circular carbon economy

00

CCE Guide Overview

A guide to the circular carbon economy (CCE)

KAPSARC

مركز الملك عبدالله للدراسات والبحوث البترولية

King Abdullah Petroleum Studies and Research Center

King Abdullah Petroleum Studies and Research Center

August 2020

Please see disclaimer

The views in this report are those of KAPSARC and do not necessarily reflect the official views of the G20 Members collectively or individually.

Acknowledgement

This report was prepared by Eric Williams, Senior G20 Advisor and Research Fellow (KAPSARC), with input and guidance from Adam Sieminski, President (KAPSARC) and Abdullah al Tuwaijri, Senior Advisor (KAPSARC). William McDonough (McDonough Innovation), Carlos Duarte (KAUST), Fareed Asaly (Saudi MOE), Khalid Abulief (Saudi MOE) and Jose Miguel Bermudez Menendez (IEA) provided constructive reviews. Chay Allen copy edited, and Judith Fish proofread.

CCE Guide series

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is partnering with leading international organizations – the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the Nuclear Energy Agency (NEA), the Organization for Economic Co-operation and Development (OECD), and the Global CCS Institute (GCCSI). These organizations have written reports on key elements of the circular carbon economy (CCE) as part of a CCE Guide for the 2020 G20, hosted by the Kingdom of Saudi Arabia. The circular carbon economy is an integrated and inclusive approach to transitioning toward more comprehensive, resilient, sustainable, and climate-friendly energy systems that support and enable sustainable development. We recognize that managing carbon alone is not sufficient and that addressing other greenhouse gas (GHG) emissions will be critical to achieving these goals. Nevertheless, the focus of the CCE Guide is on how to manage carbon emissions.[1] This focus on carbon is not intended to detract from the need for complementary measures that offer solutions for other GHG emissions.

This report introduces the concept of the circular carbon economy and serves as an overview of the CCE Guide (www.cceguide.org). The guide consists of eight reports at the time of its launch; additional reports may be added to it over time. The reports are:

- **Reduce: Energy efficiency (IEA)**
- **Reduce: Non-bio renewables (IRENA)**
- **Reduce: Nuclear (NEA)**
- **Reuse: Carbon utilization (IEA)**
- **Recycle: Bioenergy (IRENA)**
- **Remove: Carbon capture and storage and direct air capture (GCCSI)**
- **Cross-cutting: Hydrogen (IEA)**
- **Enabling policies (OECD)**

We recognize that the diversity of the reports' authors will be reflected in a diversity of assumptions about future pathways, views on current and future technologies, opinions about policy and recommendations for how to move forward. We consider this diversity of viewpoints to be a strength. They will provide policymakers with a comprehensive guide of options for how to transition toward a circular carbon economy that can manage carbon and other GHG emissions to achieve climate goals while continuing to develop sustainably.

---

[1] When we refer to carbon, we implicitly refer to carbon equivalent to include other GHG emissions that are compatible with circular economy principles. For example, agriculture can fit within 'recycle' in the CCE as part of the natural carbon cycle, but agricultural activities can also result in methane emissions. In this example, options for agriculture to minimize its methane emissions and/or to capture and use the methane it produces are implicitly part of the circular carbon economy, even if they are not the focus of the current CCE Guide.

Table of contents

Figures

Boxes

00

Toward a circular carbon economy

Toward a circular carbon economy

Experts largely agree that the challenge of achieving climate goals, such as those set forth in the Paris Agreement, will be nearly impossible to achieve without pursuing all options to manage GHG emissions. In the second half of the century, the primary energy mix that the world will rely on to reach a carbon balance,[2] net-zero emissions, or carbon neutrality will have included all sources of energy, including hydrocarbons.[3] The resulting carbon emissions from this energy mix must be managed. The concept of the circular carbon economy, an outgrowth of the idea of the circular economy, is a useful framework for understanding how the options for carbon management interrelate to achieve climate goals.

Linear economy

The conventional notion of a linear economy is based on a mindset of a once-through system of limitless resources and a limitless capacity to absorb waste. The reality is that resources are finite and so is the Earth's capacity to take on waste. A linear model of "take, make, waste" has resulted in a variety of environmental problems, including climate change, poor air and water quality, solid and hazardous waste, plastics contamination, and so on. A less than ideal approach to solving these problems is to keep the same linear model and simply make do with less by minimizing resource use and associated waste. This kind of approach inevitably means a declining quality of life for everyone, especially as populations continue to grow, putting even more stress on natural systems. Such an approach would be especially hard-hitting for the world's poor, who are still striving to fulfill their basic needs (United Nations 2019).

[2] There has been much debate within the UNFCCC around the terms 'net zero' and 'carbon neutrality.' In a nod to the language in the Paris Agreement – "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" – this paper uses the term 'carbon balance' to describe the same amount of carbon added to the atmosphere also being removed from the atmosphere during the course of one year. It is equivalent to the term 'net zero emissions.'

[3] A global energy mix does not mean the same mix for all. On the contrary, each country will base its energy mix on its natural and economic resources and cultural, social and development priorities.

Circular economy

At its core, the circular economy is about striving 1) to reduce resource use intelligently by providing the same goods and services with fewer resources, 2) to reuse as much as possible, and 3) to recycle the elemental materials of products that cannot be further reused. Through the circularity of reducing, reusing and recycling, economic activity and quality of life can be sustained and improved while keeping raw resource use and waste to a minimum.

Over the last past four decades, models of the circular economy have focused on material flows, material recycling, waste flows and energy efficiency, as well as new business models such as "products as service."

Figure 1 shows an example of one way that the circular economy can reduce energy. In this example, three products are produced in the linear economy. The same amount of energy is used to make each one. In a circular economy, the equivalent of those three products requires much less energy to produce. One initial product is produced just as it would be in the linear economy using the same amount of energy. Rather than producing products 2 and 3, the first product is reused, which may require some additional energy to refurbish it but much less than would be needed to make a new one. A product is then made using recycled materials harvested from the reused product, which also uses less energy than making a new product from raw resources. In reality, products may be reused more than once, enabling even more energy savings than represented in the figure. The combined energy needed to make the new, reused and recycled products shown in Figure 1 is less than what is needed to make three new products from raw resources.

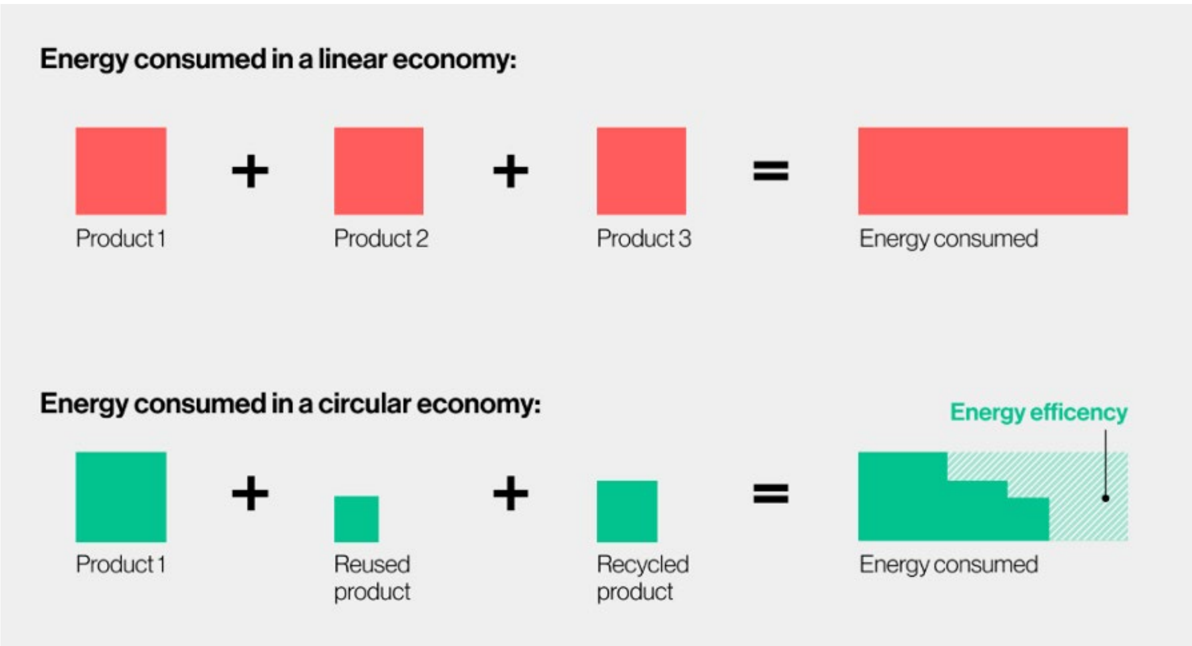

Figure 1. In a circular economy, energy efficiency is a key component

Another way to save energy through the circular economy is to design products that have much longer useful lives so that fewer products are needed over time or to develop new business strategies (e.g. the sharing economy) to need fewer products at any one time by using them more intensely. These strategies, along with the reuse strategy articulated above, works well for products that do not consume energy.

Reusing, extending or intensifying use does not always result in lower total energy consumption. As William McDonough, a circular economy visionary who co-authored the influential book *Cradle to Cradle: Remaking the Way We Make Things* has stated, “reusing a bad isn’t good” (McDonough 2020). Reusing or prolonging the use of an inefficient product that consumes much more energy than necessary is not good.

The kind of energy used also matters. Resource use can be reduced and products can be reused and materials recycled as much as possible based on circular economy principles. However, if the energy driving these processes emits carbon without being managed, then a circular economy of materials and products would do little to meet climate goals. For example, the most efficient air conditioner on the market, powered from coal-based electricity without carbon capture, is going to result in significantly higher carbon emissions than the least-efficient option powered by solar photovoltaic (PV) generation. Clearly, a special focus on energy use and carbon is worthy of special consideration.

The tension between prioritizing material and product flows versus prioritizing energy and carbon flows gets to the heart of the difference between a circular economy and the circular carbon economy. The importance of meeting climate goals and the complexity of the energy system necessitate an extension of circular economy – circular carbon economy – that prioritizes energy and carbon emissions.

01

Circular Carbon Economy

Circular carbon economy

Before describing the circular carbon economy, it is useful to first define a linear carbon economy. At its most basic, a linear carbon economy extracts hydrocarbon resources to supply useful energy for human and economic activity, and in the process emits carbon to the atmosphere.

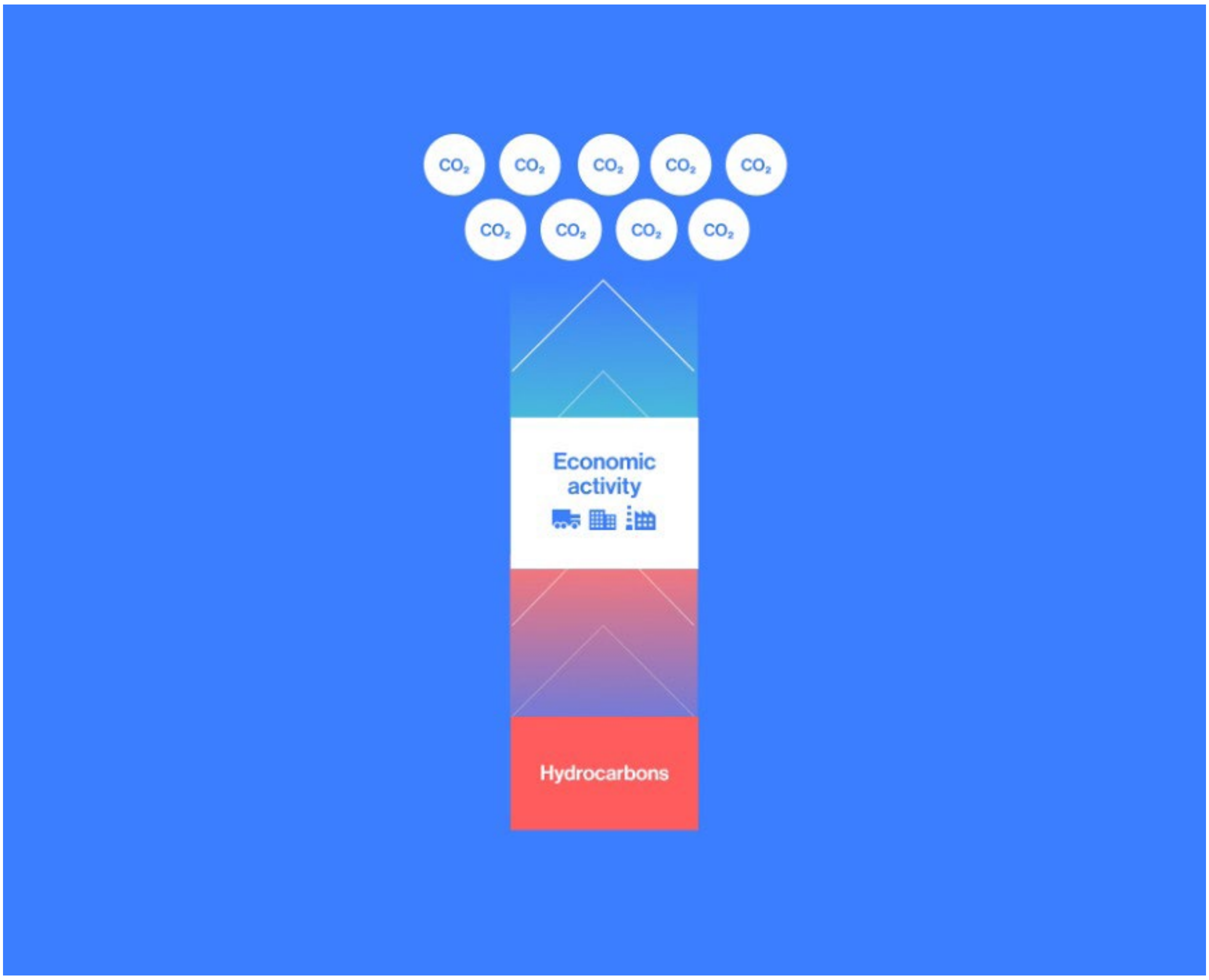

Figure 2. Linear carbon economy

The circular carbon economy is an extension of the idea of a circular economy, but its focus is on energy and carbon flows while implicitly retaining the material, energy, water and economic flows of the circular economy. The goal of the circular carbon economy is to achieve a carbon balance or net-zero emissions in the second half of this century; as such, the circularity of material flows is secondary to the circularity of carbon flows when they are in conflict.

Amory Lovins famously said that people do not want energy; they want cold drinks and hot showers (Lovins 1977). The corollary in the circular carbon economy is that people do not want bioenergy and carbon utilization or renewables and carbon storage or any other particular mitigation strategy; they want a safe climate and an improved quality of life. As such, the circular carbon economy welcomes **all** carbon mitigation options that can help achieve climate goals.

One of the circular economy's organizing principles is the 'three Rs' of reduce, reuse, and recycle. The circular carbon economy embraces these principles and adds a fourth R for 'remove.' These four Rs form the basis for carbon management in the circular carbon economy.

McDonough has offered a way to reframe how we view carbon by distinguishing between 'fugitive carbon' that is released into the atmosphere from 'living carbon' that forms the foundation of healthy ecosystems and is recycled through the natural carbon cycle, and 'durable' carbon that is embodied in stable solids and products (McDonough 2016); this Guide extends the usage of 'durable' carbon to carbon stored geologically (Figure 3). This idea goes hand-in-hand with the 4Rs of the circular carbon economy. Each of these strategies serves to minimize fugitive carbon. **Reduce** directly lowers the amount of fugitive carbon. **Reuse** and **remove** help to divert fugitive carbon into durable carbon, and **recycle** increases living carbon and perpetuates durable carbon. For further information on the *Cradle to Cradle* based circular economy, please see Appendix A.

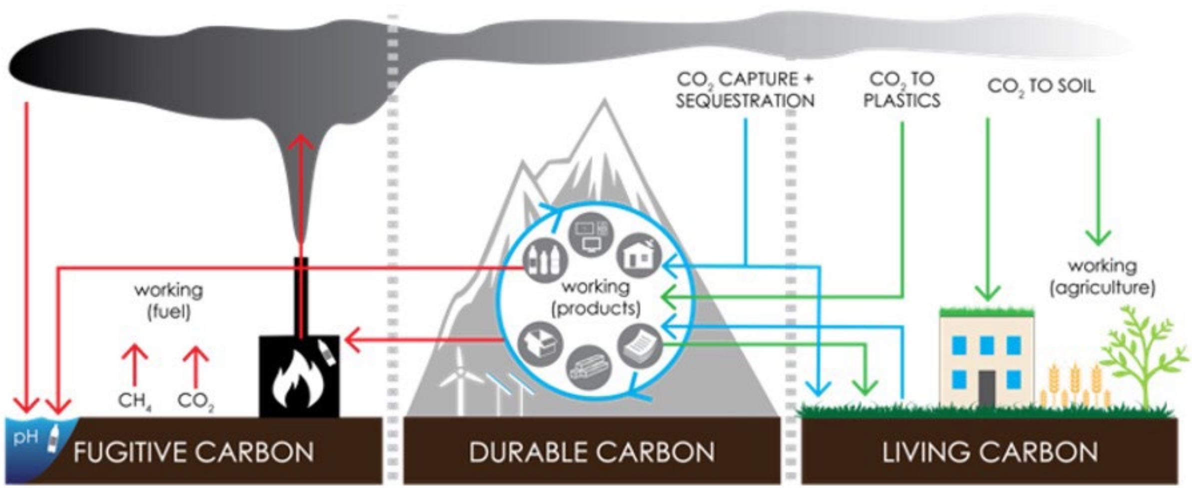

Figure 3. Fugitive, durable and living carbon

Unlike some circular economy models, the circular carbon economy does not impose a hierarchy on the order of the 4Rs. The 4Rs of the circular carbon economy guide how elements of the energy and carbon management system are interrelated so that more from one R means less is needed from another. If the world ultimately evolves in a way that meets the Paris Agreement's climate stabilization goals, all of the 4R elements will play a role. How much each of the four Rs – reduce, reuse, recycle and remove – contributes depends on many factors, such as the costs and performance of technologies, resource availability, which will be dependent on geography and geology, public acceptance, national circumstances, and enabling policies.

The reports that form the CCE Guide will provide insights into the relative opportunities of each of the elements of the circular carbon economy.

Reduce

Reduce aims to reduce the amount of fugitive carbon that must be managed to reach a carbon balance or net-zero emissions. Figure 4 illustrates how adding **reduce** strategies to a core circular economy can reduce fugitive carbon emissions to the atmosphere. One key way to do this is energy efficiency, as explained above. Reducing the consumption of energy can lead to a reduction in carbon emissions that either go into the atmosphere or must be captured and stored or reused. The two other key elements of **reduce** are nuclear and non-biomass renewables. The more that these options are used in place of hydrocarbons that emit carbon to the atmosphere, as opposed to hydrocarbons with carbon capture utilization and storage (CCUS), the more that reduce strategies will reduce the carbon that must later be managed. Another option to **reduce** carbon emissions is to switch from higher- to lower-carbon fuels. However, this option is useful only during the transition to full carbon management, as even the carbon emissions from low-carbon fuels will need to be managed to achieve climate goals.

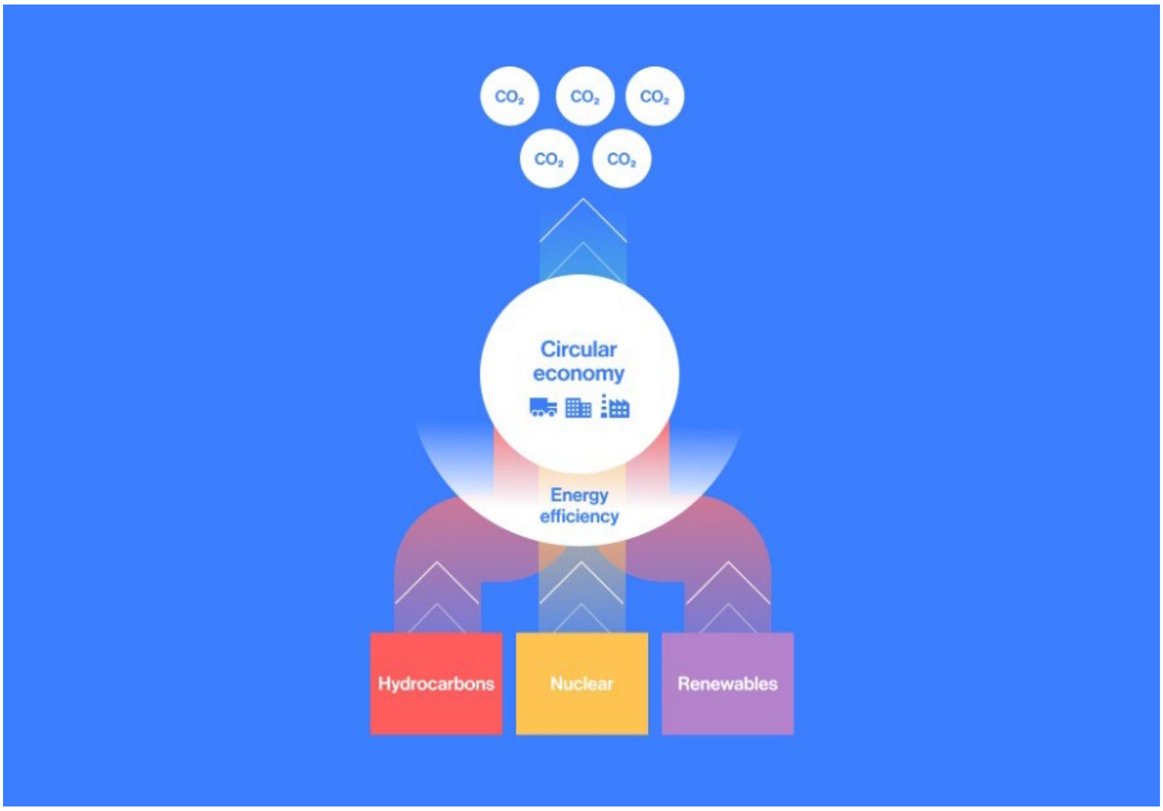

Figure 4. Adding 'reduce' to the circular carbon economy

In the "Reduce: Energy Efficiency" report of the CCE Guide, the IEA finds that "implementing the full range of currently available, economically viable efficiency solutions would result in lower emissions in 2040 compared with today, even with an expected doubling in the size of the global economy." While the potential for energy efficiency is significant – representing as much as 40% of the abatement needed to be in line with the Paris Agreement – its deployment has been slowing in recent years. Barriers to deployment of energy efficiency are not due to a lack technology innovation but to a lack of increased ambition. Governments can create a policy environment with incentives to scale up the adoption of efficient technologies.

The IEA also finds that energy efficiency offers social benefits. These include "improved public health, energy access, and job creation; economic benefits, like reduced pressure on government budgets, cost savings at the individual/household level, and improved energy security; and environmental benefits, like improved air quality and reduced pollution."

IRENA, in its "Reduce: non-bio renewables" report of the CCE Guide, concludes that renewables plus energy efficiency can provide a pathway capable of achieving over 90% of the energy-related carbon emission reductions needed to meet the Paris Agreement's climate goals. Renewable technologies are currently leading the market for new power generation capacity. Solar PV and wind are increasingly the lowest-cost electricity generating options in many markets. The variability of renewable energy generation can be addressed through utility-scale battery solutions, heat pumps and smart grids.

IRENA envisions that 80% of the investment in the energy system through 2050 will be in "renewables, energy efficiency, end-use electrification and power grids and flexibility." IRENA sees ambitious targets as key to driving markets and innovation, complemented by support measures like "pricing and competitive procurement, capital grants, tax exemptions and investment subsidies."

The NEA, in "Reduce: Nuclear," states that the IEA's modeling of a Sustainable Development Scenario finds that, by 2040, nuclear capacity increases by 35% from today's levels. This translates to a doubling of the current annual rate of capacity additions. Reaching this increased deployment of nuclear power would require the "long-term operation (LTO) of existing nuclear power plants, new nuclear builds of large Gen-III reactors and – potentially – emerging technologies such as SMRs." The NEA states that on a megawatt (MW) to MW basis, nuclear power avoids twice as much carbon dioxide (CO_2) as offshore wind and three times as much as solar PV. By 2050, the NEA states that nuclear power can avoid over 2 gigatonnes (Gt) of CO_2 per year.

Recycle

Recycle in the circular carbon economy refers to the natural carbon cycle (or 'living carbon'), in which carbon in the atmosphere is converted through photosynthesis to grow biomass, which in turn can be harvested for bioenergy. If the carbon emissions resulting from that bioenergy are released into the atmosphere, the cycle results in no net additional carbon to the atmosphere, as long as new biomass growth replaces what was harvested. Figure 5 shows how adding **recycle** as a strategy further closes the loop in the circular carbon economy. If bioenergy displaces hydrocarbons, the amount of carbon that goes into the atmosphere remains unchanged, but the amount of carbon accumulating in the atmosphere declines by the amount of hydrocarbon-based carbon that is displaced by bioenergy. The reason is that the carbon from bioenergy is recycled over and over and does not add to atmospheric stocks. If the carbon from bioenergy can be captured directly and stored, that additional amount of carbon will, in effect, be taken out of the atmosphere. As such, bioenergy with carbon capture and storage is considered a negative emissions technology. If land-use, forests, oceans, etc. are well-managed so that more biomass grows than is harvested, then these natural sinks can increase their storage of net carbon, resulting in a net reduction of the stock of carbon in the atmosphere; net carbon stored in natural sinks falls into the Remove category.

Figure 5. Adding 'recycle' to the circular carbon economy

In its "Recycle: Bioenergy" report, IRENA states that, in 2017, bioenergy represented 70% of the global renewable energy supply and 10% of the total primary energy supply (including traditional uses). Modern bioenergy has the potential to supply 23% of primary energy in 2050. Bioenergy can be used in various ways within the circular carbon economy, including as a source of energy and as a feedstock that can replace fossil fuels in end-use sectors. Bioenergy can be used to generate electricity and can contribute to balancing an electricity grid with a significant share of variable renewables.

Properly managed, bioenergy can lower the overall increase in and slow the accumulation of atmospheric CO_2 levels by replacing hydrocarbons. If bioenergy is used with carbon capture and storage (BECCS), it results in negative emissions. IRENA concludes that by avoiding hydrocarbons, bioenergy can avoid emissions of about 2.6 $GtCO_2$ per year by 2050. IRENA also points to other studies that have projected BECCS removing 3 $GtCO_2$ to 7 $GtCO_2$ per year from the atmosphere by 2050.

Remove

To reach a carbon balance or net-zero emissions, the remaining carbon from hydrocarbons that would otherwise be released into the atmosphere as fugitive carbon must be captured and **removed** or **reused** as durable carbon. **Reuse** will be discussed in the next section. Figure 6 shows how a significant portion of the carbon that would be emitted into the atmosphere is captured and stored geologically.

Figure 6. Adding 'remove' to the circular carbon economy

As mentioned above in the **recycle** section, properly managing natural sinks can also **remove** carbon. These nature-based solutions retain carbon in a shorter timeframe than geologic storage, and, as recent fires in Australia and Brazil painfully demonstrate, the carbon stored can be quickly released back into the atmosphere. While nature-based solutions are important complementary options, they are not long-term substitutes for other ways of **removing** carbon.

Carbon can be captured when using hydrocarbons to generate electricity, or in industrial applications that result in a relatively high concentration of carbon emissions, such as cement production. Direct air capture (DAC) is another approach, also represented in Figure 6, that sucks carbon out of the air to store geologically. Enhanced oil recovery (EOR) is often considered as carbon utilization, and in a literal sense it clearly does reuse carbon. Nevertheless, the aspect of EOR that reuses carbon does not in and of itself contribute to carbon management. In the process of EOR, each time carbon is injected in an oil reservoir, a percentage of carbon remains, just as it does when it is injected for carbon storage. Thus, the role of EOR in the circular carbon economy more naturally fits as a **remove** strategy than a **reuse** strategy.

Without the option to **remove** (or **reuse**) carbon, the world would need to rely entirely on **reduce** and **recycle**. While relying entirely on **reduce** and **recycle** is technically feasible with wide-scale energy storage deployment, an energy system without hydrocarbons would be far costlier than one with them (Shaner et al. 2018). **Remove** serves as a way to ensure that we can achieve a carbon balance or net-zero emissions regardless of how much **reduce** and **recycle** are deployed. It also enables the use of hydrocarbon resources, which are low-cost, energy-dense, and reliable and have been a driving force behind economic growth and improvements in quality of life since the industrial revolution.

In "Remove: CCS and DAC," the GCCSI reports that 20 large-scale CCS facilities are currently operating, three are under construction, and 36 are in development. Each of the facilities will store between hundreds of thousands and millions of tonnes of CO_2 per year. The GCCSI estimates that, to date, 260 megatonnes of CO_2 ($MtCO_2$) have been stored permanently in geological formations.

The GCCSI points to continued improvements in CCS technology. These are exemplified by a halving in capture costs for power stations over the past decade, with the next generation of technologies promising even lower costs. According to the GCCSI, "the lowest-cost opportunities for CCS can deliver multi-million tonne CO_2 abatement at a single facility, at a cost of less than US$ 20 per tonne." The GCCSI points to the Intergovernmental Panel on Climate Change (IPCC) estimates of a cumulative geologic storage potential of over 1,200 $GtCO_2$ this century. Even though the global coal fleet is expected to decline by 2050, the long lifetimes of coal plants and their recent construction suggest that coal plants alone may continue to produce 7 $GtCO_2$ in 2050. All the emissions they produce must be captured and stored to meet climate targets. Other opportunities in industry for direct capture, plus the significant potential of capture and storage with blue hydrogen production, will mean even more storage of CO_2 by 2050.

Reuse

Once carbon is captured, it can be either removed to geologic storage or reused through carbon utilization technology. Figure 7 shows the addition of reuse, completing the circular carbon economy.

Figure 7. Adding '**reuse**' to the circular carbon economy

Virtually all projections for future energy and carbon pathways find that the volume of carbon storage will exceed the volume of carbon utilization, barring an unforeseen breakthrough in utilization technology. A recent study found that the technical potential in 2050 for carbon utilization (including land management and forestry options), at an equivalent of US$ 100 per tonne of CO2 (tCO_2), is about 1.5 $GtCO_2$ per year in a 'low' scenario and about 13 $GtCO_2$ per year in a 'high' scenario. However, there are significant barriers to achieving that potential (Hepburn et al. 2019). These estimates are for tonnes **utilized**. Utilization is not the same as removal. In some utilization pathways, only a fraction of CO_2 that is utilized ends up being converted to durable carbon. Many carbon-to-fuel pathways – unless the carbon is captured from bioenergy or DAC – do not decrease fugitive emissions.

Depending on the particular utilization pathway, a tonne utilized could also be released into the atmosphere in days or months – soon to be fugitive carbon – or in decades or centuries – effectively durable carbon. Utilization pathways that delay fugitive carbon by days or months offer little carbon management from a climate perspective. Full-lifecycle GHG accounting assessments can help guide investors and policymakers toward utilization pathways that can best contribute to creating durable carbon.

Ramping up carbon utilization will, generally speaking, reduce the amount of carbon stored rather than increase the amount of carbon captured, given the high cost of capture, at least once all the 'low-hanging fruit' of inexpensive carbon capture options have been exploited. **Reuse** and **remove**, therefore, are mostly substitutes in the long-term. While **reuse** may not scale up like the other Rs of the circular carbon economy, **reuse** will, nevertheless, be important within certain companies, industries and regions. For example, the Saudi Arabian Basic Industries Corporation (SABIC) utilizes its own CO_2 waste in the world's largest carbon capture and utilization plant. The plant has the capacity to convert 0.5 million tonnes of CO_2 annually into valuable products, such as fertilizers and methanol (Smeets 2019). If carbon-to-fuel technology comes to fruition at low cost, which would depend on sustained research and development support, then **reuse** may scale up beyond current projections and play a more significant role in the circular carbon economy.

In its "Reuse: carbon utilization" report, the IEA states that new technologies that convert CO_2 into fuels, chemicals and building materials are needed to expand CO_2 use from the current 230 million tonnes of CO_2 used per year. The IEA finds that producing synthetic hydrocarbon fuels and chemical intermediates is energy-intensive and costly – current synthetic fuel costs are between US$ 200 per barrel (b) and US$ 650/b. It concludes that using CO_2 in building materials is less energy intensive and can provide a form of CO_2 storage. Some technologies enjoy a cost and product performance advantage over conventional production.

The IEA confirms that verifying emission reductions will be central to establishing the carbon management potential of CO_2 use. Determining the net-emissions outcome of CO_2 use is complex and depends on "the source of CO_2, the amount and type of energy used, whether the CO_2 is re-emitted and if the product is displacing an alternative with a larger carbon footprint (e.g., conventional fossil fuels)." Robust accounting and measurement are critical.

Beyond the complexity of measuring the net-carbon reduction of CO_2 use, the IEA points to the "size of future markets for CO_2-based products and the development of supply chains as essential in defining the potential for carbon management." The availability of hydrogen and CO_2 – both are needed for many CO_2 uses – are constrained in the near-term. High-cost CO_2-based producers will face challenges entering the market without policy support.

Cross-cutting: hydrogen

Hydrogen can play a unique role within the circular carbon economy because it can cut across all four Rs. Green hydrogen produced by non-biomass renewables does not directly emit carbon, thereby reducing the carbon needed to be managed to the extent that it displaces hydrocarbons. When blue hydrogen is produced from hydrocarbons, the carbon is captured and removed through geologic storage or reused through carbon utilization. Green hydrogen produced from bioenergy recycles carbon through the natural carbon cycle, but if the carbon is also captured, it can be reused or removed into storage.

In its report "Cross-cutting: hydrogen," the IEA remarks that currently 75 Mt of pure hydrogen is produced globally, with another 45 Mt of hydrogen mixed with other gases. However, this production releases more than 800 $MtCO_2$ to the atmosphere. For fossil-derived hydrogen to be a key part of the circular carbon economy, this carbon must be captured and stored. Another low-carbon hydrogen route is hydrogen produced via electrolysis powered by renewables (green hydrogen). The IEA finds that even fossil-derived hydrogen that captures and stores carbon (blue hydrogen) is currently about one-third the cost of hydrogen produced from renewables (green hydrogen). However, renewable-derived hydrogen costs are expected to fall sharply in the long term driven by declining costs for renewables as well as lower electrolysis costs by scaling up manufacturing capacities. Even so, fossil-based hydrogen coupled with CCUS is expected to remain cost-competitive. One of the advantages of hydrogen is its versatility. It can be used to produce a variety of synthetic fuels, many of which are compatible with existing energy infrastructure and can be used to decarbonize hard-to-abate sectors. The IEA projects that long-term costs for synthetic liquid fuels are in the range of US$ 110 – US$ 440/b, synthetic methane between US$ 20 – US$ 65 per million British thermal units (MMBtu), and synthetic ammonia between US$ 250 and US$ 1000/tonne, depending on the regional costs for electrolytic hydrogen and CO_2 feedstock costs. By comparison, the cost of producing ammonia via steam methane reformation (SMR) of natural gas with CCS is roughly US$ 215 to US$ 430 per tonne.

The IEA finds that renewable-derived hydrogen is a zero-carbon fuel; fossil-derived hydrogen coupled with CCUS, if 90% of the carbon is captured, emits between <1–2 kilograms of carbon dioxide equivalent per kilogram ($kgCO_2eq/kg$) of hydrogen. Without carbon capture, natural gas-derived hydrogen emits around 9 $kgCO_2eq/kg$ hydrogen, and coal-derived hydrogen emits over 20 $kgCO_2eq/kg$ hydrogen. Hydrogen and hydrogen-derived fuels have many end-use applications, including transportation (especially heavy-duty vehicles and freight, maritime shipping, and aviation), hard-to-abate industrial applications, heat or power generation (including as temporary energy storage and load balancing). It therefore has significant potential for managing carbon emissions and substantially reducing emissions. The IEA concludes that hydrogen used in place of natural gas in electricity peaking plants alone could reduce global emissions by 220$MtCO_2$ per year.

The IEA finds, however, that there are significant barriers to low-carbon hydrogen production beyond its high costs. For hydrogen to be used beyond refining and the chemical industry and the existing compatible infrastructure, significant investment in hydrogen-specific transport and usage infrastructure is necessary and can serve as a constraint to deployment. Industrial ports, accounting today for a significant portion of hydrogen demand, can serve as hubs to maximize the use of new hydrogen infrastructure by bringing together opportunities for low-carbon hydrogen production (such as offshore CO_2 storage or offshore renewables) and demand for hydrogen in industry and refining, while also expanding hydrogen to new uses, such as truck fleets serving the port

Box 1: 4R Taxonomies

The 4Rs offer a useful high-level framework for understanding how to manage carbon emissions. When we begin to categorize the measures and technologies within these Rs, especially those in **reuse**, **recycle** and **remove**, the complexities of the real world begin to test the limits of this simple framing. Many technologies span more than one R. Hydrogen, for example, can span all four of the Rs. The natural bioenergy carbon cycle, which we refer to as **recycle**, can also be part of **remove** if biomass stocks are managed for net growth. Imagine an algal-based synthetic fuel in an application that also captures and then stores the carbon when that synthetic fuel is combusted. Is it **recycle** because it is bioenergy? Is it **reuse** because the algae grows by injecting captured carbon? Is it **remove** because its direct carbon emissions are captured and stored? What is important is that such a technology shifts fugitive emissions to living and durable carbon in a way that helps mitigate climate change.

Observers have legitimate reasons for putting a particular technology in one R, and others have legitimate reasons for putting the same technology in another R. For example, some circular carbon economy taxonomies make a distinction between carbon that is left unaltered and carbon that is chemically transformed. Unaltered carbon is considered **reuse** in these taxonomies, and chemically altered carbon is considered **recycle**. In our view, distinguishing between altered and unaltered carbon is unnecessary. All uses of carbon, both chemically altered and unaltered, represent strategies for transforming fugitive carbon into durable carbon, and thus playing the same role in the circular carbon economy. Analysts have also historically used the term carbon utilization to include all uses of carbon, whether or not the carbon is chemically altered. For these reasons, this CCE Guide adopts the approach of using only one R – **reuse** – to represent all uses of carbon.

For better or worse, the CCE Guide developed a 4R taxonomy to begin to document the many opportunities for managing carbon emissions. We see this CCE Guide as the launching pad for research, analysis and policy development to enable the shift toward a circular carbon economy. The CCE concept and taxonomy will continually be revised, improved and expanded upon.

02

Analysis

Analysis

The circular carbon economy is a useful construct for understanding how the various carbon management options fit together to achieve a carbon balance or net-zero emissions. It reveals how applying more or less of one option requires more or less of another in order to ultimately reach climate goals.

Figures 8a and 8b, below, show a more detailed depiction of how a global circular carbon economy in 2050 can be represented as a system of energy and carbon flows, with the line sizes representing the magnitude of these flows. The figures are abstracted at a high level as a way to represent the fundamental nature of the system in a simplified view, rather than trying to represent all the possible complex connections that exist in reality. Energy flows from primary energy sources into electricity production and final energy demand sectors; energy efficiency is also depicted as 'supplying' energy to final demand. Carbon flows out of secondary energy (electricity) and end uses. Carbon flows from capture to storage and utilization are also represented, as are the carbon flows in the natural cycle through photosynthesis to natural sinks to bioenergy. Direct air capture and net additions to natural sinks are also depicted. Finally, the net $GtCO_2$ emitted into the atmosphere in 2050 is shown at the top left.

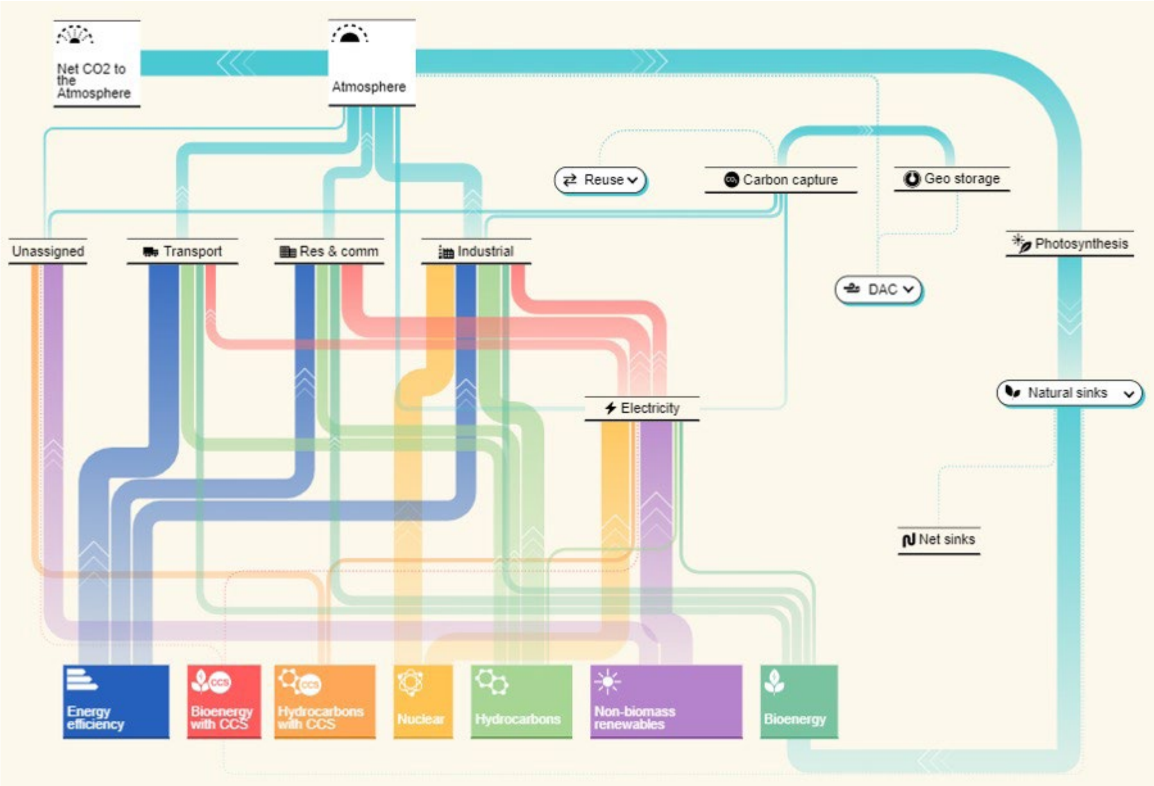

Figure 8a. Circular carbon economy: based on Faster Transitions scenario, 2050

Note: Gt = gigatonnes; CO_2 = carbon dioxide; CCS = carbon capture and storage; DAC = direct air capture; Res & comm = Residential and Commercial

Source: Huppmann et al. 2018) with KAPSARC calculations of carbon flows

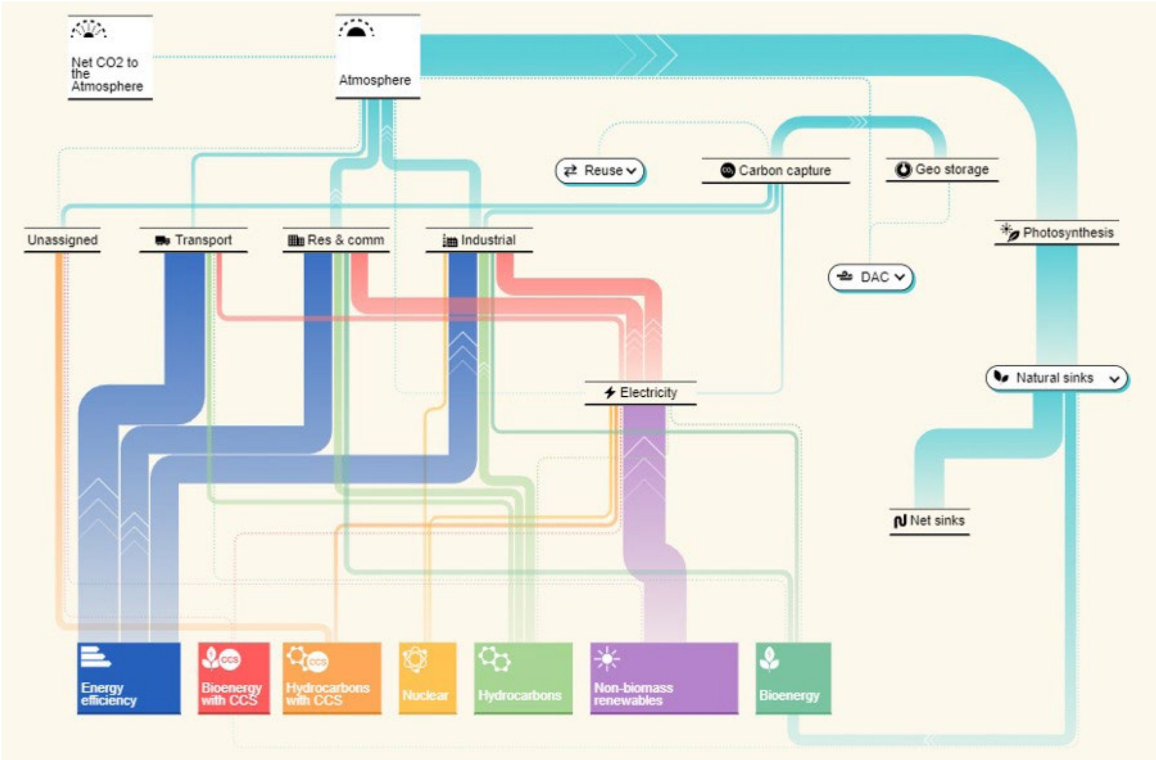

Figure 8b. Circular carbon economy: based on a 1.5 degree C scenario from TERI, 2050

Note: Gt = gigatonnes; CO_2 = carbon dioxide; CCS = carbon capture and storage; DAC = direct air capture; Res & comm = Residential and Commercial

Source: (Huppmann et al. 2018) with KAPSARC calculations of carbon flows

Both scenarios depicted in Figures 8a and 8b are expected to result in less than a 2-degrees Celsius (°C) global average temperature increase above pre-industrial levels by 2100. Visualizing energy and climate pathways through the lens of the circular carbon economy reveals how interconnected the 4Rs are. The Faster Transition scenario shows a pathway that is fairly balanced between the Rs.[4] The TERI scenario, by comparison, shows a significantly higher level of carbon capture and storage from both hydrocarbons and bioenergy, and a lower level of energy efficiency and non-biomass renewables than the Faster Transitions scenario.

Many other pathways are possible and can be explored at www.cceguide.org. How much each of the four Rs – reduce, reuse, recycle and remove – contributes depends on many factors, such as the costs and performance of technologies, resource availability based on geography and geology, public acceptance, and enabling policies.

[4] Neither scenario includes carbon utilization. The IEA estimates the potential of carbon utilization to be 0.2 $GtCO_2$ per year in the chemical sector. Shell estimates that 5.7 $GtCO_2$ per year could plausibly be embedded in materials through carbon utilization (Shell 2016). If these estimates turn out to be accurate, carbon utilization could play a significant role in reaching a carbon balance.

Figure 9 shows the 2050 primary energy mix in exajoules (EJ) for scenarios that result, by 2100, in a 1.5°C to 2°C increase in the average global temperature above pre-industrial levels. The scenario data are taken from the Integrated Assessment Modeling Consortium's (IAMC's) scenario explorer (Huppmann et al. 2018), a database of scenarios that underpins the IPCC's "Special Report on Global Warming of 1.5°C" (SR15) (Rogelj et al. 2018).

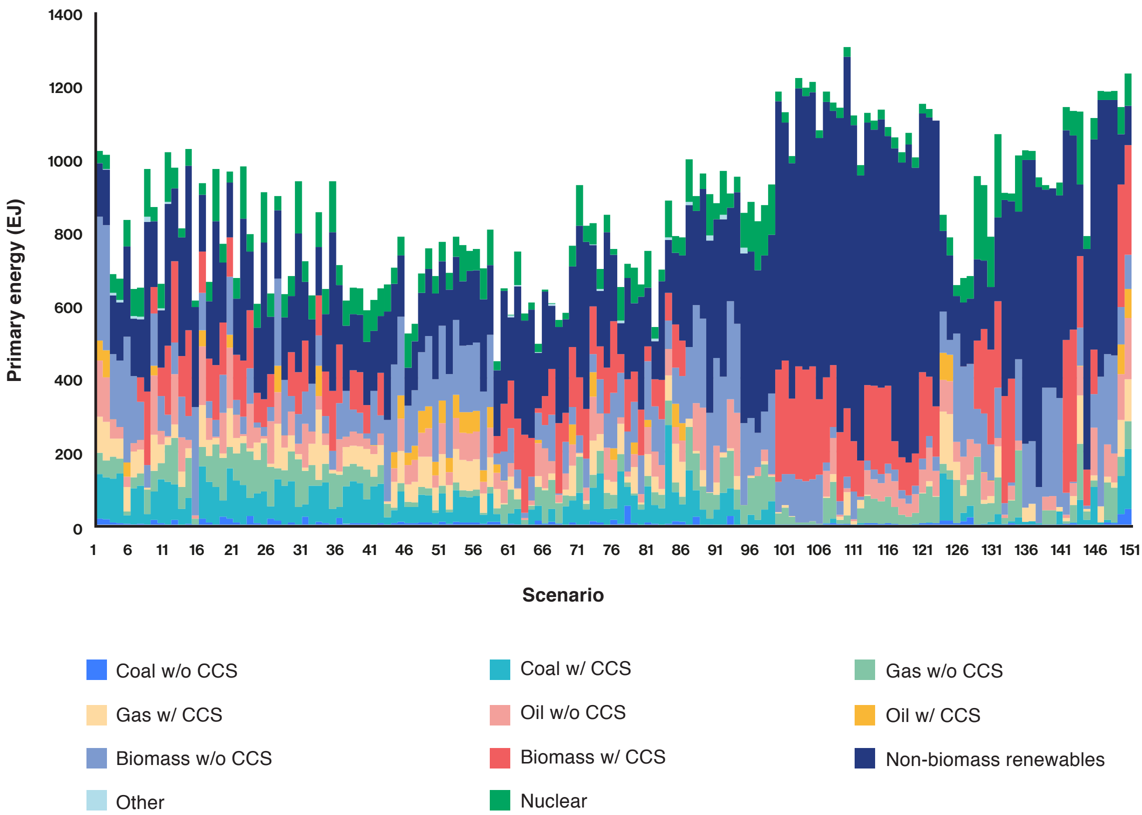

Figure 9. Primary energy mix in 2050 for scenarios in IAMC 1.5°C scenario explorer, resulting, by 2100, in a 1.5°C to 2°C increase in the average global temperature above pre-industrial levels

Figure 9 is difficult to interpret because of the number of scenarios and energy sources displayed (we show it to illustrate the range of scenarios we evaluated). We address the number of scenarios by performing a cluster analysis in Matlab that groups or clusters similar scenarios together into scenario types. The results of the clustering are five main scenario types (cluster 1: scenarios 1 – 84; cluster 2: scenarios 85 – 97; cluster 3: scenarios 98 – 104; cluster 4: scenarios 105 – 121; and cluster 5: scenarios 122 – 151). The values of the scenarios belonging to a given cluster are averaged and displayed in Figure 10. Also for Figure 10, we combined some of the primary energy sources. For example, we combined coal, gas and oil without CCS into hydrocarbons without CCS. In order to highlight the role of CCS, we show CCS of all types as one category by adding all hydrocarbons with CCS to bioenergy with CCS. Most of the scenarios fall into a cluster that is well-balanced between all primary energy options, including energy efficiency and demand reduction (scenarios 1 – 84 in Figures 9 and 10).

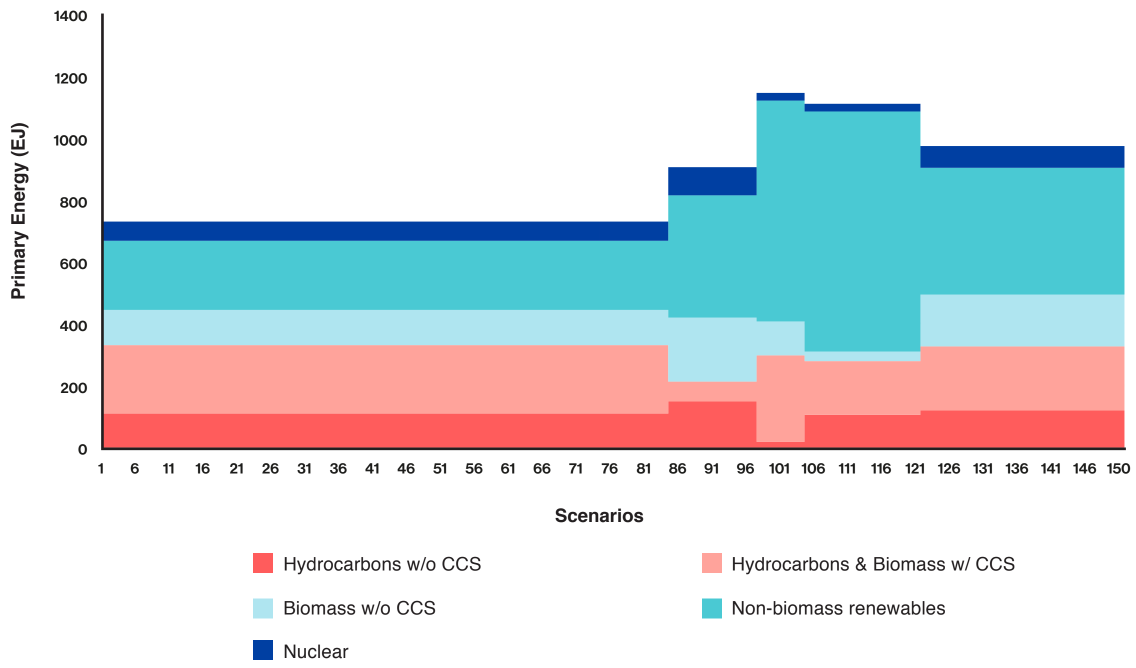

Figure 10. Average primary energy mix values in 2050 of six clusters of scenarios in IAMC 1.5°C scenario explorer, resulting, by 2100, in a 1.5°C to 2°C increase in the average global temperature above pre-industrial levels

What becomes apparent when examining the scenarios and the cluster analysis is that, while proportions vary, a pathway to the Paris Agreement's climate goals includes all options: non-biomass renewables, energy efficiency and demand reduction, nuclear energy, bioenergy, and CCUS. More of one may lead to less of another, but no single option dominates, and all options are needed. Without all options, the pathway becomes extremely difficult and may not even be possible.

Renewables, both biomass and non-biomass, play a significant role in any pathway toward a carbon balance and climate stabilization. The average share of primary energy for all types of renewables is 64%, but the share ranges from 34% to 98% across pathways. Ninety-three percent of the scenarios have total renewable shares greater than 44%, leaving no doubt about the critical importance of renewables in helping to achieve a carbon balance or net-zero emissions.

Although energy efficiency is not explicitly represented in Figures 9 and 10, which show primary energy, the difference between a reference case projection of primary energy consumption and the actual consumption in each of the scenarios implies the extent to which energy efficiency and demand reduction measures are deployed in each scenario. Unfortunately, many of the scenarios assume different reference case energy consumption in 2050, and those values are not reported in the IAMC Scenario Explorer. As a rough approximation, depending on how we calculate it, we can estimate that energy efficiency and demand reduction across the scenarios avoid an average of 21% or 35% of future energy demand in 2050.[5] However it is measured, energy efficiency clearly represents a key element of the circular carbon economy and in achieving the Paris Agreement's climate goals.

---

[5] If we assume the highest primary energy consumption in the scenarios evaluated as the benchmark to measure energy efficiency, then energy efficiency reduces energy demand by 35% on average across all the scenarios evaluated in this hypothetical reference case. Alternatively, if we assume that the IEA's Current Policies scenario represents the benchmark by which to measure energy efficiency and demand reduction, then energy efficiency reduces energy demand by 21% on average across all the scenarios in this alternative hypothetical reference case. The IEA's Current Policies scenario's energy consumption was first estimated by taking a trend line forward from 2040, the latest year that the IEA projects in its World Energy Outlook, to 2050. This projected value is less than the total primary energy consumption in many of the scenarios evaluated. We ignored any scenario with a primary energy consumption greater than this value in making the 21% calculation.

Nuclear power represents an average share of 7% of primary energy consumption in the evaluated scenarios in 2050, with as much as a 24% share in some scenarios. Nuclear power, along with solar and wind power, enjoys one of the lowest life-cycle GHG emissions of all electricity-generating technologies. Advanced nuclear energy technologies, which are not typically included in the models that generated these scenarios, offer the potential for nuclear to play an expanded role in load following and balancing variable generation in power systems, and even in hydrogen production through electrolysis. While nuclear has a smaller role than renewables and energy efficiency in the circular carbon economy, it nevertheless has a key role within the circular carbon economies of certain countries.

The advantages of renewables, energy efficiency, and nuclear in achieving climate goals are clear. However, the value of hydrocarbons in achieving climate goals may be less obvious. The scenarios evaluated also show that hydrocarbons play a significant role in a pathway to a carbon balance or net-zero emissions. Four out of the five clusters, representing 95% of all scenarios, show substantial hydrocarbons in the energy mix. Drilling down into the disaggregated data shows, for example, that oil contributes between 50 EJ and 72 EJ of primary energy in 2050 for those four scenario clusters.

The key for hydrocarbons to be able to play this role in the pathway to carbon balance or net-zero emissions is carbon capture utilization and storage. Every scenario in the IAMC scenario explorer that results in a 1.5°C to 2°C increase in the average global temperature above pre-industrial levels in 2100 has at least some deployment of CCS technology by 2050. The average share of primary energy with CCS – combining hydrocarbon and biomass CCS – across the scenarios is 24%. Eighty percent of the scenarios analyzed result in at least 10% of primary energy with CCS. Figure 11 shows the distribution of the share of CCS across the scenarios and reveals how CCS is a critical element of reaching climate goals, even though the final level of CCS may vary by scenario. One of the limitations of global energy and economic models is that they typically do not include carbon utilization as an option, and the IAMC data explorer does not report carbon utilization results, if any. Therefore, we were unable to analyze carbon utilization in the same way as CCS. Nevertheless, the more cost-competitive carbon utilization becomes, the more it will be deployed and the bigger role it will play in the circular carbon economy.

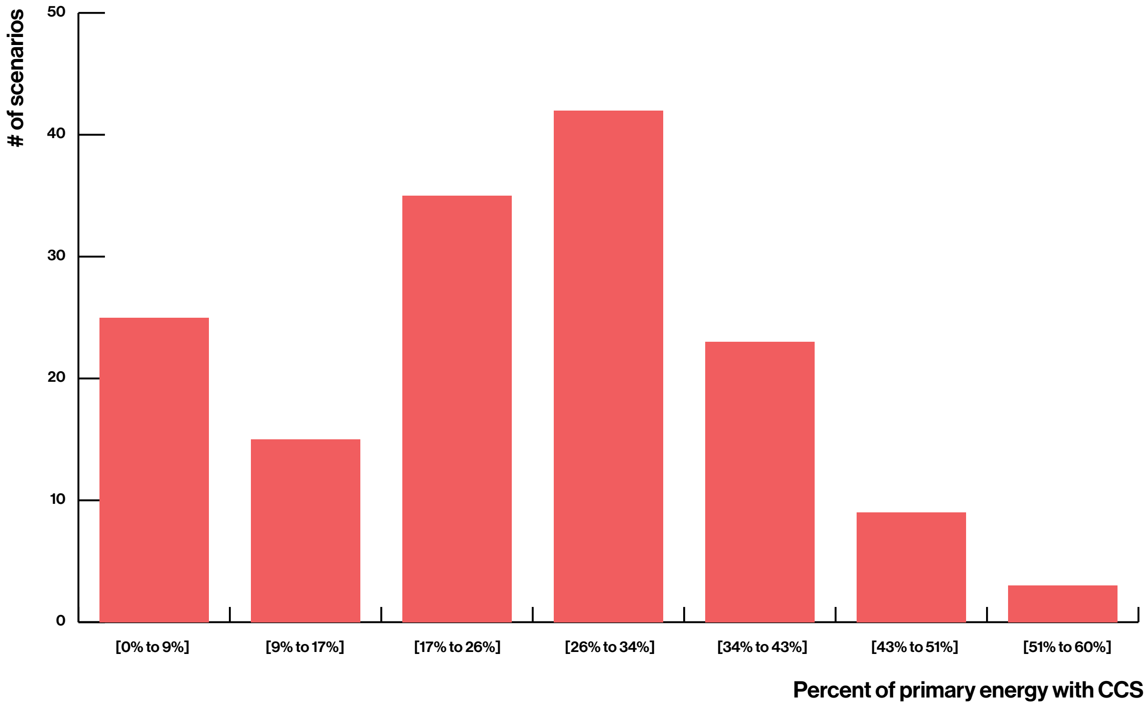

Figure 11. Distribution of the share of CCS across scenarios in the IAMC 1.5°C scenario explorer, resulting in a 1.5°C to 2°C increase in the average global temperature above pre-industrial levels in 2100

The clear relationship between total hydrocarbons in the primary energy mix and hydrocarbons with CCS shows that the more hydrocarbons in the global energy mix by 2050, the more CCS must be deployed to reach climate goals (see Figure 12). Based on what we understand today, these scenarios suggest that climate stabilization without CCS is very unlikely. Yet, CCS technology is not being deployed at a scale needed to achieve climate goals, nor are policies currently in place to encourage the deployment of CCUS needed.

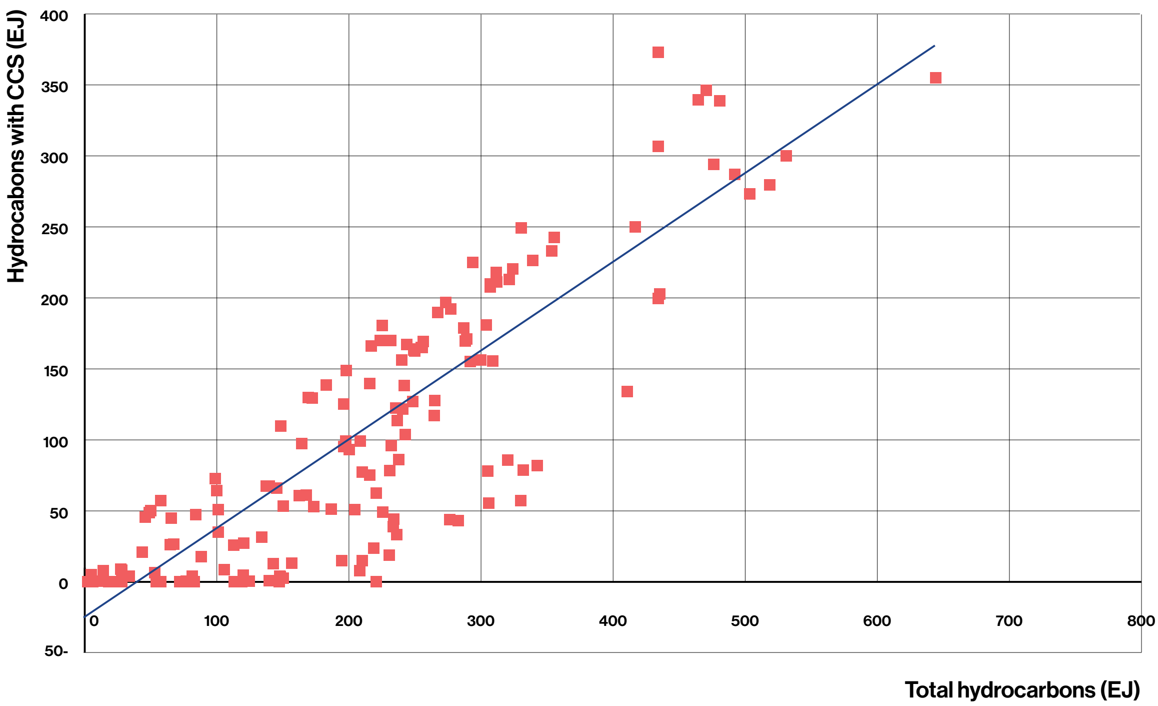

Figure 12. Relationship between total hydrocarbons and hydrocarbons with CCS in 2050 for the scenarios in the IAMC 1.5°C scenario explorer, resulting in a 1.5°C to 2°C increase in the average global temperature above pre-industrial levels in 2100

Source: Integrated Assessment Modeling Consortium (IAMC)

Carbon-based fuels are very likely to play a significant role in the future global energy mix. Even with a widespread, dedicated effort to reduce carbon by deploying energy efficiency measures, non-biomass renewables, nuclear power, and bioenergy, we must also make a significant effort to develop the technologies and to build the infrastructure to capture and use or store carbon.

03

Enabling policies

Enabling policies

While the circular carbon economy provides a useful framework for envisioning a carbon balance or net-zero emissions, this is unlikely to be achieved spontaneously. Without enabling policies, there will be insufficient incentives to develop and deploy the technology and infrastructure needed for circular carbon economy and climate goals. The process of closing the loop in the circular carbon economy will be ongoing and evolving over the coming decades. Ultimately, economics and social appropriateness will determine how large a role in the circular carbon economy each element will play. Policies that move investment toward closing the loop on resource use by providing incentives for technologies in all four Rs – reduce, reuse, recycle and remove – promise the greatest likelihood of success. These policies include public-private research and development funding consortiums spanning countries and companies, financial subsidies to offset the risks of unproven technologies, tax incentives, direct capital investment subsidies, results-based financing (e.g., money for each unit of energy produced), among others (Grubb 2004, World Bank Group and Frankfurt School of Finance and Management 2017). As much as new technologies need support, once those technologies reach maturity, technology-focused incentives should be removed so as not to distort the economic decision of choosing which mature technologies to deploy.

Geographic diversity and comparative advantage mean that companies and countries will gain from cooperating in the effort to close the loop. The diversity of endowments and circumstances among countries offers significant opportunities for efficiency gains from trade. Carbon trading offers a way of closing the loop without unduly burdening companies and countries that do not have a diversity of options to reduce, reuse, recycle and remove carbon.[6] At the same time, carbon trading provides an incentive for companies and countries with an abundance of the 4R options to do more than they need to balance their carbon emissions. For example, trading gives countries without carbon storage capacity the option to continue to use hydrocarbons by paying other companies and countries with storage capacity to store more carbon.

[6] Carbon accounting frameworks must underpin both carbon reduction trading and carbon storage trading systems. The veracity of a tonne of carbon reduced or a tonne of carbon stored is essential for trust in any trading system. Rules must balance the streamlining of accounting requirements so as not to discourage activity while maintaining sufficient trust in the framework.

Policies targeting elements of **reduce** and **recycle** have been very successful (e.g., the renewable energy incentives that drove self-reinforcing reductions in costs and deployment), but policies targeting **reuse** and **remove** have yet to achieve similar success. The chain of capturing and transporting and then utilizing or storing carbon in most situations involves multiple companies and multiple regulatory regimes. Placing a value only on capturing carbon as an externality and leaving the various parties to pass this value along the chain to the final point of carbon utilization or storage has not been successful in driving significant CCUS uptake. Policy can help build separate business models in which using or storing carbon has value independent of the carbon externality.

For example, KAPSARC has developed an idea for an innovative mechanism compatible with Article 6 of the Paris Agreement that creates a carbon storage unit (CSU) as an added financial incentive for the storage end of the carbon capture and storage value chain. Pricing the value of carbon removal provides an additional incentive to commercialize storage technology. It also facilitates a move away from linear thinking about solely reducing emissions toward circular thinking where both the value of emissions and removals are priced. A recent paper by KAPSARC researchers set out some useful policy building blocks for such an approach (Zakkour and Heidug 2019).

In "Enabling Policies," the OECD points out the need for more specific policies for **reuse** and **remove** that provide for a 'robust revenue stream' along the value chain of capture, transport and use/storage of carbon. CCUS also tends to be capital-intensive with high perceived risks, and so the OECD sees its financing costs as a barrier. The OECD suggests that governments can help reduce finance costs "through short-term guarantees during the construction phase, through public-private partnerships or blended finance, and through international collaboration and sharing of experience in financing and creating markets for CCUS."

The OECD identifies policy elements that are common across all four Rs, such as:

> **a long-term strategy and cross-government alignment to maximise the effectiveness of energy and climate policies; coherent energy pricing ... ; alignment of financial incentives; supportive innovation framework; and greater transparency on carbon accounting.**

It concludes that "even before COVID-19, low-carbon innovation was declining (as measured by patents), and public [research and development (R&D)] spending was stagnant in many regions." Yet, technology innovation is crucial for the circular carbon economy. OECD states that governments can help drive R&D through leveraging public partnerships between universities and private sector research efforts.

In the context of the current COVID-19 crisis, the OECD suggests that governments "build back better" by finding ways to accelerate the circular carbon economy through stimulus packages. The OECD argues that targeting infrastructure spending to further the circular carbon economy not only helps provide significant economic and employment benefits, but also helps pave the way for achieving social and climate goals.

04

Conclusion

Conclusion

The circular carbon economy is a holistic approach that can guide international efforts toward a more inclusive, resilient, sustainable and carbon-neutral/net-zero emissions energy system. The CCE as a construct also provides a useful way of understanding a broad range of climate change mitigation options and how they interconnect. It reveals how choke points in any one of the Rs – reduce, reuse, recycle and remove – can make carbon flows in the system unmanageable if a key technology is unavailable. For example, climate stabilization is unlikely without CCUS technology. Potential choke points, in turn, inform priorities for technology policy.

The CCE Guide report series provides practical information to help policymakers understand the challenges and opportunities presented by each element within the circular carbon economy, and to help them appreciate the degree to which each element may be able to contribute to climate goals while also improving quality of life.

References

Grubb, Michael. 2004. "Technology Innovation and Climate Change Policy: An Overview of Issues and Options." *Keio Economic Studies* no. 41 (2):103-132.

Hepburn, Cameron, Ella Adlen, John Beddington, Emily A. Carter, Sabine Fuss, Niall Mac Dowell, Jan C. Minx, Pete Smith, and Charlotte K. Williams. 2019. "The technological and economic prospects for CO_2 utilization and removal." *Nature* no. 575 (7781):87-97. doi: 10.1038/s41586-019-1681-6.

Huppmann, Daniel, Elmar Kriegler, Volker Krey, Keywan Riahi, Joeri Rogelj, Steven K. Rose, John Weyant, Nico Bauer, Christoph Bertram, Valentina Bosetti, Katherine Calvin, Jonathan Doelman, Laurent Drouet, Johannes Emmerling, Stefan Frank, Shinichiro Fujimori, David Gernaat, Arnulf Grubler, Celine Guivarch, Martin Haigh, Christian Holz, Gokul Iyer, Etsushi Kato, Kimon Keramidas, Alban Kitous, Florian Leblanc, Jing-Yu Liu, Konstantin Löffler, Gunnar Luderer, Adriana Marcucci, David McCollum, Silvana Mima, Alexander Popp, Ronald D. Sands, Fuminori Sano, Jessica Strefler, Junichi Tsutsui, Detlef Van Vuuren, Zoi Vrontisi, Marshall Wise, and Runsen Zhang. 2018. IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis.

Lovins, Amory B. 1977. *Soft energy paths: toward a durable peace*. Harmondsworth; New York etc.: Penguin.

McDonough, William. 2016. "Carbon is not the enemy." *Nature* no. 539.

McDonough, William. 2020. Circular Carbon Economy. Paper read at G20 Workshop on Circular Carbon Economy "Reduce, Reuse, Recycle, Remove," at Riyadh, Saudi Arabia.

Rogelj, Joeri, Drew Shindell, Kejun Jiang, Solomone Fifita, Piers Forster, Veronika Ginzburg, Collins Handa, Haroon Kheshgi, Shigeki Kobayashi, Elmar Kriegler, Luis Mundaca, Roland Séférian, and Mario V. Vilariño. 2018. "Mitigation pathways compatible with 1.5°C in the context of sustainable development." In *Special Report on the impacts of global warming of 1.5 °C*. Geneva: Intergovernmental Panel on Climate Change.

Shaner, Matthew R., Steven J. Davis, Nathan S. Lewis, and Ken Caldeira. 2018. "Geophysical constraints on the reliability of solar and wind power in the United States." *Energy & Environmental Science* no. 11 (4):914-925. doi: 10.1039/C7EE03029K.

Shell. 2016. A Better Life with a Healthy Planet: Pathways to Net-Zero Emissions. Royal Dutch Shell.

Smeets, Pieter. 2019. SABIC contributions to A+ 4Rs.

United Nations. 2019. *The Sustainable Development Goals Report 2019*.

van Vuuren, Detlef P., Elke Stehfest, David E. H. J. Gernaat, Maarten van den Berg, David L. Bijl, Harmen Sytze de Boer, Vassilis Daioglou, Jonathan C. Doelman, Oreane Y. Edelenbosch, Mathijs Harmsen, Andries F. Hof, and Mariësse A. E. van Sluisveld. 2018. "Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies." *Nature Climate Change* no. 8 (5):391-397. doi: 10.1038/s41558-018-0119-8.

World Bank Group, and Frankfurt School of Finance and Management. 2017. Results-Based Climate Finance in Practice: Delivering Climate Finance for Low-Carbon Development. Washington , DC: World Bank.

Zakkour, Paul, and Wolfgang Heidug. 2019. A Mechanism for CCS in the Post-Paris Era. Riyadh: KAPSARC.

Appendix – Managing Carbon With A Circular Economy: An Evolving Perspective By William McDonough

The G20 Presidency asked well-known sustainability leader William McDonough to open the March G20 Climate Stewardship Working Group and Energy Sustainability Working Group meetings by presenting a vision for the circular economy, and how it may inform a dialogue on the myriad issues involved in envisioning carbon in the circular economy. Mr. McDonough's concept integrates the innovative business models of the larger circular economy where carbon is both a valuable material and a valuable energy source.

The following is an overview of some of the earliest ideas he presented in March 2020. This work is under development, and a more comprehensive version is in preparation and will be published soon. The drawing and text here are preliminary and, as such, should not be used or adapted without permission. Please contact Brenn Huckstep at McDonough Innovation (bhuckstep@mcdonough.com) for additional information, to provide advice, and/or to request permission to use or adapt this material.

Cradle to Cradle **and the circular economy**

To manage carbon in a circular economy, one might best begin by understanding the foundation of the circular economy concept, which is gaining traction globally. The circular economy's fundamental principles were outlined in Mr. McDonough's seminal book, co-authored with Michael Braungart, published in the United States as *Cradle to Cradle, Remaking the Way We Make Things* (2002), and published in China as *Cradle to Cradle, the Design of the Circular Economy* (2005).

Human cultures have used and reused materials across multiple generations, including metals, stone, wood, cloth and paper, because they offer great value. The industrial revolution's ability to mass produce at high speed has now resulted in 'planned obsolescence.' Planned obsolescence, as currently practiced, is part of an overall system based on take, make, waste that 'churns' the economy. We can refer to this as the 'linear economy.' *Cradle to Cradle* offers an alternative strategy, the circular economy, based on the wisdom of nature – take, make, use, reuse, recover, recycle, restore, regenerate – thereby eliminating the concept of waste.

Cradle to Cradle's principles for a circular economy are:

1. Waste equals food – eliminate the concept of waste with healthy materials in restorative and regenerative cycles.
2. Use clean energy – renewable power and safely managed carbon-based energy sources.
3. Celebrate diversity – across all cultures and ecosystems.

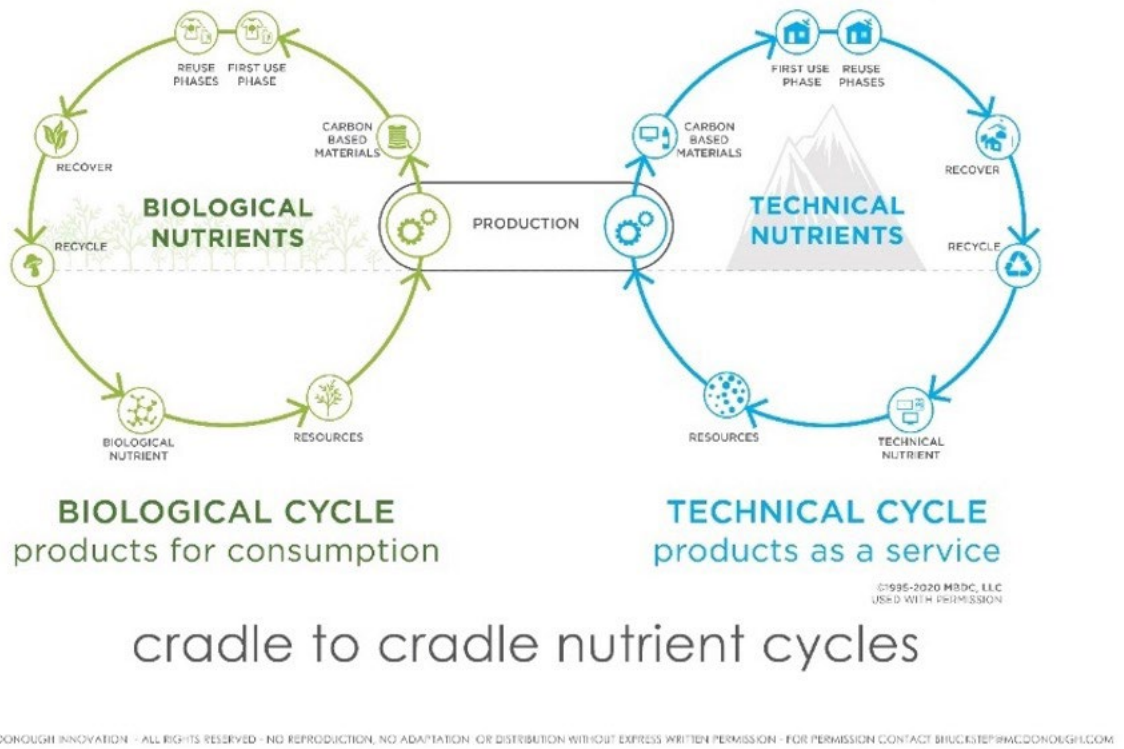

Figure 1. *Cradle to Cradle*'s biological and technical cycles

Cradle to Cradle introduced the novel concept of two 'metabolisms,' biological and technical, in which products are designed for human use and reuse (Fig. 1). Biological cycles incorporate materials that can be used, reused, recycled, and safely restored to the natural world. Technical cycles incorporate materials that can be used, reused, recycled, and safely returned to industrial systems so that they continuously benefit human society. These can be seen as products as a service, for example, light fixture companies can get paid for providing the service of the light while maintaining access to the components of light fixtures to support their future production without requiring additional natural resources.

Looking at the circular economy through a carbon lens

In November 2016, *Nature* published an article by William McDonough entitled “Carbon is Not the Enemy.” The article points out it is how and where we acquire and use carbon materials that make their use beneficial or detrimental. The article defines three types of carbon (Fig. 2):

1. ‘Living carbon’ in the biosphere naturally balances with the atmosphere and is the basis of life.
2. ‘Durable carbon’ is in the technosphere and is used in a range of applications, from long-term infrastructure to recycled plastics. It is used, reused, recovered and recycled over generations and can be an enduring biological or technical nutrient.
3. ‘Fugitive carbon’ is released into the environment in the wrong form, in the wrong place, at the wrong dose, and the wrong duration, such as excess anthropogenic carbon dioxide (CO_2) in the atmosphere or plastics in the ocean.

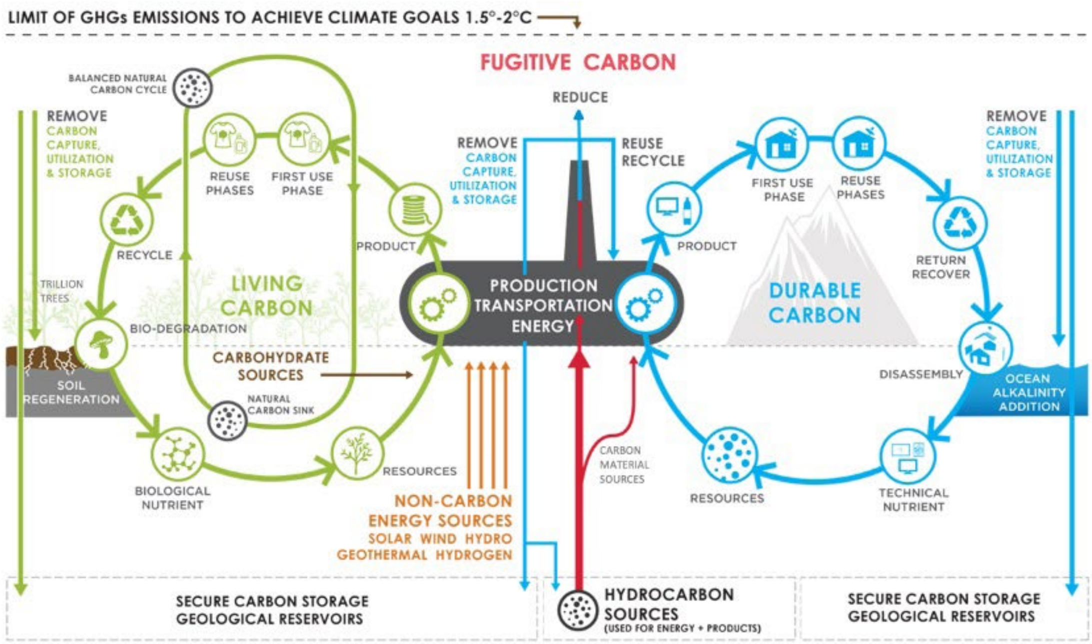

Figure 2. Looking at the circular economy through a carbon lens – a preliminary framework presented at the G20 Climate Stewardship and Energy Sustainability working groups (Riyadh, March 2020)

When the material and energy use cycles, and the resulting CO_2 emissions, are overlaid on the circular economy's biological and technical cycles, one can begin to see the carbon leaks that result in fugitive carbon in the atmosphere. A circular carbon economy begins to provide a balanced view of energy and material flows and the need to manage fugitive emissions.

Carbon as a fuel becomes critical in the circular economy because it powers the production cycle, as depicted in the center of Figure 2. Production, transportation, and energy are used to process materials from either the biosphere or the technosphere and transform them into useable goods. When this production is powered by energy-rich carbon-based fuels, the result is fugitive CO_2 emissions.

Figure 2 illustrates how the biosphere uses photosynthesis to incorporate CO_2, removing it from the atmosphere while also remineralizing organic matter to return CO_2 back to the atmosphere, thereby achieving a circular global carbon cycle. Going forward, humans can focus on nature-based solutions such as forest conservation, sound land management and reforestation, agricultural soil management, coastal ecosystem restoration, such as mangroves acting as intense carbon sinks, and support programs that help capture and store atmospheric carbon into oceanic bicarbonates. These efforts are fundamental to the successful management of carbon in the circular economy.

The biosphere alone can no longer create a balanced carbon economy because humans use vast amounts of carbon outside of natural biological cycles. It is now up to us humans to balance our own carbon emissions through additional innovations in the technosphere. Some technology-based solutions include recycling durable carbon, direct air capture (DAC), and point source carbon capture, storage, and utilization (CCSU).

Captured CO_2 from DAC and CCSU can be a feedstock that can increasingly replace hydrocarbon sources. This feedstock can be recycled into durable carbon materials in the future, such as cement and polymers. Captured fugitive carbon emissions that cannot currently be utilized can be stored for future use in geological formations or sequestered geologically or in the oceans with alkalinity addition. The technological advancements necessary for the massive scaling up of both capture and reuse are critical elements in the design of a sound carbon management strategy for the circular economy.

Assertively pursuing energy efficiency opportunities and the deployment of non-carbon-based practical energy sources such as solar, wind, geothermal, marine, and hydro power, wherever appropriate and at every scale, are critical to reducing fugitive carbon emissions.

The use of nature-based solutions to restore the natural functioning of carbon sinks, technology-based solutions to reduce, capture, and remove fugitive carbon, and the intelligent use and reuse of materials in circular economy business models will be necessary to achieve a safe and balanced climate system.

circular carbon economy