U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Manufacturing Office

Sustainable Chemistry in Manufacturing Processes Roundtable

Summary Report

November 17, 2020

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The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO) partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

This document was prepared as a collaborative effort between DOE AMO, Boston Government Services, and Energetics.

Disclaimer

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1. Executive Summary

The Advanced Manufacturing Office (AMO) at the U.S. Department of Energy (DOE) and the Green Chemistry & Commerce Council (GC3) co-hosted a virtual roundtable on *Sustainable Chemistry in Manufacturing Processes* on November 17, 2020, to collect industry stakeholders' perspectives on incorporating sustainable chemistry manufacturing practices into the manufacturing of consumer and commercial products. In attendance were 42 representatives from industry, trade associations, and academia.

Figure 1. Common Industry Perspective Themes for Sustainable Chemistry in Manufacturing

This report summarizes the presentations and small group discussions that took place at this event. Note that the results presented here are a snapshot of the viewpoints expressed by the experts who attended the roundtable and may not necessarily reflect the outlooks of the broader stakeholder community. The first half of the event included five-minute presentations from 16 representatives of businesses throughout the sustainable chemistry manufacturing supply chain, from chemical industry suppliers to formulators and retailers. Following the presentations, attendees participated in facilitated discussions regarding technology and commercialization barriers to sustainability and the research and development (R&D) needs to address those barriers in order to incorporate sustainable chemistry manufacturing practices into the manufacturing of consumer and commercial products.

To prepare for the facilitated discussions, a pre-meeting questionnaire was distributed to the participants to capture their diverse perspectives (see Appendix D for questions and compiled results). This information was supplemented by information gathered during the morning session's industry presentation series. Five common themes emerged.

Scalability

Scalability applies to both sustainable feedstock supply, which must be ramped up for commercial production, and new sustainable chemistry processes, which must progress from laboratory and prototype units to commercial-scale units. Both aspects are important for de-risking new sustainable products and processes.

Information-Sharing and Collaboration

All parties in the supply chain, from manufacturers to retailers, must have access to the same information about the chemicals used in any product to fully understand the potential for improvement.

Supply Chain Integration

Although related to scalability and information-sharing, this theme focuses on the need for a complete understanding of the lifecycle of a new product before it is manufactured. This knowledge is critical for circularity in the supply chain so product "waste" can become a raw material to manufacture a new product.

Technoeconomic and Lifecycle Analyses

Well-founded technoeconomic and lifecycle analyses (TEA and LCA, respectively) depend on reliable data. To compare sustainability factors across sustainable products and processes, analyses of sustainable products must employ a common language and standardized metrics.

Chemical Manufacturing Processes

Participants shared their successes using sustainable practices and processes to reduce and conserve energy, but further R&D of energy-efficient manufacturing processes is needed for wide acceptance of sustainable chemistry in manufacturing.

Using the common themes identified above as a starting point, the facilitated discussions addressed key opportunities for continued advances in sustainable chemistry, identified knowledge gaps, explored technology and commercialization barriers to sustainability, and determined the research and development (R&D) needs to address those barriers and realize the opportunities. A high-level summary of these are outlined in Table 1.

Table 1. Summary of Gaps, Opportunities and Research Needs for Sustainable Chemistry in Manufacturing Processes

Critical Knowledge Gaps	Key Research and Development Opportunities
Sustainable Manufacturing Products & Processes • Sustainable materials to substitute for currently available materials • Performance, toxicity and environmental impact information on sustainable products • Precision engineering to develop technologies in industrial settings • Competition with legacy capital equipment and cost optimization for traditional petrochemical based products	**Sustainable Manufacturing Products & Processes** • Process intensification approaches that dramatically reduce energy requirements • Sustainable chemistry solutions that are materials and processes for applications across many sectors (e.g. sustainable surfactants for use in detergents, cleaning products, soap products, etc.) • Adaptation of existing manufacturing platforms for sustainable manufacturing to reduce risk
Circularity • Post-consumer waste stream obscures information about its origins inhibiting use as feedstock • Consideration of product lifespan, including everything from disposable packaging to long-lasting end products	**Circularity** • Put sustainability into consideration during the product design phase so the final product can be designed to be sustainable • Development of solvent dissolution/depolymerization chemistries to enable recycling of wastes back into new products
Scaling Sustainable Manufacturing Processes • Sustainable manufacturing processes that produce commercial quantities of product while meeting performance requirements • Supply chain bottlenecks for sustainable raw materials and feedstocks • Availability of sustainable raw materials and feedstocks at cost-competitive commercial scales	**Scaling Sustainable Manufacturing Processes** • Common scalable pilot testing facility in a collaborative setting, with modular and flexible processes prioritized • Adaptation of existing manufacturing platforms for sustainable manufacturing to reduce risk
Analyses – TEA and LCA • Lack of consistent data for TEA/LCA • No common language for TEA/LCA	**Analyses – TEA and LCA** • Establishment of standard protocols for evaluating products • TEA/LCA based on primary information, not secondary information • Tools to help quantify environmental impacts and the value proposition to facilitate communication and prioritization

COLLABORATION NEEDS
• Information-sharing platform to share compositional and LCA data up and down the supply chain • Collaboration across the supply chain to identify R&D opportunities • Collaboration to bring successful R&D outcomes to scale

2. Background and Roundtable Proceedings

Background

The chemical industry is an important part of the U.S. economy and is the largest exporting sector in the United States, accounting for over 12% of the world's total chemical production, making the United States the second-largest chemical-producing nation.[1] More than 96% of the world's manufactured goods are enabled by chemistry, from the production of food and clean drinking water to medicines, cleaners, personal care products, and a host of other products that contribute to virtually every aspect of modern life. The industry is directly responsible for creating more than 500,000 jobs and indirectly for several million additional jobs via industry suppliers.

Energy is an important component of the costs within the chemical industry and, for some energy-intensive chemical products, can account for up to 85% of the total production costs.[2] Since 2010, shale gas production in North America has been causing a dramatic shift in production costs. Today, the United States is among the lowest-cost producers in the world, attracting record levels of investment in new facilities and expanded production capacity. This shift is also presenting new research and development (R&D) opportunities that may enable smaller-scale, modular manufacturing that can enable competitive processes as alternatives to more traditional, energy-intensive chemical processes.

The industry is undergoing other significant changes as it seeks to address issues related to the lifecycle energy and resource impacts of manufactured goods. Many in the chemical industry are working to address these issues by improving the environmental sustainability of their own chemical processes, as well as by providing more sustainable products and technologies to others. As global competition to manufacture more sustainable products intensifies, industry, academia, and government partners need to leverage existing resources, collaborate across supply chains, and co-invest to nurture manufacturing innovation and accelerate commercialization of sustainable products and technologies. The market demand for more sustainable manufacturing practices in the chemical industry for both consumer and commercial products is a new opportunity to create significant value for U.S. manufacturing and maintain U.S. global competitiveness.

In recognition of the manufacturing industry's evolving priorities, the U.S. Department of Energy (DOE) Advanced Manufacturing Office (AMO) is investing in R&D to address sustainable chemistry in manufacturing. Over the last two decades, AMO has invested in R&D on a number of technologies that are vitally important to the U.S. chemical manufacturing industry—from tools for catalyst design to more efficient intensified processes to enabling technologies based on modeling and simulation. The Office has worked in partnership with the chemicals industry to develop a range of resources for improving energy efficiency and has extended those efforts to incorporate sustainability issues throughout the supply chain.

An overview of DOE AMO interest in sustainable chemistry in manufacturing processes was provided by Dr. G. Jeremy Leong, Technology Manager, R&D Projects. Technology innovation through applied R&D in

[1] American Chemistry Council, 2019 Guide to the Business of Chemistry.

[2] Ibid.

advanced manufacturing and energy is a foundation for economic growth and jobs in the United States. The mission of AMO is to catalyze R&D and adoption of energy efficient advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity. As part of its mission, AMO supports a range of projects addressing chemical industry energy challenges, through a three-pronged implementation approach including funding individual R&D projects, R&D consortia, and technical assistance (see Figure 3, below).

The roundtable was cohosted with the Green Chemistry & Commerce Council (GC3). GC3 is an organization whose mission is to drive the commercial adoption of green chemistry by catalyzing and guiding action across all industries, sectors and supply chains. Their membership includes not only chemical producers but also companies using chemicals to make commercial products (e.g., shoe manufacturers) and companies selling commercial products (e.g., retail chains). All member companies are dedicated to advancing the [12 principles of green chemistry].

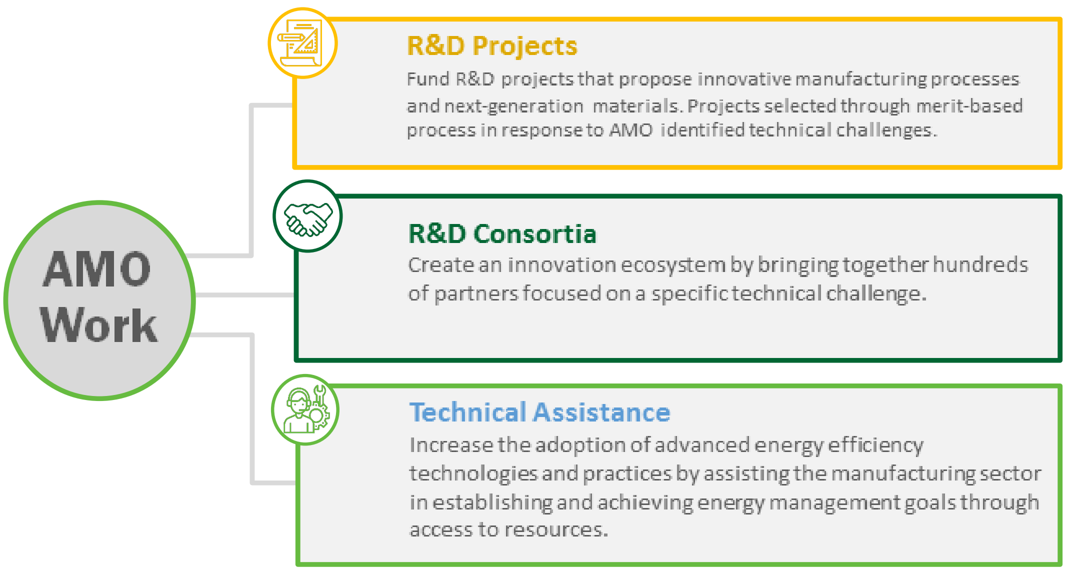

Figure 2. Three Pillars of the AMO Program

Roundtable Overview

Roundtable Purpose - *Identify R&D needs for process technologies, materials, or products in order to incorporate sustainable chemistry manufacturing practices into the manufacturing processes of consumer and commercial products.*

On November 17, 2020, AMO partnered with the Green Chemistry & Commerce Council (GC3) to host a virtual roundtable on *Sustainable Chemistry in Manufacturing Processes* to collect industry stakeholders' perspectives on future research priorities to incorporate sustainable chemistry manufacturing and practices into the manufacturing processes of consumer and commercial products. In attendance were 42 representatives from across the chemical manufacturing sector (shown in Figure 3). Attendees explored key opportunities for continued advances in sustainable chemistry, identified knowledge gaps, explored technology and commercialization barriers to sustainability, and determined the R&D needs to address those barriers and realize the opportunities.

A variety of information sharing mechanisms were used to gather valuable input and feedback from participants. Before the roundtable, participants were invited to complete a questionnaire on the barriers to sustainable chemistry in manufacturing and the R&D needs to address. This information was used to inform the breakout sessions during the roundtable.

The first half of the event included five-minute presentations from representatives of businesses throughout the sustainable chemistry manufacturing supply chain, from chemical industry suppliers to formulators and retailers. Presenters discussed their current sustainable practices and the barriers and needs for sustainable chemistry manufacturing. These presentations were punctuated by real-time meeting prompts to encourage engagement and learn about the sustainable manufacturing practices and viewpoints of each participant. Chemical industry association representatives were invited to provide their own perspectives after the mid-day break, with ensuing discussion. Throughout the day, participants were broken into smaller, parallel breakout group discussions to provide opportunities for deeper discussions.

The agenda for the roundtable can be found in Appendix A, and Appendix B provides the full list of attendees. Also included in the Appendices are the summary of results from the pre-roundtable questionnaire (Appendix D) and a summary of real time meeting prompts conducted throughout the event (Appendix E) The acronyms used in this report are defined in Appendix C.

Figure 3. Participating stakeholders from the chemical sector.

3. ROUNDTABLE PARTICIPANT PERSPECTIVES AND COMMON THEMES

Pre-meeting Participant Viewpoints

Realizing the diversity of participants in the roundtable, a pre-meeting questionnaire was helpful in capturing the diverse participant perspectives prior to the roundtable. Feedback was grouped into six questions, the responses are summarized here and outlined in further detail in Appendix D. As to be expected many attendees has similar responses to questions. To designate multiple responses, the number of times a particular concept was mentioned is shown in parentheses in Appendix D.

1. What is needed to fully implement sustainable chemistry into manufacturing chemicals, products, materials, etc.?

An identified need is that clear advantages (cost, emissions, etc.) must be demonstrated through TEA/LCA and business decision tools. These analyses must be based on reliable data inputs. At present, input data is not always available and proxy data must be used compromising the output. This point is related to an additionally identified need, information sharing. The need for effective information sharing pertained to product ingredient disclosure, transparency and traceability. Another common need was for scalable sustainable technologies capable of reproducible and resilient operations. Other common responses were the need for a complete supply chain to provide access to sustainable raw materials and new chemical process technology to replace unstainable technologies.

2. Where are the most significant impacts for incorporating sustainable chemistry practices?

Responders indicated the drivers for incorporation of sustainable chemistry being 1) replacing hazardous substances, 2) carbon footprint reduction, 3) energy reduction, and 4) waste reduction.

3. What sustainable chemistry practices have the greatest chance of being replicated across different product types?

A common response was technologies that could be implemented within and across sectors. While the nomenclature varied, many responders either named a specific chemical or described the idea of a chemical or material that can be implemented across many sectors. Specifically submitted examples were biocatalysts, colorants, recycled carbon, solvents, surfactants, reactants, preservatives, emulsifiers, and dissolution/depolymerization chemistries for applications in circularity. Also, the idea of circularity, recycling of wastes back into the front-end as a raw material was identified. Another common idea was a change is development outlook, sustainability by design. The responders indicated that by taking sustainability into consideration during the design phase means that many obstacles can be addressed in the decision-making phase like supply chain gaps. Other common responses were process intensification and the use of renewable or bio-based feedstocks.

4. What is currently working in your industry to utilize sustainable chemical processes and practices?

A common answer was using technoeconomic analyses and life-cycle analyses to identify the best areas to integrate sustainable chemistry processes and practices. Some respondents added a layer of specificity to these analyses and indicated that companies use their own specific screening algorithms/tools to identify sustainable chemistry approaches to add to their processes. Another common answer was engineering models and controls which benefit from the reduction in waste and reduced hazard of sustainable chemicals. In the supply chain, several respondents mentioned they utilize sustainably developed packaging materials.

5. What are the barriers and challenges to incorporating sustainable chemistry processes and practices?

Many responses mentioned cost as the largest barrier to incorporating sustainable chemistry. In many cases, responders noted that higher costs can be offset by sacrificing product performance. Ultimately this creates a cost/performance tradeoff for the consumer compared to incumbent products. Another related barrier mentioned is the high cost of R&D. The next most common answers, piloting and scaling technologies, are related to troubles with R&D. Without funding for R&D, there are not enough technologies to pilot, and without pilots, it is hard to scale sustainable chemistry processes and practices. An additional related barrier that was brought up is the lack of relevant business cases. Without a commercial justification, it is difficult for companies to warrant investment. Other common answers were a need for workforce development and education in sustainable chemistry processes and practices and a limited availability of sustainable raw materials.

6. What R&D is needed to facilitate the development and adoption of sustainable chemistry processes and practices into manufacturing?

Similar to previous response, a common response pertaining to needed R&D was platform chemicals and technologies. Similar examples were put forth with a full list given in Appendix D. Another shared need was scale up and process modularization to help proof of concept and feasibility studies. Collaboration tools or platforms were also mentioned as a R&D need both in the context of information sharing and also to more effectively identify challenges and solutions across the supply chain. It was noted that this type of collaboration was vital to remove the barriers to a circular economy and facilitate innovation in the transition between waste and resource. Another need was the setup of standard protocol to evaluate the sustainability of products during manufacturing thus showing an easy-recognized value/grade for customers to better understand the sustainability of the product.

Industry Perspective Themes

Sixteen industry speakers provided their unique perspectives on how sustainable chemistry is being incorporated into consumer and commercial manufacturing processes. These five-minute presentations captured current and future sustainable chemistry opportunities, barriers, and R&D needs for organizations ranging from chemical industry suppliers to formulators and retailers. Industry stakeholders also provided their perspectives through responses to the pre-meeting questionnaire (summarized above) and during breakout group discussions during the roundtable meeting (summarized below).

After all these industry perspectives were evaluated, five common themes for incorporating sustainable chemistry became apparent: chemical manufacturing processes, scalability, supply chains, information-sharing and collaboration, and analysis (Figure 4). Opportunities, barriers, and needs for sustainable chemistry implementation were discussed in the context of each of these five common themes. Specific barriers and needs were seen as dependent on where the company lay within the supply chain. Cost remains the biggest barrier for integration in the chemical manufacturing industry; offsetting 50 years of cost optimization for traditional petro-based products throughout the supply chain is a significant barrier to full adoption of sustainable chemistry.

The themes are elaborated below.

Figure 4. Common Industry Perspective Themes for Sustainable Chemistry in Manufacturing

Chemical Manufacturing Processes

Incorporating sustainable chemistry into existing processes is expected to have its greatest impacts in energy reduction and conservation. Sustainable chemistry is increasingly allowing industry to replace oil-based feedstocks with sustainable feedstocks. The switch saves energy by allowing manufacturers to replace energy-intensive processes that require use of high heat and high pressure with new processes that can happen closer to room temperature and pressure. Another advantage of sustainable feedstocks is that they can often be strategically grown closer to manufacturing sites requiring less energy to deliver than petro-based feedstocks.

While companies that participated in the roundtable are making strides in sustainability chemistry, further development of lower-energy manufacturing processes is needed. One specifically discussed R&D need involved fundamental one-carbon molecule (C_1) chemistries. Research around C_1 chemistry is foundational to carbon capture and utilization. As CO_2 is thermodynamically very stable, a significant amount of energy is needed to make use of it. Fundamental research in this area was seen as a significant opportunity by many attendees.

In the presentation lightning round and the pre-meeting questionnaire attendees noted several actions companies are taking to reduce energy usage. These ranged from better engineering controls, smart manufacturing, substitution with electrified processes, and process intensification. Process intensification was the route most discussed to reduce energy consumption with many companies actively working to suitably size plant processes and equipment while concentrating throughput. One challenge associated with process intensification for chemical manufactures is achieving the same product quality with the same single pass conversion efficiency.

Scalability

Scalability is important in terms of both the chemical process (i.e., size) and the operation (i.e., numbers).

From a supplier's perspective, scale is a problem with respect to availability of requisite sustainable feedstocks. In the case where sustainable feedstocks are available to suppliers, bottlenecks within the supply chain make conversions to the next manufacturing level difficult. For a given process or product, the scale-out rate needs to increase simultaneously

Piloting new sustainable chemistry products and processes. The ability to pilot at a commercially relevant scale is critical to de-risking investment. The cost and resources required to get to the pilot stage successfully are a significant barrier for companies (particularly small businesses) throughout the supply chain. Partnering with the national laboratories is one way to address the scalability challenge for small businesses, as well as niche products or processes. National labs could provide a flexible piloting infrastructure that accommodates, adapts, and can be repurposed for a diverse set of chemical processes.

Supply Chain

Many attendees noted that a fractured or opaque supply chain is a common barrier to integration of sustainable chemistry. This makes scaling new alternatives and integrating them across the supply chain difficult. Supply chain challenges stem from the emerging nature of the sustainable chemistry initiative, however gaps in the manufacturing supply chain also arise from scaling bottlenecks and lack of access to sustainable feedstocks. Fractured or opaque supply chains make downstream product information sharing difficult and hinders communicating the value to the customer.

Commonly discussed solutions involved:

1) A problem-focused outlook in which the full supply chain is contextualized when developing new sustainable product/processes
2) Collaboration across the supply chain that removes barriers to a circular economy (e.g. chemical composition).

Experience has shown that when the players that make all the components of a product work together toward a sustainable chemistry innovation, the results are more powerful.

Circularity in the supply chain- As stated in the pre-meeting viewpoint section. Circularity was seen by many attendees to be one of the most significant areas for highest impact of sustainable chemistry because it can be translatable to every material and every market. The consensus is that investment is needed to pivot from "waste collector" at the end of the value chain to "raw material supplier," thereby shifting the narrative away from seeing waste and recycling as "lower grade" to seeing opportunity.

Circularity overlaps with several of the recurring roundtable themes. The development and implementation of information-sharing networks and platforms to share compositional and lifecycle analysis data up and down the supply chain will allow for informed and scalable segregation of end-of-life resource streams. Further investment in R&D of the extraction, sorting, and concentration of resources at the initial end-of-life of a product will provide value in the resulting raw material's quality and ultimately facilitate the adoption of circularity of feedstocks.

Information Sharing and Collaboration

Information sharing emerged as a common theme throughout the roundtable and was primarily mentioned in connection with supply chain transparency and TEA/LCA analysis. The latter will be discussed in the next section.

Multiple attendees highlighted product transparency across the supply chain as a crucial hurdle to overcome. They noted that consumers are demanding safer products. Retailers want to meet this demand, and manufacturers, in turn, want to meet retailers' demands. However, that entire chain requires that the parties have near-equal understanding of the product ingredients, and the potential for improvement. Attendees noted that the lack of transparency across the supply chain hinders the communication of value to the customer and ultimately undermines a key motivation for use of certain sustainable products and processes.

A common idea among the roundtable participants to solve information sharing challenges was the development of virtual collaboration platforms. Highlighted as a potential opportunity, creating a virtual platform that allows companies throughout the value chain to connect, collaborate, and share information in a pre-competitive manner. Such a platform would help better identify obstacles and gaps throughout the supply chain and could also act as a central location for data.

Analysis (TEA and LCA)

As more sustainable chemistry products and practices are developed, companies are turning to analytical tools such as TEA and LCA to inform their decision-making. Reliable analysis tools help quantify environmental impacts and the value proposition in order to communicate and prioritize opportunities (for example, comparing the technoeconomic, environmental, and energy impacts of producing polyethelyene from bio-based feedstocks versus legacy feedstocks).

In fact, many companies are already employing these analyses. When discussing these analytical tools several challenges emerged. The first was that there was no common language for LCA of sustainable products and that companies need more standardized metrics within the analysis to compare sustainability factors. The second challenge relates to information sharing. Both TEA and LCA can only be as accurate as the data input into them. In many instances, such data inputs are unavailable or unknown, so proxy data must be used, compromising the accuracy of the analysis. Data inputs from primary sources are needed to properly assess emerging chemistries and demonstrate value.

These tools will also be important for product circularity, where the analysis must take into account the material recovery method and effectivity of the conversion process back to raw material to demonstrate value. An example of one such analysis was conducted by BASF for the company's ChemCycling™ method for chemically recycling plastics.[3] A LCA analysis found that for single-stream plastic waste, such as PET from water bottles, mechanical recycling has a smaller carbon footprint than chemical recycling. However, for mixed and contaminated plastics, mechanical recycling is impossible or inefficient, leading to incineration as the common disposal method. For such products, chemical recycling is a more sustainable solution, emitting 50% less CO_2 than incineration.

Other Common Themes

Also discussed during the roundtable were platform technologies and workforce development.

Platform technologies are sustainable chemistry materials or processes that translate across many industry sectors. One example of a platform technology would be a new sustainably produced surfactant. Drastically reducing energy/carbon to produce surfactants would have impacts across cleaning and cosmetic products and could have impacts across both the consumer and professional markets. Focusing on a few big cross-sector contributors would have maximum impact. In addition to surfactants, opportunities for platform technologies include biocatalysts, colorants, recycled carbon, solvents, reactants, preservatives, emulsifiers, and dissolution/depolymerization chemistries for applications in circularity.

Platform materials could also include the class of molecules called Ortho phthalates. These molecules are typically used as plasticizers in cleaning products, beauty and personal care products, office products, home improvement (in flooring, sealants, paints, etc.), electronics (in cords and cables), and textiles. The electronics and plastics production sectors are very energy-intensive. Producing polyvinyl chloride (PVC), the primary

[3] Christian Krüger and Corporate Sustainability BASF SE. "Evaluation of pyrolysis with LCA–3 case studies." *Update* (2020).

plastic using plasticizers (about 95%), is particularly energy-intensive, as it incorporates chlorine.[4] Innovation in alternative materials that do not require plasticizers—thereby reducing energy consumption—would have significant impacts.

During the industry presentation lightning round workforce development challenges were mentioned several times as a challenge for companies primarily on the supplier and formulator side of the supply chain. These companies indicated that hiring engineers and chemists has been a challenge. Specifically cited was the lack of student preparation for future sustainability challenges and that few, if any, have experience in sustainable chemistry.

Association Perspectives

Feedback was collected from six association stakeholders through the pre-meeting questionnaire. The major themes from these responses are summarized below.

Need for Federal Funding

Federal funding can play an important role in advancing sustainable chemistry technologies and processes from laboratory to commercial scales. This transition in size and complexity is often referred to as the "valley of death" for technology development and has long been recognized as an area where additional funding helps alleviate both technical and market risks. Sustainable chemistry innovations face the same hurdles as those in other market sectors, with timescales and necessary investment levels that are undesirable for conventional private investors. Directed federal funding can help inject money where it is needed in the research, development and demonstration process and would allow the government to play a more active role in setting standards and foundations for sustainable chemistry technologies and processes. In addition to straight federal funding, public–private partnerships offer an attractive route for increasing successful scale-up of sustainable chemistry innovations.

Economics and Co-Benefits Already Driving Sustainable Chemistry Adoption

Sustainable chemistry processes reduce energy use and waste and, therefore, costs—to an extent that many legacy processes are being phased out. A greater use of TEA and LCA can help accelerate this transition by demonstrating the favorable economics of other processes that can be made sustainable today. In addition, consumer demand for sustainable products is increasing, which is driving companies to reexamine legacy systems. However, producers remain reluctant to transition from legacy systems, in part because of the remaining technical and market barriers.

Legacy Systems Remain a Large Barrier

When building new capacity, industry has shown a desire to adopt sustainable processes. However, there is a lack of incentives to transition existing infrastructure to a sustainable model. Many commoditized chemicals and materials are produced through long-standing, large-scale systems, and replacing or adapting these systems entails high upfront costs. This is one area in which AMO can play large a role by assisting in the integration of a wide range of new chemicals, materials, technologies, and processes into existing manufacturing environments.

[4] European Commission. European Union Risk Assessment Report: 1,2-Benzenedicarboxylic Acid, Di-C9- 11-Branched Alkyl Esters, C10-Rich And Di-"Isodecyl" Phthalate (DIDP), CAS-Nos 68515-49-1 and 26761-40-0. Vol. 36, EUR 20785EN, Office for Official Publications of the European Communities: Luxembourg, 2003.

Wide-Ranging Energy Benefits

Not only do sustainable chemistry processes reduce energy use through employing lower-temperature and lower-pressure processes, they also consume less fossil fuel inputs. By replacing non-renewable feedstocks with bio-based alternatives, sustainable chemistry processes may reduce negative environmental aspects of chemical processes and associated emissions. Sustainable chemistry processes are also improving the lifecycle impacts of photovoltaic solar cells, energy transmission infrastructure, and energy storage technologies.

Association stakeholders also emphasized waste reduction and environmental impacts, which may have benefits for human health, reduce liability risks for companies, and improve safety for companies, consumers, and workers.

A Broad Approach to Growth is Best

Sustainable chemistry innovations will be most successful if they have broad applicability across multiple sectors and industrial processes. Such innovations could be used to increase sustainability and safety in many products, including solvents, surfactants, reactants, preservatives, emulsifiers, catalysts, plasticizers, repellents, flame retardants, preservatives, and antimicrobials. Industry requires these chemicals be drop-in replacements that have similar performance before they are adopted at large scales. Focusing on these alternatives can drive wider systematic change. Suppliers, manufacturers, and retailers should all be involved in the transition to sustainable chemistry with transparency across this supply chain.

Summary of Group Breakout Discussions

Participants contributed their individual viewpoints through facilitated discussions in small breakout groups. The facilitators followed parallel agendas. Each breakout group first reviewed the responses to the pre-meeting questionnaire to stimulate further discussions. Participants brainstormed technical and commercial barriers inhibiting further development of sustainable chemistry practices. Once identified, the barriers were grouped loosely into barrier topic areas, which were revisited each time the breakout group convened. Group members then explored the priority R&D needs to address the barriers.

Breakout Group Discussion Questions

1) What are the technical and commercial barriers to overcome in developing and integrating important new sustainable chemistry technologies in manufacturing?
2) What R&D is needed to advance sustainable chemistry in manufacturing?

A summary of the barriers and needs identified is provided below for each breakout group. Figures 4–6 depict the process that was followed by each breakout group. A synopsis of the findings across the three parallel breakout discussions is provided at the end of this section. Concepts that arose in more than one breakout group are highlighted in yellow in Figures 5–7.

Breakout Group 1

Group 1 identified eight barrier topic areas. At the end of the discussion, the group was in unanimous consensus that pilot testing was the highest R&D need. Many of the identified needs included common pilot testing capabilities. Group members noted that the testing infrastructure should be modular and flexible, scalable, and collaborative. Figure 5 summarizes the barriers and needs identified by this group.

Breakout Group 2

Group 2 identified six barrier topic areas. The group identified and prioritized an overarching need to solve for the article manufacturer's sustainability requirements by addressing cost, scale, and supply chain issues from the outset when seeking replacement chemicals. This overarching need applies to other R&D needs such as developing replacement products for surfactants or per- and polyfluoroalkyl substances (PFAS), as well as addressing integration barriers. Some participants also prioritized R&D needs to address scalability barriers, including considering large-scale production required early in the development process and using pilot-scale facilities. Figure 6 summarizes the barriers and needs identified by this group.

Breakout Group 3

Group 3 identified six barrier topic areas. The barriers varied across a number of key themes. Participants highlighted the importance of materials, processes, market conditions, end-use applications, and supply-side dynamics. The idea of "alignment" permeated the discussion, as participants recognized that aligning activities and expectations across the supply chain and industry is necessary to enable growth and to overcome barriers. Figure 7 summarizes the barriers and needs identified by this group.

Barriers		R&D Needs
Technology, development, specifications and engineering	performance expectations; resource utilization efficiency; lack of precision engineering solutions	• CHP R&D, e.g., cogeneration • Catalysis • Carbon capture, utilization, and storage • Solvent dissolution chemistry for recycling
Technology investment and transfer	technology and market risk; price expectations; transferability technology solutions in supply chain	• Stabilize technology solutions for downstream use and transferability (e.g., we can do the fermentation but cannot processes it to get to final product to be integrated) • Modular solutions and capabilities, e.g., for iron exchange or precipitation • Modular and flexible testing (priority)
Testing and pilot demonstration	flexible pilot facilities available to small businesses; efficient testing for sterilization	• Common scalable pilot testing facility (priority)
Access to information and sharing information	end user awareness, what are they currently buying; two-way transparency	• Sustainable chemistry membership test network, database of partners, network for testing facilities; e.g., RAPID • Blanket agreement and infrastructure for information sharing, at the process level
Scalability	infrastructure cost; economic accountability for co-products and byproducts (viable chemistry); scale in recycling/modularity	• Scalable pilot testing facility in collaborative setting (priority); National labs have a role to play in pilot testing
Standards, modeling and analysis	cost modeling of performance standards with validation and confirmation of consumer interest; coordination between sustainability and performance standards; current LCA uses proxy data, not specific, doesn't have consistent data	• Analysis of what is in the recycling stream for high tech solutions • A spectrum of tools are needed that will help articulate the sustainability value, flexible and cost appropriate, aligned across the industry for consistency • Tools to quantify environmental impacts and financial value proposition • Consistent data to quantify and prioritize substitutions • AI for LCA and carbon footprints, it may be quicker
Infrastructure and supply chain	international infrastructure limitations (e.g., high quality processors); the right technology in the right place, import/export of waste; supply chain deficits	• Transportation solutions to minimize and optimize logistics
De-risking	commercial-scale marketplace acceptance; deployment risk aversion; cost/benefit of replacing customers current products	• Involving investors (VCs) in the business of de-risking

Figure 5. Breakout Group 1, Barriers and R&D Needs for Sustainable Chemistry in Manufacturing

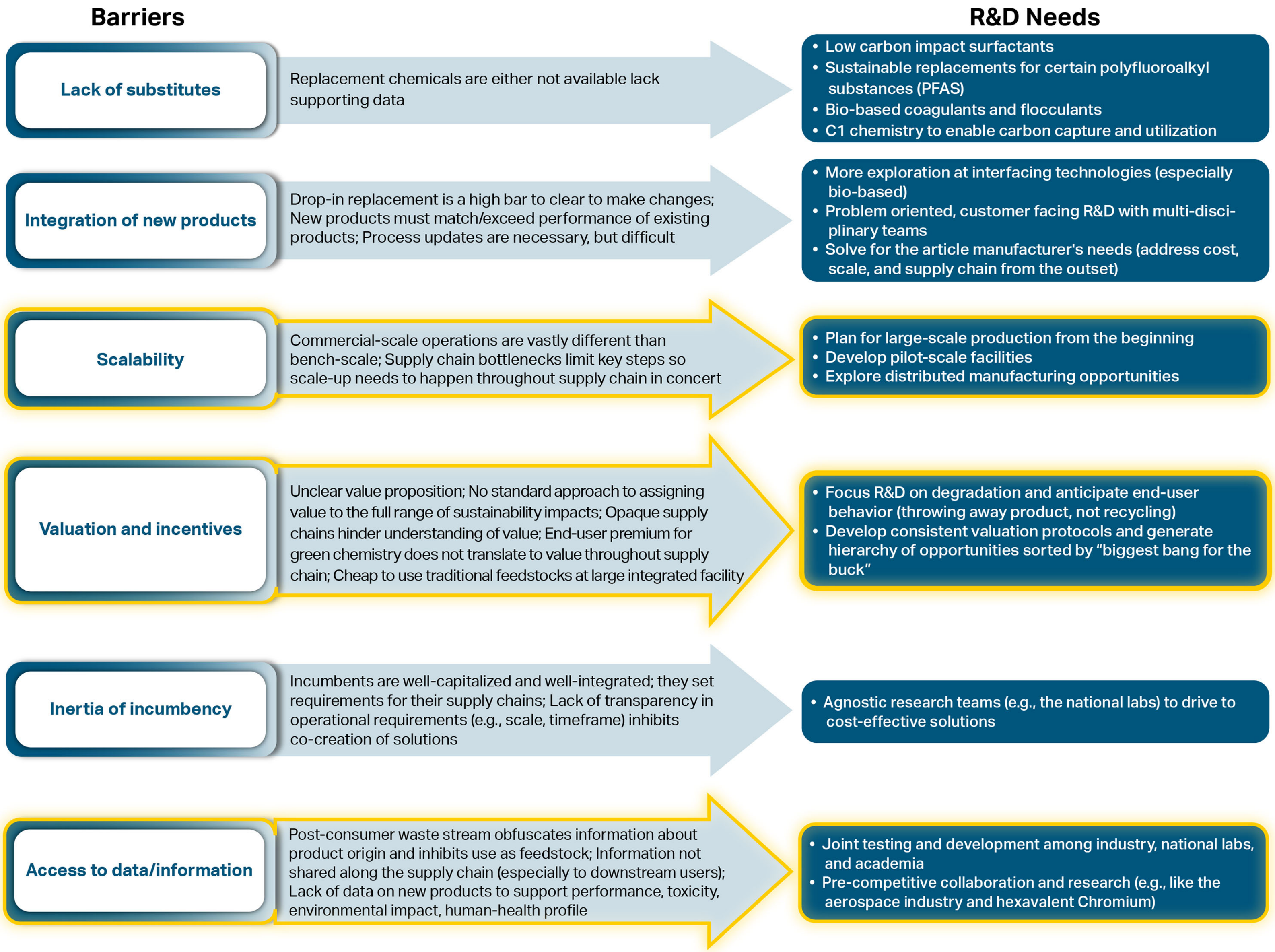

Figure 6. Breakout Group 2, Barriers and R&D Needs for Sustainable Chemistry in Manufacturing

Barriers		R&D Needs
Application Diversity	Specialty chemicals or process that are not easily applied across products or manufacturing sectors	• Chemistries that work in multiple products • Platform chemicals • Multi-use materials, appropriate for different applications
Awareness	Lack of awareness concerning needs/opportunities; technical expertise is not always in-house; connection across the supply chain in a pre-competitive manner	• Better understanding of portfolio of products, better understanding of sustainable/unsustainable. • Generating or producing a standard to communicate environmental benefits; scale for communicating sustainability level. • Quantified degree of environmental responsibility that supplier can use to communicate and evaluate sustainability in their product or process. • Increasing collaboration within and across industries to help identify opportunities; collaborate to bring R&D to scale.
Investment	Financial analysis should support innovation, value proposition; return on capital must exceed cost of capital; new chemistries must contribute to a company's bottom line; market demand; alignment of DOE funding opportunities	• Investor attractiveness; sufficient investment addresses other issues. • Aligning R&D efforts with the needs of customers on customer-led, sustainability-focused projects. • Aligning outputs of one program with the inputs of the next one
Chemistry Platforms	Industry bias toward existing chemicals used in production (consistency, cost, scale, performance with petroleum products); infrastructure and logistics of materials	• Formulation development, new molecules and new chemistry. • Supply solutions, interplaying with cost; must be available at a usable scale.
De-Risking Research	Lacking application development to demonstrate value to customer; big chemical companies taking risk and moving away from traditional production methods	• Gov-subsidized R&D, new products will be expensive, need support. • Specific R&D and incentives for application-specific work.
Integration	Aligning value chains from suppliers to end customers, typical chemist unaware of how new chemistry fits in to manufacturing process; chemical companies are not doing the downsream development work.	• Holistic development strategy for sustainable chemistry development. • To ensure new chemistry success, production needs to fit into existing manufacturing platforms; new platforms introduces risk.
Scaling	Market migration and adoption; kinetics of scaling; value chain partners want green, and cost and performance requirements aren't met immediately; market penetration	• Quickly getting to scale - can facilities be repurposed? Can we reduce investment needed for new facilities? Can this be accomplished through partnerships? What funding can support this? • Reduce investment needed for new facilities through partnerships and funding • Toobox of options - including places to manufacturing R&D, pursue pieces and parts in parallel to meet needs

Figure 7. Breakout Group 3, Barriers and R&D Needs for Sustainable Chemistry in Manufacturing

Synopsis of R&D Needs from Breakout Group Discussions

The input received in parallel breakout groups proved to have many consistencies and correlations. The following topics were discussed in more than one breakout group include:

(1) Access to information, awareness, and information sharing promoting effective supply-chain collaboration

(2) Scalability and pilot-scale testing

(3) Valuation and investment

(4) Integration and transfer of new products

(5) De-risking investment

(6) Application diversity/substitution

(7) Tools and analysis

4.THE RESEARCH AND DEVELOPMENT NEEDS TO ACCELERATE SUSTAINABLE CHEMICAL MANUFACTURING

Workshop participants highlighted that the incorporation of sustainable chemistry into consumer and commercial manufacturing processes requires collaboration and information sharing across the entire supply chain. The R&D to advance the incorporation of sustainable chemistry into material manufacturing and industrial practices is broad in terms of industry diversity.

Below are the R&D needs applicable to the AMO mission to accelerate sustainable chemistry.

Materials:

- Material and feedstock substitution via sustainable raw materials such as biobased feedstocks, CO_2 utilization, and advanced recycling.
- Innovation in platform molecules that can be applied broadly across industrial sectors in key chemical functions. These platform materials include biocatalysts, colorants, recycled carbon, solvents, surfactants, reactants, preservatives, and emulsifiers.

Processes and practices:

- New process technologies including industrial electrification, process intensification, combined heat and power, and integration of carbon capture utilization and storage into industrial processes.
- Modular and flexible processes, as well as smart manufacturing. These approaches are avenues toward incorporation of sustainable chemistry practices into manufacturing processes.
- More sustainable industrial approaches that allow greater molecular fine tuning, creating libraries of platform molecules and derivative chemistries in addition to advanced fermentation, purification, and extraction processes.
- Shared piloting facilities that are flexible in design provide companies a route to rapidly assess process challenges and expected efficiencies, as well as demonstrate cost-effective and resilient operation.

The R&D should demonstrate reductions in carbon emissions, increased energy efficiency, reduced toxicity, or increased material use and reuse across the supply chain and minimize any trade-offs (including toxicity) between sustainability attributes. The materials and processes that utilize sustainable chemistry practices need to be comparable in cost and performance to standard materials and processes as well as scalable in terms of material availability and scaling operations.

To fully incorporate sustainable chemistry into the manufacturing of chemicals, products, and materials, participants highlighted the importance of collaboration across the entire supply chain. R&D efforts should involve suppliers, formulators/fabricators, packagers/fillers, retailers, consumers, and waste management specialists. Collaborations can build a stronger understanding of the functional, application, and sustainability requirements and encourage the sharing of data to assess the end product’s sustainability through the entire supply chain. Also, holistic approaches and methodologies to evaluate the safety and sustainability of sustainable chemistry solutions along the lifecycle can be further developed.

5. Roundtable Conclusion

The roundtable concluded with Dr. G. Jeremy Leong thanking all of the participants for attending and providing valuable, broad stakeholder input as well as identifying the key R&D challenges, needs and opportunities that will inform AMO's future programmatic direction in sustainable chemistry. Dr. Leong also acknowledged both GC3 as the meeting co-host and the AMO/Energetics facilitation & planning team for a successful run of show.

Attendees were informed that the presentations are available on the DOE AMO website and that an early draft of this roundtable report would be made available to all attendees for final input prior to final publication.

APPENDIX A. AGENDA

DOE/EERE Advanced Manufacturing Office Stakeholder Engagement Roundtable

Topic: Sustainable Chemistry in Manufacturing Processes

Co-hosted by the Green Chemistry & Commerce Council (GC3)

10 AM – 12:30 PM and 1:30 – 3:15 PM EST, November 17, 2020

Time EST	Activity
10:00 AM – 10:15 AM *	**Welcome and EERE Advanced Manufacturing Office Perspectives** – Valri Lightner, Deputy Director, Advanced Manufacturing Office – Jeremy Leong, Technology Manager, Advanced Manufacturing Office
10:15 AM – 10:20 AM	**Roundtable Logistics and Facilitation** – Michele Jalbert, Green Chemistry & Commerce Council (GC3) – Sabine Brueske and Diane Sellers, Energetics (Facilitators)
10:20 AM – 12:30 PM	**Industry Stakeholder Presentations** *Lightning round perspectives on how sustainable chemistry is being incorporated into consumer and commercial manufacturing processes.* SPEAKER BLOCK 1 (10:20 AM – 10:42 AM: 4 PRESENTERS + 2 INTERACTIVE POLLS) – Todd Cline, Procter & Gamble – Dhruv Raina, Tarkett – Alper Kiziltas, Ford Motor Company – Jennifer DuBuisson, The LEGO Group SPEAKER BLOCK 2 (10:42 AM – 11:04 AM: 4 PRESENTERS + 2 INTERACTIVE POLLS) – Brent Aufdembrink, Cargill – Jeffrey Whitford, MilliporeSigma – Pankaj Gupta, Dow Chemical Company – Curtis Zimmermann, BASF BREAK OUT: WHAT ARE THE TECHNICAL BARRIERS TO OVERCOME IN DEVELOPING AND INTEGRATING IMPORTANT NEW SUSTAINABLE CHEMISTRY TECHNOLOGIES IN TO MANUFACTURING? – 11:04 AM – 11:25 AM SPEAKER BLOCK 3 (11:25 AM – 11:47 AM: 4 PRESENTERS + 2 INTERACTIVE POLLS) – Jennifer Duran, Reckitt Benckiser – Eric Raftery, Beautycounter – Rick Williamson, B. Braun Medical, Inc. – Bob Skoglund, Covestro SPEAKER BLOCK 4 (11:47 AM – 12:09 PM: 4 PRESENTERS + 1 INTERACTIVE POLLS) – Genet Garamendi, Checkerspot – Neil Burn P2 Science

	– Christoph Krumm, Sironix Renewables – Darcy Prather, Kalion BREAK OUT: WHAT ARE THE BARRIERS TO BE OVERCOME IN COMMERCIALIZATION AND DEPLOYMENT OF NEW SUSTAINABLE CHEMISTRY TECHNOLOGIES IN MANUFACTURING (E.G., SCALE-UP, ECONOMICS, SUNK ASSETS, ETC.)? – 12:09 PM – 12:30 PM
12:30 PM – 1:30 PM	**BREAK**
1:30 PM – 3:10 PM	**Facilitated Discussions** SUMMARY – 1:30 PM – 1:40 PM ASSOCIATION PERSPECTIVES – 1:40 PM – 2:10 PM GAP ANALYSIS: WHAT IS MISSING? – 2:10 PM – 2:30 PM BREAK OUT: GIVEN THE BARRIERS AND PROBLEMS THAT HAVE BEEN IDENTIFIED SO FAR, WHAT R&D IS NEEDED TO ADVANCE SUSTAINABLE CHEMISTRY IN MANUFACTURING? – 2:30 PM – 3:00 PM R&D NEEDS REPORT OUT – 3:00 PM – 3:10 PM
3:10 PM – 3:15 PM	**Next Steps and Adjourn** – Jeremy Leong, Technology Manager, Advanced Manufacturing Office

Appendix B. List of Roundtable Participants

Name	Organization	Name	Organization
Ezinne Achinivu	DOE/AMO	Jeremy Leong *	DOE/AMO
Brent Aufdembrink	Cargill	Valri Lightner	DOE/AMO
Clinton Boyd	Steelcase	Jin Liu	General Motors
Sabine Brueske *	Energetics	Felicia Lucci *	DOE/AMO
Bob Buck	Chemours	Julie Manley *	GC3
Neil Burns	P2 Science	Theresa Miller *	Energetics
Kim Carmichael	Croda	Scott Morgan *	Energetics
Chris Cassell	Lowes	Marty Muenzmaier	Cargill
Isaac Chan	DOE/AMO	Ignasi Palou-Rivera	AIChE/RAPID
Todd Cline	Procter & Gamble	Kate Peretti	DOE/AMO
Sarah Decato	DuPont	Darcy Prather	Kalion
Sharon Dubrow	American Chemical Council	Jordan Quinn	ANGUS Chemical Company
Jennifer DuBuisson	The LEGO Group	Eric Raftery	Beautycounter
Jennifer Duran	Reckitt Benckiser	Dhruv Raina	Tarkett
Scott Franklin	Checkerspot	Paul Scott	Estee Lauder
Shawn Freitas	Cleanbay Renewables	Diane Sellers *	Energetics
Linda Gallegos	Levi Strauss & Co.	Bob Skoglund	Covestro
Genét Garamendi	Checkerspot	Homer Swei	Johnson & Johnson
Pankaj Gupta	Dow Chemical Company	Emmanuel Taylor	Energetics
Michele Jalbert *	GC3	Sarah Teter	Novozymes
Mary Kirchhoff	American Chemical Society	Joel Tickner	GC3
Alper Kiziltas	Ford Motor Company	Jeffrey Whitford	MilliporeSigma
Christoph Krumm	Sironix Renewables	Rick Williamson	B. Braun Medical Inc.
Jennifer Landry *	GC3	Curtis Zimmermann	BASF
Michelle Legatt	Hasbro		

** planning team and facilitators*

Appendix C. List of Acronyms

AI	Artificial Intelligence
AIChE	American Institute of Chemical Engineers
AMO	Advanced Manufacturing Office
C1	One Carbon Molecules
CO_2	Carbon Dioxide
DOE	Department of Energy
GC3	Green Chemistry & Commerce Council
LCA	Life-cycle Analysis
PE	Polyethylene
PVC	Polyvinyl chloride
R&D	Research and Development
RAPID	Rapid Advancement in Process Intensification Deployment
TEA	Technoeconomic Analysis
VC	Venture Capital

Appendix D. Summary of Attendee Questionnaire Results

Table 2. Summary of Pre-Meeting Questionnaire Results. Parentheses indicate the number of submitters that mentioned the concept.

1. What is needed to fully implement sustainable chemistry into manufacturing chemicals, products, materials, etc.
Show clear advantages (costs, emissions, etc.) through contrasted TEA/LCA (5) • Data inputs based on primary information not secondary information
Information-sharing (3)
Scale-up showing reproducible and resilient operations (5)
Full material disclosure, transparency and traceability (3)
U.S.-based supply chain gaps (3)
Sustainable chemistry must be economically favorable (2)
Alternatives to unsustainable technologies must exist (2)
New chemical process technology (2)
Access to sustainable raw materials (2)
Trained chemists/engineers (2)
Vertical government investment in production process
Better product lifecycle management
Product stewardship
Testing and assessment standardization • Standardization for the measurement of sustainable chemistry to lead to increasing adoption of more sustainable chemicals and decrease legal concerns on external communications
Shared rewards/risks
Platforms to elevate tangible challenges allowing users to either self-identify or utilize digital solutions in a pre-competitive space.
Durability and long-term performance studies of materials, especially materials new to the market.
2. Where are the most significant impacts for incorporating sustainable chemistry practices (conserve energy, reduce waste, replace hazardous substances, other…)?
Replace hazardous substances (6)
Carbon footprint reduction (e.g., recyclability) (6)
Energy reductions (5)
Waste reduction (5)
All the above matter (4)
Viable materials for circular economy (2)
Conserve finite resources (i.e., critical materials)
Creation of value by lowering cost

Reducing import dependence
3. What sustainable chemistry practices have the greatest chance of being replicated across different product types?
Solutions that can become "platform technologies" for material types that go across many sectors. (6) • solvents, surfactants, reactants, preservatives, emulsifiers, catalysts, dissolution/depolymerization chemistries, C1 chemistry, and biocatalysis.
Recycling of wastes back into front-end (e.g. circularity of plastics). (4)
Put sustainability into consideration during the product design phase so the final product can be designed to be sustainable. (3)
Process intensification approaches that dramatically reduces energy requirements. (3) • Modularization concepts or concepts for design of resilience in process technology
Raw material alternatives, use of renewable crops and other feedstocks (3) • Incorporation of bio-based raw materials into chemical processes. • Finding a low-cost, safe replacement for PVC such as using regrind/recyclable material. • Complete removal of DEHP and/or Phthalates.
Packaging materials (2)- compostable at home packaging/carbon neutral
Alternative forms of sterilization
Green hydrogen production
Battery design for recyclability
Electrified processes for technology to reduce carbon emissions
4. What is currently working in your industry to utilize sustainable chemical processes and practices?
Technoeconomic analysis and life-cycle analysis (4)
Sustainable chemistry for packaging (3)
Better engineering controls (3)
Integration of sustainable feedstock in manufacturing (2)
Company specific screening algorithms/tools (2)
Modularization to enable cost-effective distributed processing
Adoption of sustainable processes when building new capacity
Material recycling/water recycling approaches/upcycling
Promoting closed loop technologies to reduce waste
Sustainable solution steering
5. What are the barriers and challenges to incorporating sustainable chemistry processes and practices (technical and other)?
Cost, (8) • Cost/performance tradeoffs (6) • R&D costs (2)
Scalability (5)
Commercially relevant piloting to properly assess process challenges and expected efficiencies. (3)

Workforce development/knowledge gap (3)
Relevant business cases (3)
Availability of sustainable raw materials (3).
Economic and political uncertainty
Resilience
Existing infrastructure
Limited testing and methodologies, lack of clarity on green claims
Quantifiable standards for sustainable chemistry
Inadvertent contamination
Incumbency of legacy products/processes (2)
6. What RD&D is needed to facilitate the development and adoption of sustainable chemistry processes and practices into manufacturing?
Platform chemicals and technologies (5) • Widely used chemicals such as plasticizers, water & stain repellent, flame retardants, preservatives & antimicrobial, surfactants and solvents.
Scale-up/scale-down facilities to help proof-of-concept and feasibility studies (4)
Develop new molecules that are better for the environment, are safer to manufacture, and are manufactured using processes that conserve energy and generate less waste.(4)
New sustainable technology innovations (3) (e.g. recycling technology that seeks to tackle multi-component material streams and a sustainable alternative to sterilization processes).
Supporting advanced plastics recycling (3)
Set up a standard protocol to evaluate the sustainability of products during manufacturing thus showing an easily recognized value/grade for customers to better understand the sustainability of the product. (3)
Innovation in the transition between waste to resource requires R&D collaboration (2)
Precision engineering solutions (2)
Collaborative solutions across the supply chain that remove the barriers to a circular economy (e.g., chemical composition) (2)
Quantifying energy usage during manufacturing processes (e.g., injection molding)
Quantification of sustainable attributes of chemistry and processes combined with technoeconomic analysis in FOA's
Help develop a carbon index to account for product benefits that help reduce GHG emissions
Drive an inclusive and thoughtful dialog to address carbon, climate change and plastic issues all together
Greater government support/funding for sustainable chemistry and technology
Better methods of sharing information on chemicals used to manufacture products
Harmonized tools (lower the barrier for companies) and certifications (consumers are starting to lose trust in sustainability)
Development of common language, definitions and criteria that define sustainable chemistry
Economic solution for alternative sterilization
Economic substitute for PVC tubing
Economic packaging alternatives

Better collaboration across domains (government, NGO, academic), across industries, across markets, etc. We need more platforms to elevate the concrete (tangible) challenges we are facing as an industry and allow us to either self-identify or utilize digital solutions to connect us to these challenges where we can contribute in a pre-competitive space.
Quantifying energy usage during manufacturing processes
Requesting technoeconomic analysis in FOA's
Develop a carbon index to account for product benefits that help reduce GHG emissions
Precision engineering
Improved photochemical conversion options for renewable and sustainable commodity chemicals (primarily C_1-C_4)
Interoffice collaboration with DOE Metal Hydride Center of Excellence to facilitate technology transfer specifically for sustainable metal hydride and nanocarbon approaches
Supporting advanced plastics recycling
Chemistry to support durable articles

Appendix E. Summary of Interactive Meeting Prompts

Seven real-time interactive meeting prompts where conducted during the morning lightning round industry speaker presentations, a summary of the poll results are included here.

1. Adoption of sustainable chemistry can improve waste reduction, water pollutants, air pollutants (non-carbon), carbon emissions, and energy demand.

2. Adoption of sustainable chemistry practices in manufacturing will require supply chain integration.

3. Raw materials and chemical processes were identified as areas for the greatest transformative R&D opportunity.

4. New materials development and supply chain integration were identified as an area of focus for adoption of R&D needs.

5. From the Principles of Green Chemistry, use of renewable feedstocks, designing for energy efficiency, and designing safer chemicals were principles identified for improving the sustainability of chemical manufacturing.

6. From the Principles of Green Chemistry, use of renewable feedstocks, design for degradation, and design for energy efficiency were identified as the greatest opportunity for transformative R&D.

7. From the Principles of Green Chemistry, catalysis was largely identified as the principle providing the greatest opportunity for energy efficiency through R&D.

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