i.e., 122 to 48 cents/lb in Figure 1) are not simple linear interpolations between the process utilizations between no waste PE use and 5 Mt/year of waste PE use, however, the main features remain consistent. The reduced use of methanol leads to a decrease in use of methane from natural gas. Production of methyl *tert*-butyl ether switches to isobutane and *n*-butane from NGLs as raw materials. Additional mappings of the flows shown in Figure 4 and detailed characterizations of the changes at various cost points are provided in Figures S1−S9 in the SI.

To examine the features of a network where PE recycling might displace ethane and propane cracking, the second base case with expansion of natural gas and NGLs availability was simulated. As shown in Table 4 and Figure 5, for this case, waste PE leads to displacement of ethane cracking, rather than MTO processes, since ethane cracking dominates ethylene production in the base case. Figure 6 shows the network changes driven by the availability of waste PE for Case 2.

Table 4. Comparison of Production of Ethylene from Different Processes in Case 2

	production when PE recycling cost is 100 cents, Mt/yr	production when PE cost recycling is 0 cent, Mt/yr	change, Mt/yr
ethane cracking	10.87	9.56	−1.31
MTO	7.70	7.23	−0.47
waste PE	0	1.77	+1.77

In cases where the waste PE streams largely displace ethane cracking, the use of NGLs decreases. This results in changes in the supply of propane, isobutane, and *n*-butane, and these changes propagate throughout the network.

A defining feature of Figures 4 and 6 is the number of processes that are impacted by the availability of a relatively small number of products from polyethylene recycling. If a goal is to minimize the extent to which the use of waste polyethylene disrupts downstream manufacturing flows, in principle, a strategy could be to match the product yields obtained from ethane cracking. If, for example, the polyethylene pyrolysis yields could be changed so that they matched the most extensively used ethane cracking technology, it might be assumed that the network effects would be minimal, however, this is not the case. If the yield of ethylene from PE recycling increases from 35% to 55%, and the yields of ethane, propylene, and propane become 8%, 2%, and 1%, respectively, the yields match those from ethane cracking. Figure 7 shows the changes in networks flows for a case where the light gases produced by thermal pyrolysis of PE are assumed to be almost exclusively ethylene. Matching the yields of the recycling process to the yields of ethane cracking changes the processes that see modified use, but the number of processes that have changes is still extensive. The case study summarized in Figure 7 demonstrates the difficulty associated with attempting to perform drop-in displacement of processes in chemical manufacturing networks.

■ IMPLICATIONS

The recycling of waste PE has the potential to be utilized by the chemical manufacturing industry if a process can be built and operated at a cost below 122−148 cents/lb of waste PE. More widespread utilization of waste PE feedstocks occurs if costs are less than 36−38 cents/lb. The supply of recycled materials (mainly ethylene and propylene) displaces the supply of those from conventional olefin manufacturing processes and leads to additional complex changes in the chemical manufacturing network, because the displacement leads to changes in byproduct production.

The large number of process flows impacted by the introduction of large-scale chemical recycling of plastics may impact the assessment of the net benefits of plastics recycling, and it may impact the degree to which feedstocks from chemical recycling of plastics is utilized. For example, if a goal is to reduce greenhouse gas (GHG) emissions in the chemical manufacturing sector, then the changes in flows of all affected processes should be accounted for. Table S5 in the SI lists the changes in process utilization shown in Figure 4 along with the greenhouse gas emissions associated with each process. The greenhouse gas emission factors were drawn from Chen et al.[29] The net change in greenhouse gas emissions for this scenario is dominated, not by the changes in primary ethylene production, but instead by changes in refinery processes.

Another impact of the large number of changes in process utilization is the need for increased capacity for some processes and idled capacity for other processes. For the case where all 5 Mt/yr of waste PE is utilized, the total capital required to increase capacity of the processes that expand production is $11 billion. Idled capacity is valued at $14 billion.

These capital costs can be compared to the capital required for the PE pyrolysis process. Capital investment for a plastics pyrolysis plant with processing capacity of 100000 tons/yr is approximately $43 million.[30] In another study, the capital investment required for a plastics pyrolysis process with a processing capacity of 365000 tons/yr is estimated to be $118 million.[31] This suggests that, to process 5 Mt/yr of waste PE by pyrolysis, the total capital required is about $1.6 billion to $2.2 billion. The capital required to enable the optimal use of pyrolysis products ($11 billion) is estimated to be roughly five times the capital required for the pyrolysis facility. Further, the idled capital investment ($14 billion) by adopting PE recycling is more than six times the total capital investment required for processing PE wastes by pyrolysis. Overall, these costs suggest that the use of feedstocks from PE recycling is most likely to be adopted in regions where the existing capacity required for the use of the feedstocks is available.

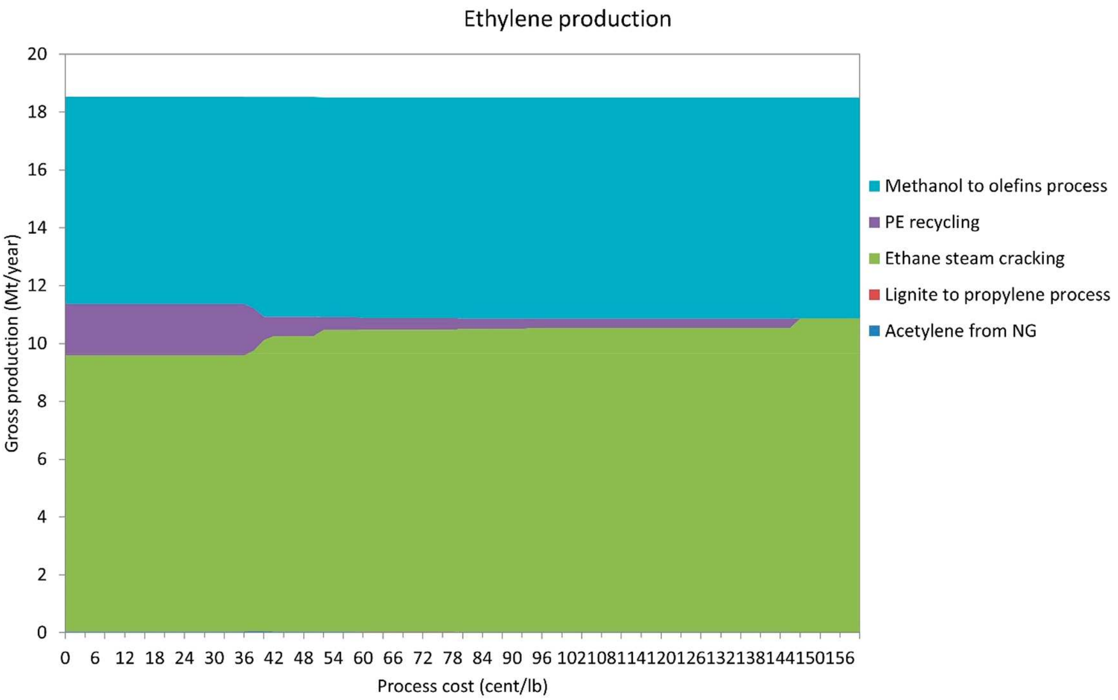


Figure 5. Production of ethylene by different processes vs process cost of recycling PE in the case with large scale supply of natural gas and NGLs (case 2).

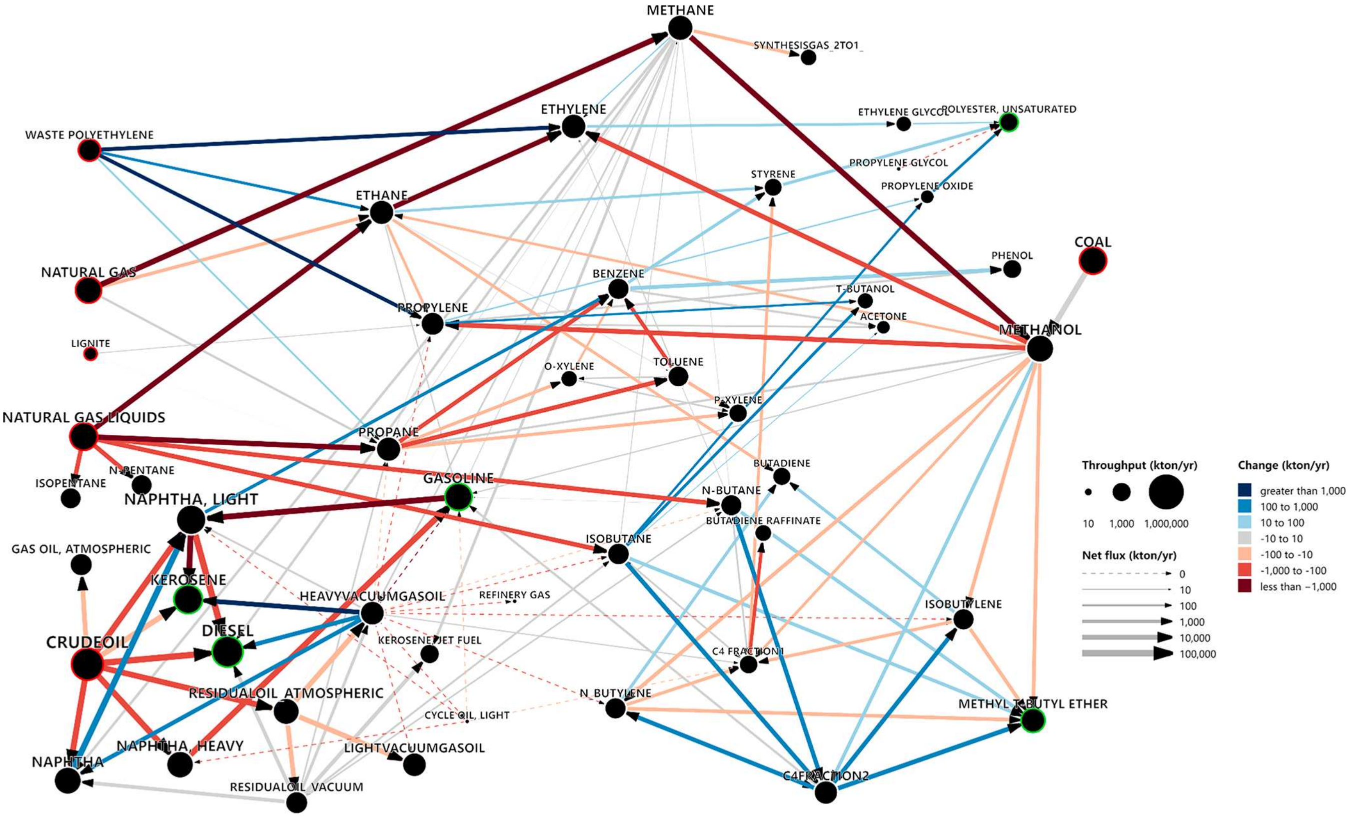


Figure 6. Network of chemical manufacturing: changes between no use of waste PE and 5 Mt/year of waste PE use; the base case for this analysis has more extensive NGLs availability than the cases modeled in Figures 3 and 4. Only processes that have changes in flow are shown in the figure. The magnitude of the change in flow is shown by different colors and the line width indicates the flow at 5 Mt/year of waste PE use. Dashed lines indicate the processes that are no longer used at 5 Mt/year of waste PE use.

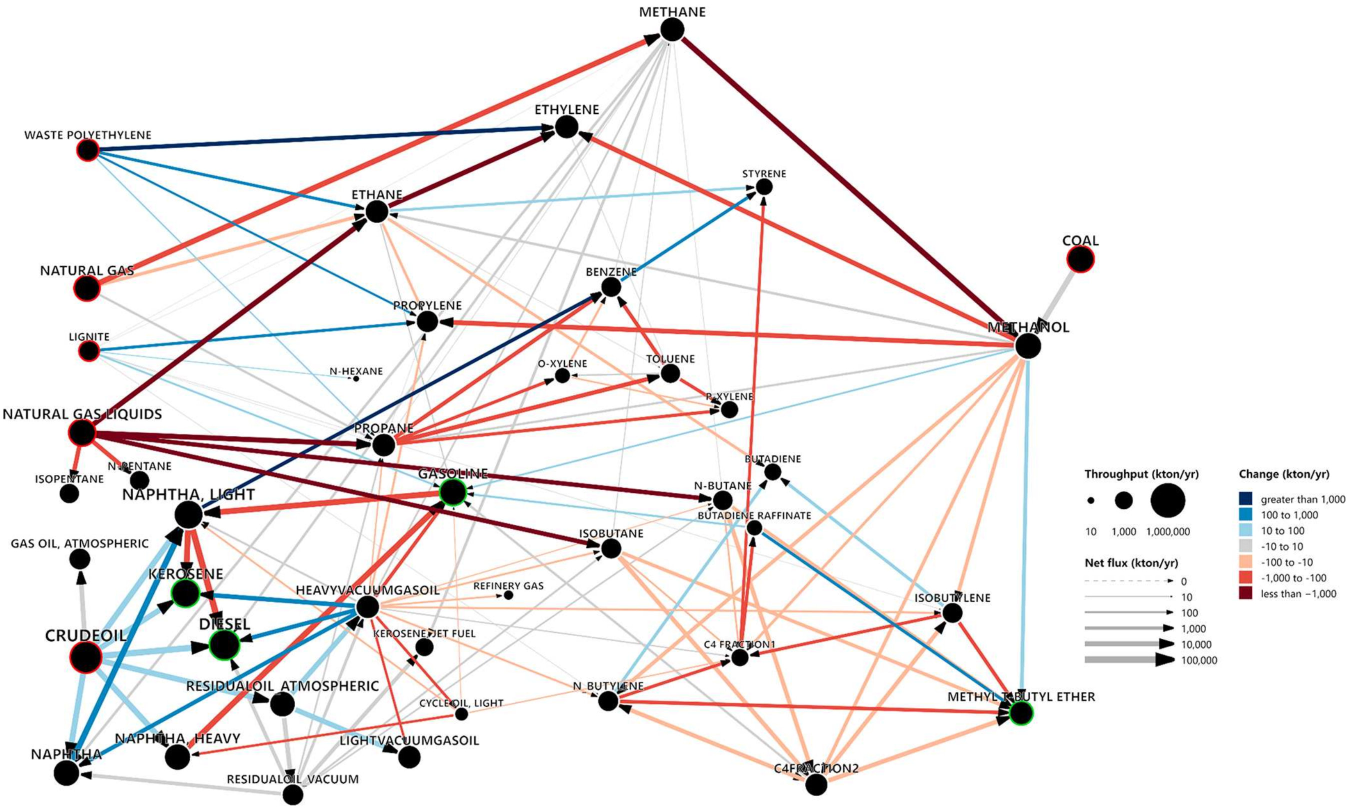


Figure 7. Network of chemical manufacturing: changes between no use of waste PE and 5 Mt/year of waste PE use; the base case for this analysis has more extensive NGL availability than the cases modeled in Figures 3 and 4 and the PE recycling technology process yields were assumed to match typical yield for ethane cracking. Only processes that have changes in flow are shown in the figure. The magnitude of the change in flow is shown by different colors, and the line width indicates the flow at 5 Mt/year of waste PE use.

CONCLUSIONS

Chemical manufacturing involves networks of highly interconnected processes, and changes such as large-scale chemical recycling of plastics have the potential to propagate change throughout the network. These changes have the potential to influence the overall costs and benefits of plastics recycling. This work has demonstrated a framework for evaluating these network changes and has shown that, for some impacts, such as the capital cost implications of adopting plastics recycling, the consequences of network changes can be large compared to relatively simple assessments of change.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.3c00990.

> The stoichiometry of PE recycling process; Calculation of energy requirement for thermal pyrolysis of PE; Components of NGLs as raw materials; Visualization of network; Figures for mapping the network of chemical manufacturing in different scenarios; Changes in greenhouse gas emissions for processes when PE recycling is fully utilized (PDF)

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Notes

The authors declare the following competing financial interest(s): One of the authors (D.T.A.) has served as chair and is currently a member of the Environmental Protection Agency, Science Advisory Board; in this role, he is a Special Governmental Employee. D.T.A. has current research support from the National Science Foundation, the Department of Energy, the Texas Commission on Environmental Quality, the Gas Technology Institute - Collaboratory to Advance Methane Science, the ExxonMobil Upstream Research Company, Pioneer Natural Resources, a consortium of natural gas companies, and the Environmental Defense Fund. He has also worked on greenhouse gas emission measurement projects that have been supported by multiple natural gas producers and the Environmental Defense Fund. D.T.A. has done work as a consultant for multiple companies, including British Petroleum, Cheniere, Eastern Research Group, ExxonMobil, KeyLogic, and SLR International.

■ ACKNOWLEDGMENTS

This paper is based on work supported by the V. Kann Rasmussen Foundation and the National Science Foundation under Award Number 2029397. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the V. Kann Rasmussen Foundation.

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