The Circular Carbon Economy – From Concept to Realization

Mission Innovation Think Tank Report #2
March 2024

Contents

This report was developed by the organisers of the event: Patrick McCauley (Natural Resources Canada), Ingrida Murauskaite-Bull (Joint Research Centre, European Commission) and Brian Efird (KAPSARC).

The recording of the event is available here.

Executive Summary and Key Takeaways

The circular carbon economy (CCE) builds on the principles of the circular economy and applies them to managing carbon emissions: to reduce the carbon that must be managed in the first place, to reuse carbon as an input to create feedstocks and fuels, to recycle carbon through the natural carbon cycle with bioenergy, and, unique to the CCE, to remove excess carbon and store it. Realizing a circular carbon economy requires efforts to bring down the costs of key technologies. As Mission Innovation (MI) member governments advance collaboration to scale-up relevant technologies from carbon management to clean fuels – the CCE can provide a useful framework to guide action and investment. To bring together expert voices on this topic with the broader clean energy community – MI and the King Abdullah Petroleum Studies and Research Center (KAPSARC) convened an MI Think Tank webinar to share knowledge on the CCE.

During the event, expert speakers from KAPSARC, Mission Innovation Integrated Biorefineries Mission, Institute of Energy Economics Japan, European Commission, APChemi, and Worley Consulting shared their perspectives on the CCE - from its concept and implementation in a national policy and economic context, to the specific technologies needed for its realization. The CCE has cross-cutting relevance across MI's focus areas. MI Member Governments continue to collaborate and accelerate clean energy innovation in technologies critical to the realization of the CCE – including carbon dioxide removal, clean hydrogen, zero-emissions shipping, and bio-based fuels, chemicals, and materials. Discussion on this topic through the MI Think Tank will accelerate the development of these technologies and strengthen the policy, programming, and financial frameworks to support them.

Key Takeaways from the Think Tank Webinar

- The Circular Carbon Economy (CCE) framework builds from the core idea that a narrow focus on reduction of carbon dioxide (CO2) with a limited set of technologies and approaches, particularly to renewable energy and energy efficiency alone, will be insufficient to achieve net-zero emissions. While their deployment and scaling up remains critical, holistic solutions will also consider approaches such as switching to lower-carbon intensity fuels, nuclear energy, carbon capture and storage (CCS) based reductions, among others. In addition, the capture of CO2 for reuse and recycling in value-added applications and the removal of CO2 from the atmosphere through technological and nature-based approaches are needed to achieve global net-zero goals.

- The CCE is technology-neutral and encourages the use of all available decarbonization means to achieve net-zero emissions. This holistic approach can provide flexibility for national circumstances.

- Bio-based resources will play an important role in achieving a CCE, to enable the replacement of fossil-based fuels, chemicals, and materials with bio-based alternatives. MI's Integrated Biorefineries Mission is advancing collaboration on research and development; pilots and demonstrations; and markets, policies, and regulations to accelerate the development of these technologies and processes.

- Robust measurement, reporting, and verification systems are critical to enabling a CCE, as are clear metrics that enable comparisons across countries. Through the CCE Index, KAPSARC is strengthening the knowledge base and measurement of the CCE to provide important insights for policymakers.

- Network planning for CO2 infrastructure – to connect emitters with transportation and storage - is important to consider in the early stages of CO2 market development. Markets will develop around the actions of early adopters of carbon management technologies (e.g., capture of CO2 for storage, capture of CO2 for utilisation, and removal of CO2 from the atmosphere).

- A wide range of technologies exist to support the utilization of CO2 in line with the principles of the CCE – from advanced technologies to valorize plastic waste, to the sequestration of CO2 in building materials.

Resulting from the CCE Think Tank Webinar, this **Think Tank Report** provides a record of discussion and a lasting document to support knowledge sharing and dissemination among the MI and the broader clean energy community on this topic.

Context

On January 31, 2024, **Mission Innovation (MI)** and the **King Abdullah Petroleum Studies and Research Center (KAPSARC)** convened an MI Think Tank Webinar: *The Circular Carbon Economy – From Concept to Realization*. This event brought together experts from research organizations, governments, and industry to share their perspectives on the Circular Carbon Economy (CCE) at the theoretical, policy and economic implementation, and technology levels. As MI Member Governments and the broader clean energy community accelerate collaboration to scale up relevant technologies from carbon management to clean fuels, the CCE can provide a valuable framework to guide action and investment.

*The **MI Think Tank** was launched in July 2023 to supercharge knowledge sharing and dissemination on high-impact clean energy innovation topics among the MI Community and beyond. Through member and partner-driven workshops and events, the MI Think Tank accelerates collaboration and best practice exchange between the MI Community and partners on cross-cutting issues.*

The Circular Carbon Economy – From Concept to Realization was the second MI Think Tank event, following the MI Financing Masterclass in October 2023.

Event Overview

This MI Think Tank event brought together perspectives from international research organizations, MI member governments, and industry. Guest speakers included:

- Eleanor Webster – Head of Secretariat, Mission Innovation
- Brian Efird – Director for Strategic Partnerships, KAPSARC
- Adam Sieminski – Senior Advisor to the Board of Trustees, KAPSARC
- Kees Kwant – Mission Director, MI Integrated Biorefineries Mission
- Mari Luomi – Fellow II, Climate and Sustainability, KAPSARC
- Yoshikazu Kobayashi – Executive Analyst, Manager, Research Strategy Group, Institute of Energy Economics Japan (IEEJ)
- Johanna Fiksdahl – Policy Officer, Directorate General Energy, European Commission
- Dražen Tumara – Project Officer, Joint Research Center, European Commission
- Suhas Dixit – CEO, APChemi
- Erica Bhasin – Low Carbon Consultant, Worley Consulting

The event had three parts. First, presentations highlighted the CCE at the conceptual level. Second, presentations highlighted the implementation and measurement of the CCE at the national policy and economic levels. Finally, presentations from industry highlighted the present and future technologies needed to actualize the CCE.

Event Summary

The event kicked off with introductory remarks from Eleanor Webster, MI's Head of Secretariat, who emphasized the important role the MI Think Tank can play in strengthening cross-cutting knowledge sharing among the MI Community and beyond. Eleanor also introduced the moderator for the event – Brian Efird, Director of Strategic Partnerships at KAPSARC.

Part 1 – The Concept of the Circular Carbon Economy

Part 1 of the event featured presentations from Adam Sieminski, Senior Advisor to the Board of Trustees at KAPSARC, and Kees Kwant, Mission Director of MI's Integrated Biorefineries Mission.

In his presentation, Adam Sieminski of **KAPSARC** introduced the CCE concept. The CCE builds from the circular economy concept and responds to a core idea – that a narrow focus only on reducing fossil fuels will result in significant, undesirable socio-economic consequences for both consumers and producers. In this vein, the CCE emphasizes the need for a broad range of approaches, covering the *reduction* of carbon emissions (e.g. through energy efficiency, renewables, nuclear); capturing CO2 for *reuse* without chemical alteration; *recycling* CO2 through chemical alteration (e.g. carbon for polymers, chemicals, fuels, or other materials); and importantly, *removing* CO2 through direct air capture, mineralization, and storage, and through nature-based solutions (see Figure 1).

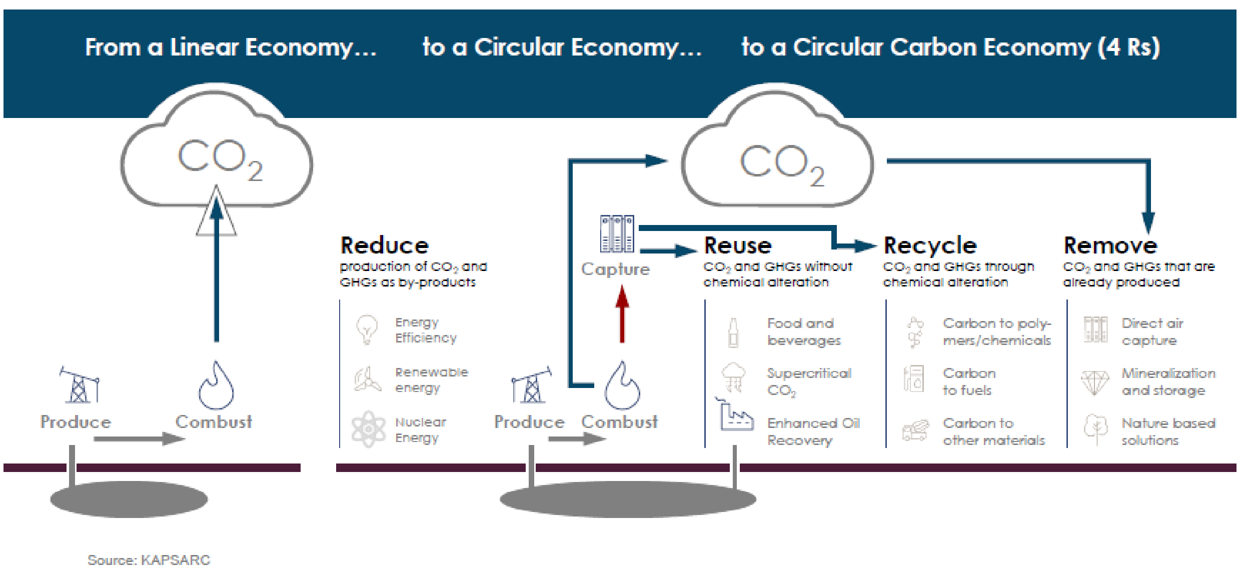

Figure 1 – The 4 Rs of the CCE (KAPSARC)

Internationally, the CCE framework received initial attention in 2019 and 2020, culminating with its endorsement by the G20 leaders in November 2020. The same year, KAPSARC's CCE Guide convened perspectives from international organizations focused on different aspects of the CCE's "4 R's".[1] This Guide included contributions from the International Energy Agency (IEA),

[1] To learn more about the CCE through KAPSARC's CCE Guide, please visit: https://www.cceguide.org/guide/

Nuclear Energy Agency (NEA), International Renewable Energy Agency (IRENA), Global CCS institute, the OECD, and King Abdullah University of Science and Technology (KAUST). Adam highlighted three key areas critical for the CCE's implementation: technology, policy, and markets. Advancing research, development, and demonstration projects will be important to scale the necessary technologies. These technologies also need an enabling environment, supported by robust measurement, reporting and verification systems. Finally, to scale up the CCE, carbon hubs are critical to create markets and bring together activities that leverage carbon as a value-added product and not as an economic burden.

Kees Kwant, the Mission Director of **MI's Integrated Biorefineries Mission** provided an overview of the work of the Mission and its links to the CCE concept. The Mission's work is focused across three pillars of activities between member governments: research and development; pilot and demonstration projects; and markets, policies, and regulations.[2] Co-led by the Netherlands and India – Brazil, Canada, the UK, and European Commission are also contributing to the work of the Mission. Kees highlighted the importance of carbon accounting and life cycle analysis in scaling up bio-based carbon neutral fuels, chemicals, and materials to replace their fossil-based equivalents. Kees also highlighted the role of integrated biorefineries in the carbon cycle. While electricity and heat are lower-value applications of bioenergy, biorefineries can convert biomass to bio-based fuels, chemicals, and materials for higher-value applications. Specific accounting measures are needed to help understand the extent of CO2 reduction and storage (e.g. through CCUS, bio-based plastics, etc.).

> *Launched in India in 2022, the **MI Integrated Biorefineries Mission** has a goal to develop and demonstrate innovative solutions to accelerate commercialization of integrated biorefineries, with a target of replacing 10% of fossil-based fuels, chemicals and materials with bio-based alternatives by 2030.*

Part 2 – Measuring and Implementing the CCE at a National Level

Part 2 of the event featured presentations from Mari Luomi, Climate and Sustainability Fellow at KAPSARC; Yoshikazu Kobayashi, Executive Analyst, Manager, Research Strategy Group at the Institute of Energy Economics Japan (IEEJ); Johanna Fiksdahl, Policy Officer, Directorate General Energy at the European Commission; and Dražen Tumara, Project Office, Joint Research Center at the European Commission.

[2] To learn more about the MI Integrated Biorefineries Mission, please visit: https://mission-innovation.net/missions/integrated-biorefineries-mission/

Mari Luomi, Climate and Sustainability Fellow at **KAPSARC**, kicked-off the second part of the event – bridging the gap between the CCE at a conceptual level, and the implementation of CCE approaches in practice. In 2021, KAPSARC launched the CCE Index.[3] The CCE Index focuses on answering three key questions: 1) how are countries engaging with climate change mitigation options and technologies in terms of depth and diversity; 2) how are countries positioned to accelerate progress toward CCE; and 3) how do different countries compare to each other on their current CCE performance and transition potential? The 2023 edition of the CCE Index is built upon a framework of 38 indicators – 8 focus on CCE performance across key technologies (e.g., renewable energy, energy efficiency, electrification, CCUS, and hydrogen) and the other 30 focus on the enabling environment for the CCE (i.e. policy, technology, finance, business environment, and system resilience). The CCE Index ranks major economies from all regions accounting for 90% of global emissions with a score between 0 and 100 on each indicator. These are aggregated to form scores on CCE Performance, CCE Enablers, and a total CCE score. In 2023, the top three countries in the total CCE Index were Norway, the UK, and the Netherlands. Although all but three of the top 20 performers are high-income countries, this is not the only determinant of success. Each region has success stories to tell from countries excelling in individual indicators or areas. While the lowest-scoring countries tend to be lower-income countries from Sub-Saharan Africa, countries from other developing regions also score low on the Index, and there is a wide gap between the top- and bottom-ranked countries. Mari emphasized that this provides a clear policy message that we

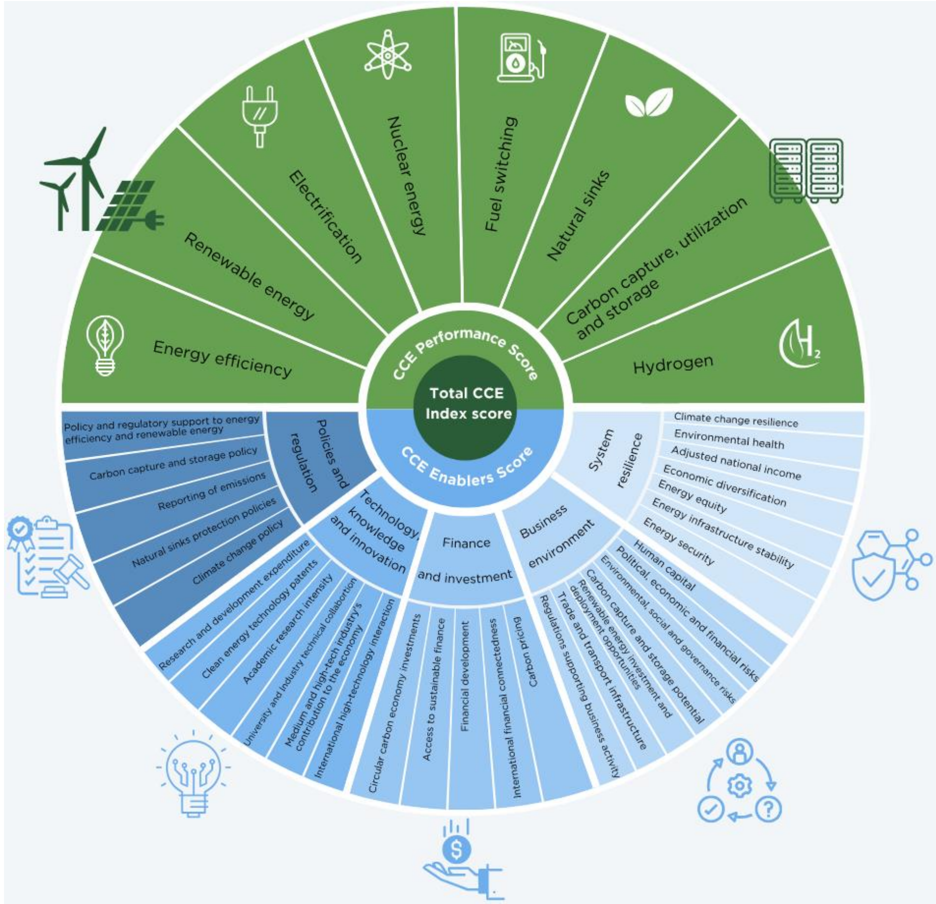

Figure 2 – The CCE Index Indicator Framework (KAPSARC)

[3] The CCE Index can be hound here: https://cceindex.kapsarc.org/cceindex/home

are leaving countries behind in the energy transition or are at least at risk in doing so. For example, Mari highlighted the significant differences between the countries with the highest and lowest levels of CCE investments (scaled to economy size). The data used in the CCE Index is made publicly available by KAPSARC, along with the methodology, additional analysis and regional case studies.

Yoshikazu Kobayashi, a representative from the **Institute of Energy Economics Japan**, provided an overview of the implementation of the CCE in the Japanese context. The CCE is important for Japan given the country's broader energy policy context. While Japan is the world's 5th largest energy market, it has only limited renewable energy resources, and nuclear has been slow to return after the 2011 earthquake and tsunami. As such, Japan's pathway to net-zero emissions has emphasized energy efficiency improvements, followed by zero emissions energy (e.g. renewables and nuclear), hydrogen and ammonia, CCS and carbon recycling, and carbon removal. The Japanese Government has traditionally emphasized the principle of "*3E + S*" – *energy* security, *environment*, and *economic* competitiveness, plus safety. The technology-neutral emphasis of the CCE is a strong fit in the Japanese context. On carbon recycling specifically, Yoshikazu highlighted a recently published government roadmap, which provides targets for key carbon recycling products, as well as policy actions to support the scale up relevant technologies, including technology development for commercialization, support for inter-industry collaboration, environmental value assessment and international deployment, and the creation of a broader ecosystem of carbon recycling technology development and deployment. Japan also has set a target to store 120 to 240 million tonnes of CO2 annually by 2050. As a first step to realize this target, the government aims to secure 6 to 12 million tonnes of CO2 storage capacity in Japan by 2030. In line with these goals, the Japanese Government will be supporting five domestic and two international CCS demonstration projects. Feasibility studies for these projects are underway. An additional demonstration project to test the shipping of CO2 is scheduled to begin in 2024. Japan is also taking action to build a legislative framework for CCS through the temporarily named CCS Business Act, which is expected to be enacted in the first half of 2024.

> *"Endowed with limited renewable resources, Japan needs to adopt all available decarbonization means to achieve carbon neutrality. [The CCE's] holistic approach based on technology neutrality perfectly matches Japan's traditional energy and climate policymaking." – Yoshikazu Kobayashi, IEEJ*

Johanna Fiksdahl, Policy Officer at the **European Commission** Directorate-General Energy, highlighted the Commission's work on the EU Industrial Carbon Management Strategy, which emphasizes capture of CO2 for storage, capture of CO2 for utilization, and removal of CO2 from the atmosphere, all of which are enabled by CO2 transport infrastructure. This strategy focuses on building a CO2 market in the EU, as well as strengthening standardization and harmonization so CO2 can flow freely across Europe. This involves connecting the dots between emitters and CO2 storage providers, as well as transportation infrastructure as a key enabler of CO2 value chains. Since this market is largely being built from scratch, there remains uncertainty on how the infrastructure and market will develop. Efforts to build the market in an efficient and cost-optimized way are needed while also prioritizing efforts to connect all of Europe to this infrastructure. Network planning at this early stage is important and the Commission has established positive dialogue with its industry stakeholders. The EU Industrial Carbon Management Strategy was released on February 6th, 2024.[4]

Dražen Tumara, a representative from the European Commission's Joint Research Center (JRC) provided an overview of the CO2 transportation network in Europe and the JRC's work to provide independent evidence-based knowledge and science to support EU policies. The JRC has provided research and analysis in support of the EU's Industrial Carbon Management Strategy, specifically on modelling Europe's CO2 transportation network – matching CO2 sources and sinks/storage in a cost-optimized way up to 2050[5]. The methodology for this CO2 transport modelling consisted of four steps: 1) identification and clustering of CO2 sources and sinks; 2) routing of potential connections between nodes; 3) assumptions about the evolution of captured CO2 emissions and storage capacities, and 4) selection of the optimal network and evolution over time. Some key challenges were faced in this modelling – namely data availability, knowledge gaps, and inconsistencies in databases of CCUS projects. Eight different scenarios were tested through the model, investigating results under different assumptions. For example, testing results with CO2 storage in only the EU versus storage in EU + Norway and

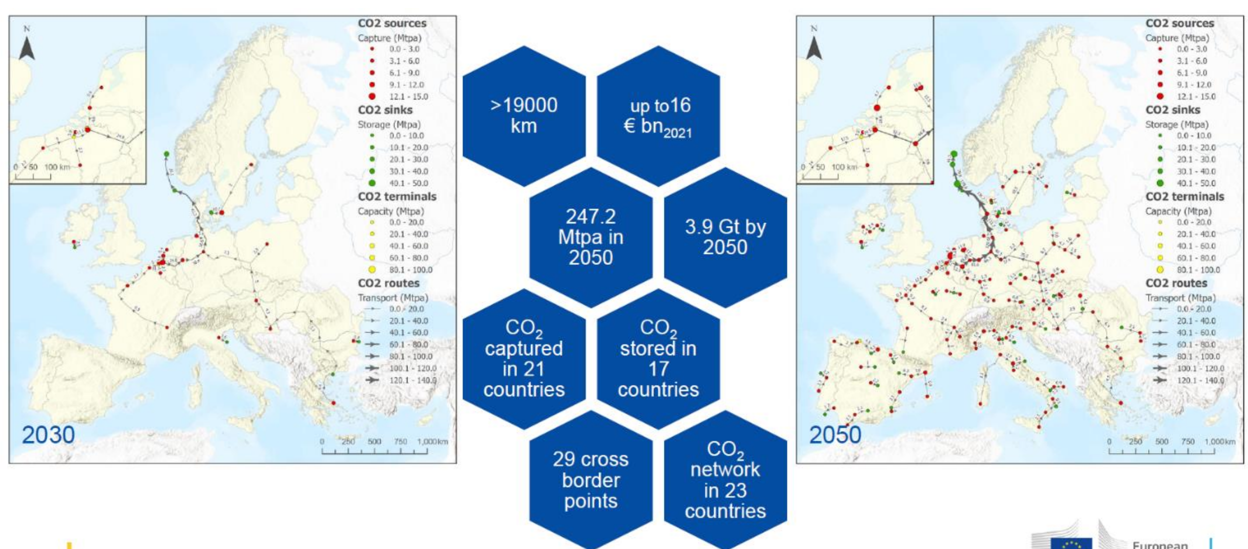

Figure 3 - Modelled CO2 Transportation Network in Europe (EU JRC)

[4] The European Union Industrial Carbon Management Strategy can be found here: https://ec.europa.eu/commission/presscorner/detail/en/qanda_24_586

[5] Tumara, D., Uihlein, A. and Hidalgo Gonzalez, I., Shaping the future CO2 transport network for Europe, Publications Office of the European Union, Luxembourg, 2024.

the UK, as well as storage onshore versus offshore, and associated impacts on the broader transportation and storage network. Overall, the analysis (see Figure 3) estimated that the CO_2 network could reach up to 19,000 km in 2050, with up to 250 megatonnes of CO_2 per year captured, transported, and stored. This network could reach up to 21 countries where CO_2 is captured, and 17 countries where CO_2 is stored. Early adopters of CCS in Europe will play a significant role in how the overall network evolves, as the initial network will evolve around them. Storage capacity in the early stages of network development is one concern, but an updated CO_2 storage atlas to provide better data as well as quality standards for CO_2 transport and storage are aimed at helping to support scale-up.

Part 3 – Present and Future Technologies to Actualize the CCE

Part 3 of the event featured presentations from Suhas Dixit, CEO of APChemi, and Erica Bhasin, Low Carbon Consultant at Worley Consulting.

Suhas Dixit, CEO of **APChemi**, kicked off the final part of the event, focused on the technologies needed to actualize the CCE. APChemi is focused on biochar-based carbon sequestration and the CCE for plastic via chemical/advanced recycling. APChemi is supported by Shell E4 and recently collaborated with Alwar University in India to convert plastic and biomass into hydrogen. Suhas highlighted the key advantage of biochar-based CCS which removes the logistics and storage challenges of CCS by putting very high-quality biochar directly into soil. APChemi has licensed its technologies to supply biomass pyrolysis plants. The company is also focused on chemical/advanced recycling. Globally, less than 10% of 350 million metric tonnes of plastic is recycled annually, with the rest ending up in landfills, rivers, oceans, or burned, creating significant CO_2 emissions. At the same time, 400 million metric tonnes of crude oil are pumped every year to make new plastics. The plastics value chains remain linear. To address these challenges, APChemi is converting plastic waste into purified oil, which can serve as a feedstock for circular plastics, as well as for hydrogen, diesel, and sustainable aviation fuel production. APChemi's approaches can reduce the carbon footprint of the chemical recycling of plastic waste.

APChemi's efforts since 2007 have supported:

- 47 projects
- Transformation of 179,000,000 kilograms of plastic waste
- 1.3 million hours of technology performance
- 3000 jobs
- 12 patents (5 granted)

Erica Bhasin, Low Carbon Consultant at **Worley Consulting** provided the event's final presentation, highlighting emerging CO_2 utilization technologies critical to a CCE. Erica presented key conversion opportunities for CO_2 and their associated technological readiness levels (TRL) and commercial readiness indices (CRI) (see Figure 4). The biggest applications, with very high TRLs include enhanced oil recovery in the oil and gas sector, and CO_2 for food and beverage applications. As an example in the food and beverage sector, the Netherlands is advancing new CO_2 applications in greenhouses – supplying CO_2 for horticulture applications and crop enrichment. Erica highlighted three emerging areas in CO2 utilization: building blocks, supercritical CO2, and CO2 in household cleaners/surfactants. CO2 conversion into building blocks (e.g. cement, concrete, carbonates) can provide a carbon sink for the construction industry where the carbon is sequestered rather than only delayed in combustion, as in many other CO2 reuse applications. Purity of the CO2 also plays an important role in its conversion to new applications. If CO2 is converted and delayed in release, biogenic CO2 is preferred. If the CO2 is being sequestered, captured CO2 can be leveraged instead. While supercritical CO2 - CO2 in its fluid state held above its critical temperature and critical pressure - faces challenges in its transportation, research is being led in Germany on potential applications of supercritical CO2 for industrial heat recovery. While CO2 applications in surfactants and household cleaners are at a lower TRL, investments are being made. Erica emphasized that there isn't a silver bullet in CO2 utilization and that a suite of applications will be necessary.

Conversion Technology	TRL	CRI	
CO_2 to hydrocarbon fuels	9	High	Fuel
CO_2 to synthetic methane fuel	6	Medium	Fuel
CO_2 to methanol fuels	7	Medium	Fuel
CO2 to green urea	9	Medium	Chemical
CO2 to methanol	9	High	Chemical
CO2 to polyolefins	9	High	Polymer
CO2 to polyols	7	Medium	Polymer
CO2 in carbon nano tubes	3	Low	Building Block
CO2 in graphene	1	Low	Building Block
CO2 to concrete blocks	9	Medium	Building Block
CO2 to cement / concrete	9	Medium	Building Block
CO2 to carbonate	4	Low	Building Block
CO_2 to surfactants	3	Low	Other
CO_2 in pharmaceuticals	9	High	Other
CO_2 in medical applications	9	High	Other

Figure 4 - Readiness of Key CO2 Conversion Technologies (Worley Consulting)

Q&A and Discussion

Following the event's presentations, Brian Efird of **KAPSARC** moderated a discussion period with the audience. First, Adam Sieminski and Kees Kwant were asked about the risk that a CCE approach may inadvertently lock in technologies (such as the combustion engine) that are less efficient and slow down the net zero transition. In response, Kees emphasized the importance of valorizing CO2 as much as possible and pursuing the highest-value applications. For example, while bio-resources may not always be the best positioned to use in contexts where renewables are well-established (e.g., for electricity and heat), other sectors that are more difficult to electrify can benefit from using CO2 through bioresources to produce the fuels, chemicals, and materials needed to replace fossil fuels. Adam emphasized that it is critical to ensure that enabling policies are in place to scale-up CCE technologies as soon as possible and observed that the framework of how these technologies are classified (e.g. as reduce, reuse, recycle, and remove) should be a secondary issue. Yoshikazu Kobayashi also noted that one strength of the CCE is that it does not reject the importance of reducing emissions. Rather, it acknowledges that reductions alone will not be sufficient – and that reuse, recycling and removal will be important in reaching carbon neutrality.

Mari Luomi of KAPSARC, who highlighted a disparity between developed and developing countries in the CCE Index during her presentation, was asked by an attendee whether an emissions-relative index would be better suited to measuring CCE progress between these countries, also noting that developing countries are most vulnerable to the impacts of climate change and may be further behind in the deployment of CCE technologies. As a part of the "system resilience" indicator of the CCE Index, Mari noted that countries' climate risk is assessed. This indicator shows that it is not only the poorest countries that are prone to climate risk, but also the poorest countries that are least capable of being resilient to these risks. Speaking to the idea of an emissions-relative index, Mari noted that there is already a wealth of publicly available emissions data that allows for such comparisons, but KAPSARC's aims in the CCE Index have been focused on drawing attention to technology pathways, along with enabling environments for CCE transitions.

Erica Bhasin of Worley Consulting responded to a final question – on how the real estate sector can advance the CCE. Erica noted that there is good potential for the reuse of CO2 in the construction sector, for example through sequestration in building materials like concrete and cement. Beyond construction, there are opportunities for energy efficiency improvements and smart buildings that can have positive impacts on the CCE. Incorporating the principles of the CCE into development plans from the beginning, particularly in greenfield developments, can have a positive impact in advancing a CCE in the buildings sector.

Mission Innovation and the Circular Carbon Economy

MI member governments are actively collaborating to advance many of the technologies that will be critical to realizing a circular carbon economy – including through seven Missions to catalyse global action behind ambitious and inspirational innovation goals that will lead to tipping points in the cost and scale of clean energy innovation.[6] In particular, efforts of the Integrated Biorefineries Mission are highly aligned with the CCE in its efforts to accelerate a circular bioeconomy through integrated biorefineries. Other Missions, including the Carbon Dioxide Removal Mission, are well-aligned with other aspects of the CCE. The CCE Framework can provide a useful framework for decision-making in advancing net-zero solutions, both collaboratively through MI initiatives, and in national contexts.

Learn More

- Mission Innovation
- Integrated Biorefineries Mission
- KAPSARC

[6] To learn more about MI's Missions, please visit: https://mission-innovation.net/missions/

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