Beyond Energy:

Incentivizing Decarbonization through the Circular Economy

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1. Introduction

The past two decades have seen governments adopting decarbonization policies to transition their economies away from high-emissions growth pathways. The predominant approach has included two areas of policy focus: the scaling up of renewable energy (mainly solar and wind) in electricity production through targeted policy support schemes,[1] resulting in technology cost reductions, and widespread uptake around the world,[2] and, measures to improve energy use efficiency.

In combination, these two areas have contributed the largest proportions of offsets to CO_2 emissions from economic growth in recent years; for instance between 2017 and 2018, they contributed around 60 per cent to total avoided emissions, while energy use efficiency played a key role (among other factors) in keeping energy-related CO_2 emissions flat in 2019 (IEA, 2018a; 2019b).[3] The average global carbon intensity of electricity generation has also fallen by around 10 per cent over the last decade (IEA, 2019a).[4]

There has, however, been a recent acceleration of ambitions on decarbonization, with numerous countries adopting targets to achieve net-zero carbon emissions by the middle of this century.[5] This has, in large part, been driven by evidence from the Intergovernmental Panel on Climate Change[6] (IPCC, 2018) indicating that limiting global warming to 1.5°C would require 'global net human-caused emissions of CO_2 to fall by about 45 per cent from 2010 levels by 2030, reaching "net-zero" around 2050.' This is in line with the goal of the Paris Agreement (UNFCCC, 2016).[7] Achieving net-zero emissions would entail reducing emissions from economic activity to as close to zero as possible, and offsetting any remaining emissions through the removal of carbon, resulting in a net-neutral impact on the climate. As the global consensus on climate-related policy action deepens, it is likely that other jurisdictions will move to adopt similar targets.

There are two implications of the predominant approach to decarbonization adopted thus far, for countries' net-zero ambitions:

First, as electricity production comprises the largest single source of CO_2 emissions, past gains in emissions reduction have primarily been achieved by the replacement of fossil fuels with renewables in electricity. Although governments are, as a next step, moving towards the renewable-based electrification of entire economic sectors (namely decarbonization by 'electrons'), there is evidence that direct electrification may not be possible, for technical and/or economic reasons, in 'hard-to-abate'

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[1] Either through direct support (such as feed-in tariffs or investment support) or indirect measures (like carbon trading schemes such as the EU–ETS) which encouraged a switch to low-carbon energy production. For instance, in the EU, non-hydro renewables as a share of electricity generation grew from roughly 2 per cent in 1990 to 21 per cent in 2019 (IEA–WEO, 2020; IEA, 2009). This focus area has given rise to other policy issues, such as the integration of renewables into electricity systems, which are not within the scope of this paper.

[2] Since 2009–10, the price of solar PV modules has fallen by 80 per cent based on learning rates of 18–22 per cent, and the price of onshore wind turbines by 38 per cent. Between 2010 and 2016, the global weighted average cost of electricity from utility-scale solar PV plants commissioned fell by 69 per cent, and that from onshore wind by 18 per cent (IRENA, 2017). Battery costs fell from over US$1,100 per kilowatt-hour (kWh) in 2010 to US$156/kWh in 2019, and are predicted to be close to US$100/kWh by 2023 (BNEF, 2019).

[3] 'Avoided emissions' refers to emissions that were prevented as a result of these measures – emissions that would have otherwise resulted from higher economic growth and energy demand. Around 0.8 GtCO_2 of emissions were avoided between 2017 and 2018 (out of 1.3 Gt CO_2 that would have been generated in total from economic growth) (IEA, 2018a).

[4] In 2018 this was 475 grams of carbon dioxide per kilowatt-hour (gCO_2/kWh), a 10 per cent improvement on 2010. (IEA, 2019a).

[5] These include, for instance, EU countries, UK, Bhutan, Costa Rica, Fiji, Japan, the Marshall Islands, China, South Korea, and Uruguay. Additionally, over 100 countries have joined an alliance aiming for net-zero emissions by 2050.

[6] The UN body for assessing the science related to climate change.

[7] To limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels.

sectors outside of electricity generation. These, for instance, include heavy industries that require high-temperature heat and which have significant process emissions, indicating that there will be some sectors that may be left un-decarbonized based on the predominant approach (see Figure 1) (IEA, 2020b). For example, it has been estimated that around half of the CO_2 emissions from industry come from steel, cement, ammonia, and ethylene production.[8] Around 45 per cent of these sectors' emissions result from feedstocks (these cannot be abated by a change in fuels and would require changes to processes); a further 35 per cent come from burning fossil fuels to generate high-temperature heat (a switch to renewable-based fuels would require changes to furnace designs); and the remaining 20 per cent come from other energy requirements (such as medium- and low-temperature heat) (IEA, 2018b; de Pee et al., 2018; Brown et al. 2012). These industrial processes are also highly integrated, requiring a change in one part of the process to be accompanied by changes to other parts; in addition, industrial production facilities have relatively long lifetimes (stretching to around 50 years), with decarbonization requiring costly rebuilds or retrofits (de Pee et al., 2018).[9] Other decarbonization methods can be used to bring industry emissions as close to net-zero as possible (in other words, decarbonization through 'molecules'), for example through hydrogen, and carbon capture (use) and storage. However, these options are also presently limited by economic factors (for instance, these industries supply products that are internationally traded, with companies competing mainly on price) and thus, in the absence of an economy-wide system that prices in environmental externalities, decarbonization measures which add to the cost of production could reduce their competitiveness.

The second implication for net-zero ambitions is that the predominant approach to decarbonization has largely disregarded the globalization of trade and supply chains, and spatial dissociation between places of extraction, production, and consumption. The boundaries of net-zero carbon targets are not clearly defined or coordinated between different jurisdictions, often even within the same national borders.[10] International trade enables the costs of decarbonization to be shifted outside national borders, creating negative externalities[11] elsewhere (Parrique et al., 2019). The focus on emissions from energy production implies advanced (high-income, high-consumption) countries that have managed to decouple emissions from economic output may have done so through externalizing the negative environmental impacts to low-income, low-consumption countries[12] or to developing economies where energy-intensive industries have been relocated, due to lower costs.[13] At the global level, realistically, emissions reduction in one country is unlikely to be exactly offset by increases in another country and vice versa, particularly given the uneven levels of economic development. It is, for instance, estimated that emerging and developing economies could account for around 70 per cent of energy demand (and hence emissions) growth to 2050, some of which (but not all) could be offset by slowdowns in advanced economies.[14] For so long as economies continue to grow, and energy from unabated hydrocarbons is used to produce more goods and services, emissions will continue to be

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[8] CO_2 emissions are estimated, in some studies, to account for around 90 per cent of total industrial emissions (de Pee at al., 2018).

[9] These industries have long-lived capital assets that are 'locked in' as fixed investments over decades; they also produce emissions from chemical reactions that are inherent to the production process (Eurelectric, 2018; IEA, 2020b).

[10] For example, several cities across the world have independently pledged to become emissions-neutral by 2050.

[11] Costs generated as an unintended by-product of an economic activity that do not accrue to the parties involved in the activity, and where no compensation takes place. (Owen, 2004).

[12] Research on 'just energy transitions', for instance, shows that the transition to transport electrification in some countries in Western Europe led to the displacement of second-hand fossil fuel car fleets from their markets to those in developing countries (Sovacool et al., 2019).

[13] Wang et al. (2018) compare consumption-based (material footprint) and production-based (domestic material) measurements of resource use for three OECD and three BRICS countries, finding that Australia, Japan, India, and the USA have managed to weaken coupling, but only because they shifted their material resource supply abroad. Moreau and Vuille (2018) find that a decrease in Switzerland's territorial final energy intensity of total (not just energy) production, from 2000 to 2014 is offset by an increase in the energy embodied in imports.

[14] BP Energy Outlook (2020).

generated throughout the supply chain.[15] In this 'linear' decarbonization model, emissions from energy production would need to decline very rapidly to offset the expansion in economic output, which is not the case at present.[16] In the absence of rapid declines, the net effect on reducing the absolute level of emissions will continue to be limited. This is suggested, for instance, from Figure 2, which shows that absolute emissions have continued to increase, alongside apparent improvements in the emissions intensity of GDP.[17]

Figure 1: Composition of per capita CO_2 emissions from fuel combustion, 2018 (%)
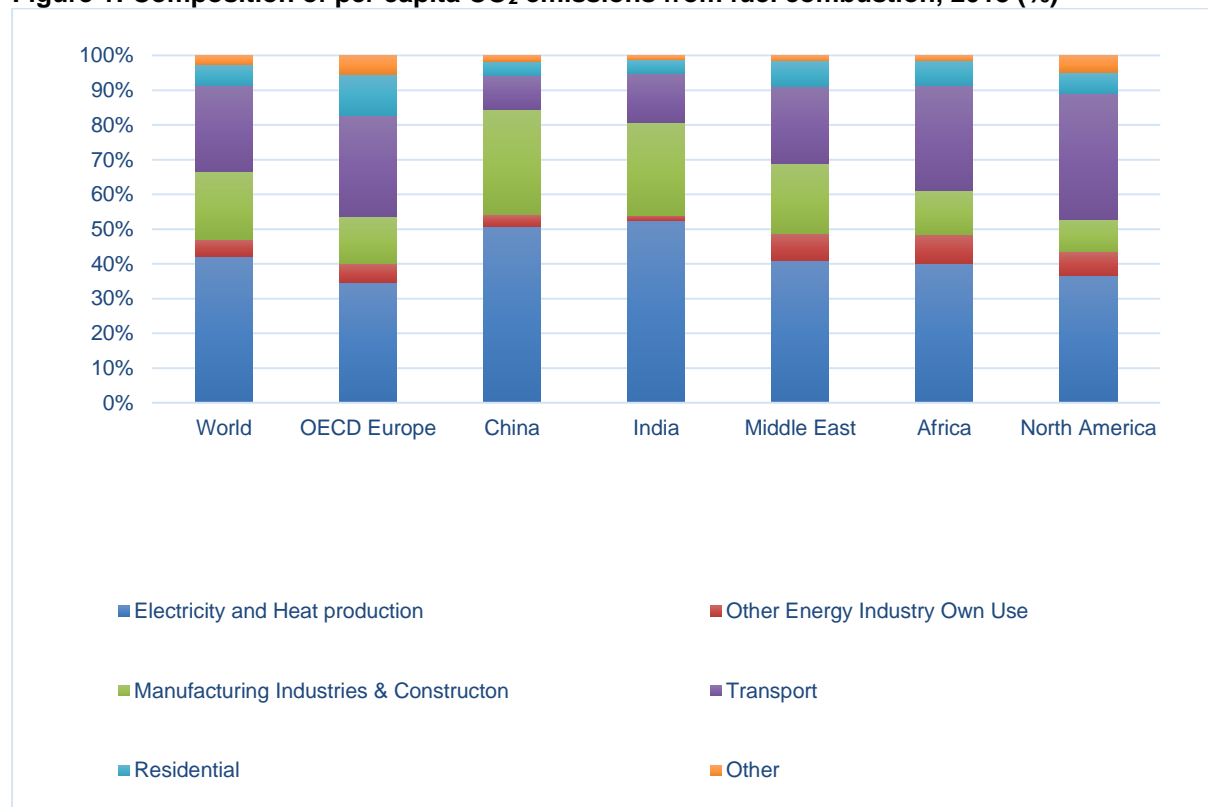
Source: IEA (2019a, II.58); WDI (2016).

[15] Research by the Ellen MacArthur Foundation suggests that mitigation measures focusing on the reduction of emissions from energy production can only address 55 per cent of required emissions reductions (EMF, 2019).

[16] It has been estimated that in order to achieve a 90 per cent emission reduction in 2050 compared to current levels, the global average emission intensity of economic output would need to decline at an average rate of 8 per cent per year until 2050 – reducing the average carbon content of economic output to 20 gCO_2/US\$, or roughly 1/26th of what it was in 2019 (roughly 497 gCO_2/US\$) (Parrique et al., 2019).

[17] The emissions intensity of global GDP is estimated to have fallen by around 30 per cent from 1990 to 2017. Absolute global emissions have continued to rise, rather than fall, increasing by around 63 per cent from 1990 to 2016 (WDI, 2016).

Figure 2: World annual CO$_2$ emissions and emissions intensity of GDP
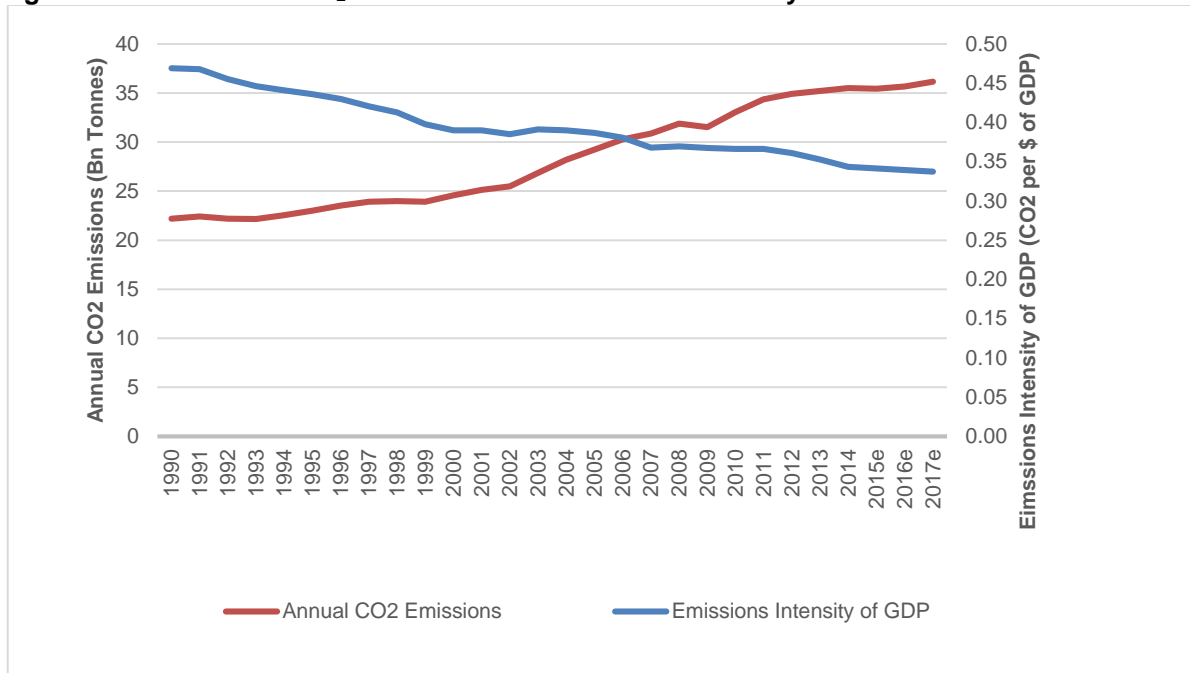
Source: IEA (2019a, II.58); WDI (2016).

The above implications raise the question: what *other* solutions (beyond the predominant focus on energy production) can be used to enhance decarbonization in order to meet net-zero carbon targets?

The circular economy, which is a traditional concept in the economics of production and the management of resources, has recently risen high in the agendas of policymakers as an additional way of enhancing decarbonization through non-energy means, and a potential solution to the current 'partial decarbonization' approach. The original concept of the circular economy was initially adopted with the aim of improving short-to-medium-term efficiency (for example, allocative and technical efficiency) in the operations of large organizations.[18] Circular economy business models were presented as offering profitability and business growth, by means of increased production efficiency, risk mitigation, and the pursuit of new revenue opportunities, with the environmental and ecological benefits from reduced resource (material) consumption, reuse, and recycling, seen as positive externalities (Whalen and Whalen, 2020). The approach has evolved over time to include the aim of sustainability, and a move from 'linear' to 'circular' supply chains within organizations, facilitating the decoupling of an organization's financial growth from a dependence on finite resources (WBSCD, 2020). The circular economy concept is fundamentally based on closing the loops around systems of extraction, production, and consumption; materials and products are kept within the loop for as long as possible, with leakages minimized or ideally eliminated, thereby offering a way to deal with the limitations of a 'partial' or 'linear' decarbonization paradigm, which has been described above. The circular economy concept also addresses wider questions that are frequently raised in relation to the impact of decarbonization on economic growth in developing economies, as it incorporates the decoupling of economic growth from resource consumption.

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[18] Corporate circular economy models have been developed since the 1970s (WBSCD, 2020).

In this paper, we begin by analyzing the implications of the circular economy approach for the decarbonization of electricity generation and use, but also consider its wider implications. We review corporate circular economy approaches and their transferability to the macroeconomic level, and we argue that a clear public policy framework is necessary to ensure that these approaches, even when adopted at the organizational level, do not result in net negative impacts on decarbonization at the macro level (for example from the spillover of negative externalities). We consider what existing framework of policy signals can incentivize and facilitate circular economy solutions to complement existing energy policy, to encourage full decarbonization. Finally, we highlight the main barriers to the implementation of circular economy approaches. We conclude by arguing that circular economy approaches, if implemented appropriately, should become an inherent part of the instruments of decarbonization. Moreover, given their original underpinning objective of improving allocative and technical efficiency, circular economy approaches would continue to be relevant even beyond a time when full decarbonization has been achieved, making it a 'no-regrets' strategy for governments.[19]

2. Beyond energy production: enhancing decarbonization through material efficiency and the circular economy

Improvements in material efficiency constitute a complementary solution to the predominant decarbonization policies seen currently (the addition of renewables and energy use efficiency); such improvements can potentially reduce energy use and hence the greenhouse gas (GHG) emissions associated with materials production. 'Material efficiency' is defined simply as 'providing material services with less material production and processing' (Gilbert et al., 2017). A multi-fold increase in renewable capacity addition rates during the energy transition has implications for renewable material supply chains, particularly with predicted future rises in energy demand. Although renewable energy has relatively low life-cycle emissions compared with unabated fossil fuel energy[20], its mineral intensity is not insignificant; one study estimates that 1 kilowatt-hour (kWh) of renewable energy could require ten times more metals than 1 kWh of fossil fuel energy (Arnsperger and Bourg, 2017)[21] despite offsetting emissions. There are also constraints to energy efficiency gains – for instance, rebound effects could lead to an increased consumption of the same product (translating into increased energy production), or 'freed' resources could be allocated to other types of carbon-emitting activity (Parrique et al., 2019).

Material efficiency improvements involve elements which indirectly translate into lower carbon and GHG emissions, such as:

- the reuse of components;
- reduction in yield losses;
- less raw material for the same service;
- longer-life products and services;
- re-manufacturing.

Material efficiency also provides a route to minimize primary energy use and waste, and to address issues around resource scarcity (Gilbert et al., 2017). An example of the use of material efficiency in

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[19] 'No-regrets' strategies generally refer to policy actions specific to addressing a particular problem, which make sense in developmental terms regardless of whether the problem materializes in the future. This is achieved by building resilience to changing economic, social, and environmental conditions. Increased resilience is argued to be the basis for sustainable growth in a world of multiple hazards (Heltberg et al., 2009).

[20] Discussed in Section 2.2.

[21] This is likely to be context-specific.

this way is in shipping (a 'hard-to-abate sector'). Gilbert et al. (2020) conduct a case study of the ship building sector and a shipping vessel's steel hull, applying a Life Cycle Emission Assessment approach, to determine the effectiveness of material efficiency in reducing CO_2 emissions in the shipping supply chain. When compared to a business-as-usual case (which includes recycling of steel scraps after vessel decommissioning), they find that designing and manufacturing for 100 per cent hull reuse provides an emissions reduction of 29 per cent,[22] whereas 50 per cent reuse provides a 10 per cent reduction.

Material efficiency over multiple life cycles is thus a means of enhancing decarbonization through non-energy means, but its effectiveness is limited by the economic paradigm within which economic agents in the sector operate – for instance, ship building is a sub-sector within steelmaking, and the current prevailing 'business model' for steel producers is to make and sell products in a linear economy. Despite the potential contributions of improved materials efficiency to emissions reductions, efficiency improvements can still be offset by stronger economic growth; empirical studies suggest that additional measures are needed[23] to manage the demand for goods and services that is driving global CO_2 emissions, or to produce imported goods and services in an environmentally sustainable manner, in order to produce a positive net effect.[24] [25]A focus on materials efficiency without regard to the wider system within which materials operate risks creating a trade-off between decarbonization and 'de-materialization' (Plank et al., 2020).

2.1 The circular economy approach at the firm or organizational level

Material efficiency forms an intrinsic part of the wider circular economy approach. Although the circular economy as a concept has gained greater traction with governments in recent years, for reasons discussed earlier, it was originally popularized and adopted in the corporate sector[26] and in the operations of large organizations, through a reassessment of company value chains (Geissdoerfer et al., 2018; Ferasso et al., 2020). The approach has evolved over time to include the shift from linear to circular supply chains within organizations, in order to facilitate the decoupling of financial growth from a dependence on finite resources and to improve long-term efficiency (WBSCD, 2020). Circular economy approaches that have been adopted within corporate organizations claim to 'create, deliver, and capture value while implementing circular strategies that can prolong the useful life of products and parts (such as repair and re-manufacturing) and close material loops (for example recycling)' (Nußholz, 2018; Ferasso et al., 2020).

One such method that has been used to implement circular economy approaches in organizations is *resource value extension*, for instance: using renewable inputs as a substitute for non-renewables,[27] recycling materials,[28] and engaging in resource recovery (for example using waste as an energy source) (Whalen and Whalen, 2020). Circular economy principles also shape revenue streams in an organization by creating new value propositions for companies, where the ownership structure might shift, boosting the demand for services along the product life cycle, while different revenue models such as renting, leasing, or subscriptions could potentially become more central to a business (Tunn, Bocken, van den Hende, & Schoormans, 2019; Ferasso et al., 2020).

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[22] From 221,978 tCO$_2$ to 158,285 tCO$_2$.

[23] Discussed later on in this paper.

[24] For instance, Plank et al. (2020) investigate the relationship between resource efficiency and decarbonization for Austria from 2000 to 2015, and find that the pursuit of material efficiency in a policy 'silo' risks coinciding with higher emissions.

[25] There are also studies underway which examine the potential for replacing energy intensive, bulky materials, with newer and lighter technologies – such as composites.

[26] Corporate circular economy models have been developed since the 1970s (WBSCD, 2020).

[27] For example, Royal DSM a Dutch multinational, produces cellulosic bioethanol, derived from corn and other plant materials (Whalen and Whalen, 2020).

[28] For example, solar panels makers recycle their panels – one such example being China's Trina Solar, one of the world's largest solar panel makers (Whalen and Whalen, 2020).

Organizations in the corporate sector have developed a set of metrics over the years to measure 'circularity' within divisions; these focus mainly on creating return loops for material flows and minimizing waste. Broadly, these metrics differentiate between measuring two types of cycles:

- 'biological cycles' in which non-toxic materials are restored into the biosphere while rebuilding natural capital, after having been cascaded into different applications;

- 'technical cycles' in which products, components, and materials are restored into the market at the 'highest possible quality' and for as long as possible, through repair and maintenance, reuse, refurbishment, remanufacture and, ultimately, recycling (EMF, 2019).

Table 1 summarizes some examples of these organizational metrics.

An extension of the concept of circularity within organizations to entire economic or industrial sectors would involve viewing the circular economy as a cyclic system that aims to eliminate waste by turning goods that are at the end of their life cycle into resources for new ones, and by maximizing the utilization capacity of goods (for example by means of product-sharing, or the product-as-a-service) (Stahel, 2016; Ferasso et al., 2020). Closing material loops in industrial ecosystems can create a continual use of resources; this can, in theory, be achieved through long-lasting design, proactive maintenance, recycling, repairing, refurbishment, and remanufacturing (Geissdoerfer et al., 2018; Ferasso et al., 2020). As around a quarter of global energy use is estimated to serve the production of major materials,[29] the more efficient use of these materials presents a significant opportunity for emissions reduction (Hertwich et al., 2019).[30] The circular economy concept, when extended to entire economic systems, is based on several major schools of thought and their proponents These include: the functional service economy (performance economy) of Walter Stahel; the 'cradle to cradle' design philosophy of William McDonough and Michael Braungart; Janine Benyus's 'biomimicry'; the industrial ecology of Reid Lifset and Thomas Graedel; 'natural capitalism' by Amory and Hunter Lovins and Paul Hawken; and the 'blue economy' systems approach by Gunter Pauli (see EMF, 2019; 2015; 2012b).

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[29] The production of major materials (iron and steel, aluminium, cement, chemical products, and pulp and paper) accounted for around 26% of global final energy use and 18% of CO_2 emissions from fossil fuels and industrial processes in 2014 (Hertwich et al., 2019).

[30] Parrique et al. (2019), for instance, argue that while the world economy had been gradually 'dematerializing' for several years, this trend has been reversed in the last two decades. While in the last century the use of materials was relatively decoupling from GDP at the global level, the trend has stalled since the turn of the century. Krausmann et al. (2018) show that changes in material intensity went from a negative 0.9 per cent per year between 1945–2002 to a positive 0.4 per cent per year between 2002 and 2015; this was partly because between 2002 and 2015, global material extraction increased by 53 per cent, due to higher economic growth (and higher demand) from certain world regions.

Table 1: Metrics to measure the circular economy in organizations – key examples

		Summary	Metrics & Indicators[31]	Composite Measure
APPLICATIVE INDEXES	**Circulytics**[32]	Measures circularity based on *enablers* and *outcomes* within an organization. *Enablers:* indicators assessing the pathway of company transformation – from strategic prioritization of the circular economy to the complete implementation of circular economy principles. *Outcomes:* the extent to which circular economy principles are applied to each of 6 specific themes: products and materials, services, plant property and equipment assets, water, energy, and finance.	*Material Circularity Indicator* (Measures virgin feedstock, unrecoverable waste, linear material flow, recycling rates, & recycling efficiencies) *Complementary Material Risk Indicators* (Measures materials price variation, supply chain risks, scarcity, toxicity) *Complementary Impact Indicators* (Measures energy usage & CO_2 emissions; and water usage)	*Weighted scoring system* for enablers & outcomes, based on industry benchmarks.
	Circular Transition Index[33]	Visualizes circular economy within a company as a 'loop' – with overall circularity performance representing the balance between 'linear' (e.g., non-renewable, non-recyclable, or non-reusable) and 'circular' material inflows and outflows.	*Outflow measures*: material 'recovery potential' (can be improved through optimizing design); 'actual recovery' (can be improved through adopting new business models – e.g. product-as-a-service or buyback/take-back scheme – or collaborating with value chain partners that drive circularity).	*Circularity Performance* – the average between the percentage of circular inflow to the percentage of circular outflow. Improvements towards circularity are made through identifying the largest 'linear' inflow streams and searching for

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[31] A 'metric' is a method employed to understand change over time across a number of dimensions, and can be expressed as a calculated or combined set of indicators (referring to a single value and its unit).
[32] Ellen MacArthur Foundation (EMF, 2019; 2015, 2012b).
[33] World Business Council for Sustainable Development (WBSCD, 2020).

		The aim is to 'close the loop', followed by 'optimizing the loop', and then 'valuing the loop'.	*Progress towards circular transitions measured through*: renewables as % of energy consumption,[34] standard material recovery rates, the mass of material inflows defined as 'critical' or 'scarce' as a percentage of the total mass of linear inflows,[35] and the value (revenue) a company generates per unit of linear inflow.	renewable or non-virgin alternatives.
CONCEPTUAL INDEXES	**CirculAbility**[36]	A single index of circularity combining the 'circularity in the flows of materials and energy' and the 'circularity in the use' approach (i.e. the circularity deriving from the increase of the use factor of an asset).	*Circular Use*: Life extension; sharing; product-as-a-service. *Circular Flow*: Material Inputs; Materials Output.	*Overall Circularity Index*
	Circle Scan[37]	Based on metrics to address three questions: • *Why does the business in question need to change?* • *What should be changed in the value chain?* • *How can the required change be brought about?*	*Headline Indicators:* % circularity; share of scarce resource. *Performance Indicators:* Recycling rate; Share of secondary resources; Share of renewable energy. *Process Indicators:* Share of sustainable products in portfolio; Customer attitude towards green products; Awareness among employees.	Combines established composite measures; *Circularity Gap* measure.

Source: Compiled from EMF (2012a; 2012b; 2020); WBSCD (2020); Enel (2018)[38]

[34] A modified approach to the circular economy that has been proposed is the 'circular carbon economy' in which emissions of carbon from all sectors are managed in a way that allows the carbon to move in a closed-loop system (see Al-Khowaiter and Mufti, 2020). This could be a starting point for economies that are heavily resource-dependent.

[35] 'Critical' materials are those that are likely to become scarce in the near future and are therefore difficult to substitute (WBSCD, 2020)

[36] Enel (2018).

[37] Circle Economy (2020).

[38] Other metrics not represented in the table due to data limitations include 'Circularity Check' by Ecopreneur.

2.2   Application to decarbonization of energy

The circular economy is relevant to the decarbonization of the energy sector in that it supports the decarbonization of the supply chain of each energy carrier by moving the focus from solely addressing the emissions from energy production, to addressing emissions from the underlying energy installations. The predominant policy approach thus far[39] has been based on measuring the direct energy production emissions generated within national boundaries, using Emission Factors for fossil fuels and electricity based on IPCC standards (IPCC, 2006).[40] This approach is, however, limited when trying to fully account for emissions associated with the use of any specific technologies, including the supply chain (in other words, emissions from energy installations), particularly when that chain is situated across national boundaries. This is applicable to all energy generation technologies. For example, nuclear energy exhibits negligible emission levels for GHGs at the stage of power generation, but emissions arise in other parts of the supply chain, such as in manufacturing components for plants, transporting fuels and other materials, or at the decommissioning stage (Dones et al., 2004). The system boundaries for the calculation of the Emission Factor of each energy carrier are therefore limited and do not necessarily consider the whole life cycle. In contrast, circular economy approaches are based on Life Cycle Analysis (LCA) of GHG emissions, which accounts for all energy and material flows associated with a system or process, and therefore considers the whole supply chain of an energy carrier (Owen, 2004). This approach is, by definition, in closer alignment with 'net-zero emissions' ambitions, and with the move away from a linear decarbonization paradigm. The scope for decarbonization of the energy sector based on circular economy approaches varies according to the scope for reductions in life cycle emissions from various energy carriers: for example for electricity, this would be the life cycle GHG emissions for each kilowatt-hour (kWh) of electricity provided by a specific technology.

A key barrier here is that measurements of life cycle GHG emissions in technology supply chains using LCAs have tended to vary significantly for two reasons:

- Many technologies tend to be highly context-specific. In the example of solar PV and wind, contextual factors include: resource inputs and technology, transportation, manufacturing, location, sizing and capacity, longevity, optional equipment, and even different configurations of the same installation (Nugent and Sovacool, 2014).

- There is no single and internationally-harmonized method of measurement and reporting of life cycle emissions and therefore empirical literature tends to rely on a variety of methods, yielding a range of estimates of life cycle GHG emissions.[41,42, 43]

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[39] With the exception of countries that already have policies in place to address emissions underlying the supply chain.

[40] Dones et al. (2004) argue that this is the most straightforward accounting of greenhouse gas (GHG) emissions – based on Emission Factors associated with combustion of various fuels, which can also be used for estimating national emission inventories.

[41] Geographically, LCAs have largely been carried out at city or even municipality level and there are ongoing efforts to scale these up. An example of local LCA initiatives is the Covenant of Mayors launched in January 2008 under the auspices of the European Commission, signatories to which have committed to prepare Baseline Emission Inventories for their city-regions, as part of constructing energy strategies to reduce GHG emissions under the Sustainable Energy Action Plan (Cellura et al., 2018).

[42] Cellura et al. (2018) review recent literature on LCAs carried out for city-regions across different countries. They also use data from an Italian municipality to demonstrate the difference between emissions estimated under the 'use phase' (focus on emissions from energy production, using Emission Factors for fossil fuels and electricity consumption based on the standard of the IPCC) and 'life cycle' (using GHG Emission Factors for fossil fuels and electricity consumption based on the European Reference Life Cycle Database and site-specific data for electricity consumption) approaches. They find that emissions are 24 per cent and 21 per cent higher under the life cycle approach.

[43] We do not claim to propose or promote any specific method of estimation either, but simply highlight the fact that there is a lack of consensus in the measurement of lifecycle emissions, often because the boundaries are not well-defined.

As conducting an LCA is beyond the scope of this paper, we rely on secondary literature to broadly illustrate the scope for circular economy approaches in reducing life cycle emissions across the energy supply chain. Within the multitude of LCA studies, Nugent and Sovacool (2014) provide a critically evaluated screening (using a consistent methodology) of 153 life cycle studies over the preceding 10 year period, covering a broad range of electricity generation technologies (focusing mainly on solar and wind), analysing the range of life cycle estimates, and determining the average life cycle emissions estimates for each these technologies.[44] These are shown in Table 2 – it should be noted that they are intended to be illustrative and not determinate, due to issues around variations in estimates discussed above. The mean estimates are broadly consistent with those reported in other studies and reports, including Jordaan et al. (2020), World Nuclear Association (2011), and Sovacool (2008).

Table 2 shows, as per Nugent and Sovacool (2014), that unabated fossil fuels account for relatively higher life cycle emissions, ranging from a mean estimate of 14 grams of carbon dioxide equivalent per kilowatt-hour (gCO_2e/kWh) for biomass (forest wood co-combustion with hard coal) to 1,050 gCO_2e/kWh (coal without scrubbing).[45] It should be noted that Nugent and Sovacool (2014) does not include abated fossil fuel technologies (such as natural gas with CCS) in their evaluation. Again, estimates in the literature vary here and are context-specific, for instance, EIA (2015) suggests that capturing 90 per cent of carbon could result in 70–80 per cent reductions in life cycle emissions of fossil fuel technologies (with CCS); IPCC (2014) suggests that similar reductions are possible for carbon-abated natural gas.[46] In contrast, renewables (hydro and intermittent) account for relatively lower life cycle emissions – ranging from a mean estimate of 10 gCO_2e/kWh (hydro reservoir) to 50 gCO_2e/kWh (solar photovoltaic, various sizes and configurations). This suggests a first-order reduction in life cycle emissions from the addition of renewable technologies, displacing carbon-intensive technologies in electricity generation.

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[44] Nugent and Sovacool (2014) employ critical evaluation criteria to narrow down the sample to 41 'best' representative studies, from which they determine average life cycle emissions estimates. They consider the life cycle as having five stages:
  • material cultivation and fabrication (which includes resource extraction, processing of materials, and amalgamation of final products),
  • construction (which includes transportation of materials to the site),
  • operation,
  • maintenance,
  • decommissioning (which includes deconstruction, disposal, recycling and land reclamation if applicable).
[45] For fossil fuels in power generation, life cycle emissions would typically include upstream and midstream processes.
[46] IPCC (2014, p.538) states that modern-to-advanced natural gas combined-cycle plants have emissions in the range of 410–650 gCO_2eq/kWh, while the use of CCS could bring this down to 65–245 gCO_2eq/kWh.

Table 2: Comparative life cycle estimates of GHG emissions per kWh of electricity – illustrative example

Technology	Capacity/Configuration/Fuel	Mean Estimate of gCO_2e/kWh
Hydroelectric	3.1 MW, reservoir	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW, run-of-river	13
Solar Thermal	80 MW, parabolic trough	13
Biomass	Forest wood co-combustion with hard coal	14
Biomass	Forest wood steam turbine	22
Biomass	Short rotation forestry co-combustion with hard coal	23
Biomass	Forest wood reciprocating engine	27
Biomass	Waste wood steam turbine	31
Wind	Various sizes and configurations	34
Biomass	Short rotation forestry steam turbine	35
Geothermal	80 MW, hot dry rock	38
Biomass	Short rotation forestry reciprocating engine	41
Solar Photovoltaic	Various sizes and configurations	50
Nuclear	Various reactor types	66
Natural Gas (Conventional)	Various combined cycle turbines	443
Natural Gas (Fracking)	Combined cycle turbines using fuel from hydraulic fracturing	492
Natural Gas (LNG)	Combined cycle turbines utilizing LNG	611
Fuel Cell	Fuel cell hydrogen from gas reforming	664
Diesel	Diesel various generator and turbine types	778
Heavy Oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1,050

Source: Nugent and Sovacool (2014)

Although wind and solar energy production emit carbon at least one order of magnitude less than most unabated fossil fuel technologies, no technology is totally emissions-free when assessed on the LCA metric (see Figure 3). Examples relate to land use and water use (for example biomass or solar farms) and, the demand for raw materials and rare earths (such as neodymium for wind turbine generators and copper for all renewable installations) (Capellán-Pérez et al., 2017; Havlík et al., 2011; Yang et al., 2012; Valero et al., 2018). Taking wind and solar PV as an example, gains in material efficiency at the cultivation and fabrication stage – which incorporates resource extraction, processing of materials, and

the amalgamation of final products – provide opportunities for further reducing life cycle emissions. This would intuitively apply to most other sectors. The decommissioning stage, which includes recycling, is accounted for in some studies as a means of mitigating future GHG production,[47] and thus of decreasing the total GHGs produced over the life cycle of the generator (Nugent and Sovacool, 2014). We later argue that this is not always the case for other sectors.

Figure 3: Life cycle emissions for wind and solar PV (% of total)
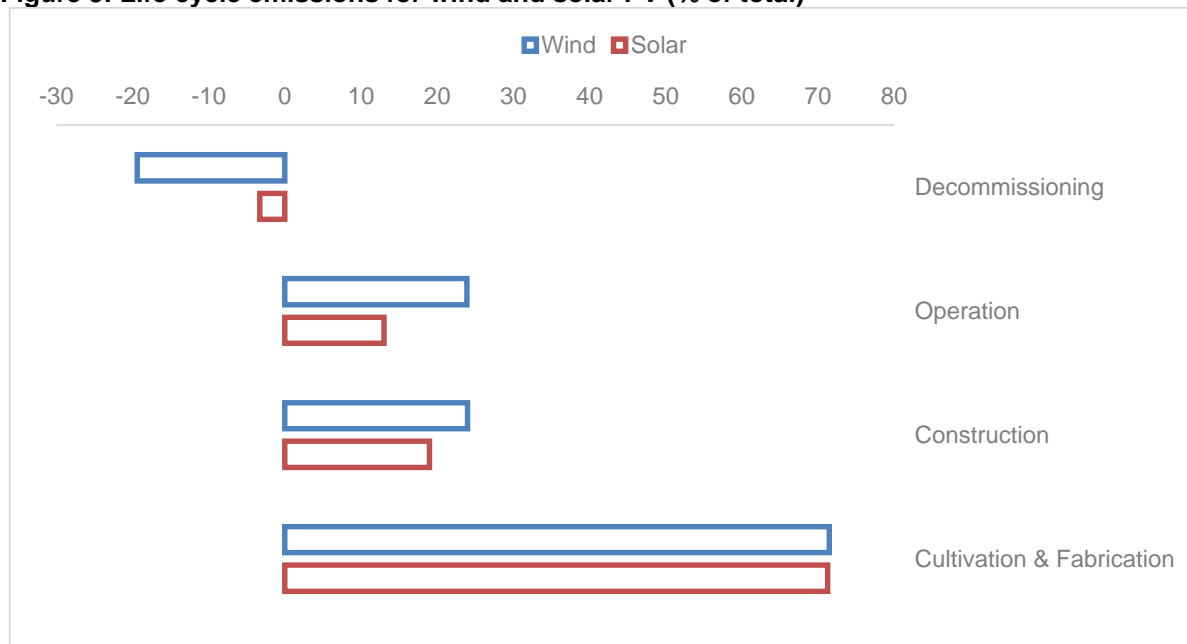
Source: Nugent and Sovacool (2014)

Extending the example of solar and wind supply chains (see Table 3), improvements in material efficiency through the different stages of the value chain across other energy-intensive industries can help mitigate emissions resulting from the increasing demand for materials that is driven by economic growth (IEA, 2018b). Such improvements could also potentially aid emissions reduction, by enabling more moderate deployment of other industry CO_2 mitigation levers, and by facilitating emissions reduction in hard-to-abate, intermediate-use, energy-intensive sectors (IEA, 2018b). This could potentially lead to a second-order effect in reducing overall life cycle emissions (which is especially pertinent in the case of hard-to-abate sectors).

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[47] As it offsets the need for producing/manufacturing new material. Around of 85–90% of the weight of a wind turbine is recyclable, but as the complexity of the composite material requires specific processes for recycling, the actual recycling rates are lower (Wind Europe, 2020).

Table 3: Material efficiency strategies

Stage of Supply Chain	Strategies
Design Stage	Using fewer materials to provide the same service; designing for long life could result in higher initial material demand but enable outweighing life-cycle emissions savings (e.g., bigger wind turbines).
Fabrication stage	Waste and overuse can be reduced when manufacturing materials, during production and in construction; substituting higher-emissions materials with lower-emissions materials.
Use stage	More intensive use and extending product or buildings lifetimes through repair and refurbishment can reduce the need for materials to produce new products.
End of life	Reuse can reduce new materials needs; recycling can enable lower-emission secondary production routes.

Source: IEA (2018b)

Beyond the energy sector, there is a substantial body of literature on how different material efficiency strategies can be applied at each stage of the supply value chains of energy-intensive, hard-to-abate sectors (see Figure 4), including those strategies that:

- reduce material demand,

- increase demand for some materials while enabling outweighing CO_2 emissions benefits at other stages of the value chain,

- shift to using lower-emission materials or lower-emission production routes.

The IEA's Clean Technology Scenario, [48] which aligns with the objectives of the Paris Climate Agreement, estimates that improved materials efficiency from a combination of the above methods applied to the steel, aluminium, and cement sectors could contribute 30 per cent of the combined emissions reduction for steel, cement, and aluminium by 2060, compared with a Reference Technology Scenario.[49]

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[48] The Clean Technology Scenario lays out an energy system pathway and a CO_2 emissions trajectory in which CO_2 emissions related to the energy sector are reduced by around three-quarters from today's levels by 2060 (IEA, 2018b).
[49] The Reference Technology Scenario accounts for current country commitments to limit emissions and improve energy efficiency, including nationally determined contributions pledged under the Paris Agreement (IEA, 2018b).

Figure 4: Scope for emissions reduction from materials efficiency improvements in the supply chain

(a)   (b)   (c)
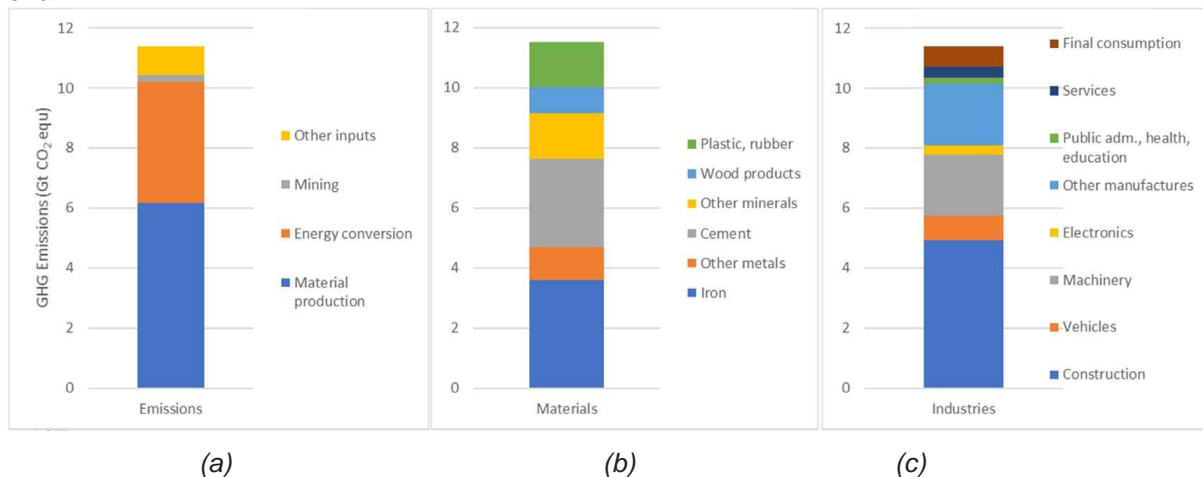
Note: Illustrative breakdown, based on data from 2015. (a) Source of GHG emissions, i.e., material production itself (scope 1), energy inputs (scope 2), mining or other purchases (scope 3). (b) Cradle-to-gate greenhouse gas emissions from the production of key materials in 2015, identified by material. (c) Material-related GHG emissions by industries using materials.

Source: Hertwich et al. (2019).

2.3   Conditions for circular economy

Many governments have announced or published 'circular economy roadmaps', some of which pre-date net-zero carbon goals.[50] These have set out objectives on resource efficiency, recycling rates, or disposal quotas – often pertaining to specific sectors such as food, energy, waste, and water. Although the circular economy has recently gained in popularity due to accelerated decarbonization goals, there are some fundamental questions around the conditions in which it can be beneficial at the economywide, which should be considered prior to implementation as a complement to existing decarbonization policies.

One fundamental question is related to the amount of energy that is required (and the corresponding level of emissions) to operate a circular economy versus a linear economy. This is especially pertinent, as empirical studies conducted at the macroeconomic level tend to argue that circular economy-enabling policies will have a positive impact on aggregate economic outcomes (OECD, 2017).[51] The circular economy approach has not been a stated policy goal per se; rather, it is the economic, environmental, and social gains that might accompany such a transition that have been of interest for governments (OECD, 2017). The answer to this question is context-specific, but there are some broad conditions for circular economy approaches that may need to be fulfilled for the process to lead to net economic *as well as* environmental benefits. One of these conditions, suggested in Boulding (1966), is cited as the origin of the phrase 'circular economy' – a circular economy can be achieved 'if global demand for both the volume and composition of products could be stabilised' (Allwood, 2014). In other

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[50] Examples include China (2013) and the EU (2008 Waste Directive; 2015 and 2020 Circular Economy Action Plans).
[51] For instance, a recent report assessing the state-of-the-art of Circular Economy in the EU-27 plus the UK associates it with significant macroeconomic gains – connecting it to gains in GDP, labour productivity, investment, and employment (Ambrosetti and Enel Foundation, 2020). The Ellen MacArthur Foundation argues that pursuing circular business models could help boost economic growth in Europe by 7 per cent by 2030 (EMF, 2015, 12).

words, a circular economy can be conceptualized as a system predominantly involving the management and optimization of existing stock, rather than one based on linear flows.

To this end, circular economy incentives within firms and organizations may not always lead firms to reduce energy use, or to a net environmental benefit at the economywide level (Whalen and Whalen, 2020). For instance, Allwood (2014) provides comprehensive examples for some 'hard-to-abate' sectors in which recycling[52] could lead to negligible benefits, or conversely to unintended effects. These include:

- Recycling cement would require energy inputs comparable to making new cement.

- The energy used to separate critical metals that are used in compounds as part of a recycling process may be greater than the energy needed for virgin production.

- The recycling of plastics is constrained because the variety in their composition (which is also ironically the most attractive property of plastics) increases the complexity of the process (including energy used) of recycling them.

- Although steel has one of the highest rates of recycling (up to 90 per cent), recycled steel contributes only around a third of current steel demand because of the higher rate of demand growth for steel.

In reality, a circular economy in its purest intended form may never be practically achievable, but one argument for its implementation as a complement to existing decarbonization instruments is that even a partial increase in the current levels of circularity in the global economy could aid in getting to net-zero carbon targets that are consistent with limiting temperature rises.[53]

Regardless of the benefits assumed by partial or complete circularity, from an economic point of view there is a strong case for the establishment of clear public policy frameworks to ensure that circular economy approaches can complement decarbonization policies, and also that these approaches, particularly when adopted at the organizational or sectoral level, do not result in net negative impacts on decarbonization at the macro level (for example from the spillover of unintended consequences). Whalen and Whalen (2020) and Zink and Geyer (2017), for instance, identify a potential 'circular economy rebound effect' that could occur in the absence of a cohesive framework. For instance:

- Secondary goods can be created through circular economy approaches (for example refurbished goods) that do not compete with the production and sale of primary goods, resulting in a net increase in production and consumption (and of energy).

- On the other hand, secondary goods might compete directly with primary goods, causing prices to fall and triggering income and substitution effects that cause increased overall consumption of those goods (and energy).

- Specific strategies adopted by business could create constraints to circularity – for example, product-leasing strategies could impede materials efficiency by restricting second-hand market activity.

Public policy frameworks are therefore necessary to create the institutional conditions to incentivize circular economy approaches within organizations and sectors, while also mitigating negative externalities or spillover effects at the economywide level. These frameworks could, for instance, aid by extending business time horizons, internalizing externalities, promoting the diffusion of best practices in the production and management of resources, and encouraging the use of standardized indicators

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[52] Almost all recycling processes work by breaking down a solid waste stream into a liquid, which is then purified (Allwood, 2014).

[53] Circle Economy (2021) states that adding a further 8.4 per cent to the current 8.6 per cent level of circularity of the world economy could, along with current emission reduction pledges, bring the world below a 2°C path by 2032.

for measuring circularity (Whalen and Whalen, 2020). Based on the above, public policy frameworks could enable some broad conditions for circular economy, including:

1. The more intensive use of an existing (or reduced) stock of resources.

2. The development of secondary markets to aid circular flows.

3. Mechanisms/measures to prevent or mitigate unintended consequences or circular economy rebound effects.

3. Framework of economic signals to incentivize further decarbonization through the circular economy

Following from the above, circular economy approaches could be aided by the development of a cohesive public policy framework of incentives to:

- enhance decarbonization (alongside existing measures),
- optimize material flow,
- minimize waste across supply chains.

The types of existing policy signals can be broadly categorized into:

- incentive mechanisms that promote market-based outcomes (such as carbon prices, emissions trading systems, and tradable permits or standards),
- regulatory incentives (for example industry-specific regulations, technology mandates, or non-tradable performance standards).

Although there is an existing set of policy instruments aimed at incentivizing decarbonization across countries, in practice, no major market economy has achieved a cohesive set of policy measures to incentivize 'full' decarbonization (Day and Sturge, 2019). Most countries have a mix of policy signals (including taxes, subsidies, standards, and regulations) which give rise to uneven incentives to reduce carbon (and other GHG) emissions across their economies. An effective framework of policy signals would ideally reflect some key consistent features (Stahel, 2013) such as:

- applying to emissions across the supply chain,
- correctly pricing in externalities,
- incentivizing accurate and cost-effective emissions measurement, verification, and reporting.

Policies to drive circular economy transitions at the macro level are also likely to result in structural shifts involving the decline of certain sectors and the rise of others, with potential reallocations of capital and labour (OECD, 2017). A public policy framework would therefore need to include mechanisms which mitigate any negative effects.
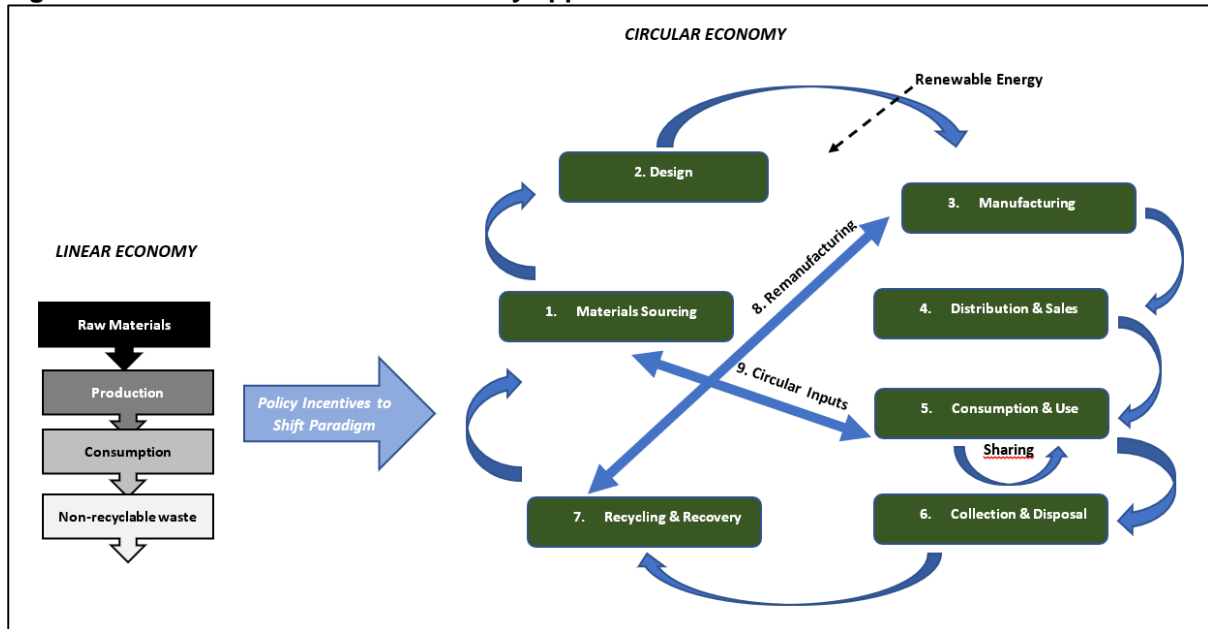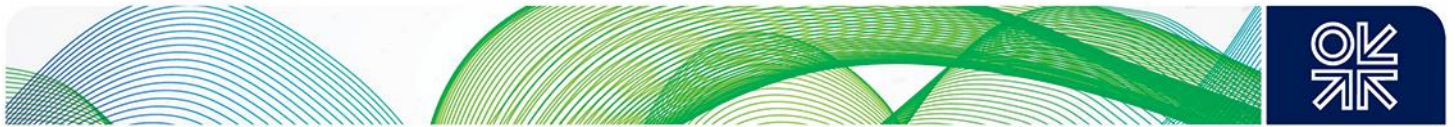
Figure 5: Linear versus circular economy approaches

Source: Kalmykova et al. (2018); Govt. of the Netherlands (2017)

Table 4 synthesises the circular economy objectives and metrics that have been used by companies and organizations, and attempts to map them onto existing policy measures that create economic incentives to induce shifts in the current linear paradigm (also see Figure 5). Column 1 of the table represents the key features of circular economy:

- efficiency,
- substitution,
- durability,
- ecodesign,
- increased intensity of use (through consumer choice and a focus on services),
- recyclability,
- industrial symbiosis.

Column 2 summarizes the relevant objective. Column 3 details metrics commonly used at the organization level. Column 4 represents complementary instruments of decarbonization. Column 5 illustrates some country examples.

3.1 Market-based incentives

Amongst market-based incentives in Table 4, *carbon prices* penalize the negative externalities according to the 'polluter pays' principle; energy producers and consumers internalize the costs of carbon-intensive fuels and activities, and the use of low- and zero-carbon energy sources and activities is encouraged. They also help to equate the marginal abatement cost of all sources of emissions (Blazquez and Dale, 2020). Economy-wide carbon prices have proved difficult to implement thus far and what exists in most countries is a 'patchwork mix' of taxes (such as VAT and excise duties) and subsidies (for example feed-in tariffs and agricultural subsidies). Day and Sturge (2019) distil these

taxes and subsidies to compute 'effective carbon prices' [54] for different fuels and economic sectors/activities in the UK and argue that they are too low to incentivize emissions reduction, particularly in sectors such as residential gas, agriculture, and aviation.[55] Explicit carbon prices are imposed through cap-and-trade schemes, in which the total allowable emissions in a country or region are set in advance; permits to emit are created to match these and are then allocated or auctioned to companies, which then trade permits, creating a market to achieve emissions reduction at least-cost (Bowen, 2012). The effectiveness of cap-and-trade schemes can be constrained by the fact that the carbon price set by the scheme needs to be sufficiently high to encourage behavioural change, and the scheme itself should be wide enough in its scope and coverage to prevent carbon leakage[56] (Bowen, 2012). These constraints often mean that governments may intervene to re-set allocations or introduce secondary measures to mitigate leakages, potentially undermining the long-term credibility of the market.[57] In Table 4, carbon prices and carbon-related efficiency trading schemes are signals to incentivize *efficiency* and *substitution*; however, in contrast with a linear approach in which incentives (such as carbon allowances or credits) are provided to reduce emissions, in a circular model, mechanisms could be designed to minimize and then prevent emissions (Stahel, 2013).

Fiscal incentives offer an alternative set of market-based incentives to enable the optimization of existing stock. For instance, taxing negative externalities at the ends of the supply chain could make resources relatively costlier upstream; in theory, this might stimulate greater reuse and recycling of materials,[58] and stimulate circular approaches downstream (for example through recycling). However, this approach is not without tradeoffs, Day and Sturge (2019) argue, for instance, that any such changes should be accompanied by policy measures to improve efficiency and stimulate innovation. Similarly, it has been argued that lower VAT rates on labour-intensive services could incentivize repair and reuse, and reduce waste (Bock, 2017). Fiscal incentives could be applied in the context of decarbonization to incentivize *durability*, *ecodesign*, *increase the intensity of use*, and *recyclability*. The caveat to these measures is the assumption that consumers will respond to these in a rational or expected manner which, evidence suggests, is not always the case (this is discussed further in Section 4).

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[54] A measure of how much a firm or an individual is paid or rewarded per tonne of carbon (or CO_2e) saved when they make a choice that lowers emissions.

[55] For instance, because VAT on some of these sectors/activities was relatively low (Day and Sturge, 2019).

[56] Polluting companies may move to jurisdictions which lie outside the borders of the scheme. This reduces the effectiveness of unilateral or multilateral carbon pricing (Blazquez and Dale, 2020).

[57] This was the case with the initial launch of the EU Emissions Trading Scheme, which was later remedied to correct for leakages and distortions. Similarly, under India's PAT scheme, market participants who overachieve efficiency targets are issued certificates equivalent to 1 tonne of savings, which they can trade. Early rounds of the PAT yielded low market clearing prices, indicating a potential oversupply of certificates.

[58] In this aspect, the circular economy does not differ from the industrial economy and can benefit from efficient markets matching supply with demand for the service-life extension of goods – processes such as component repairs, remanufacturing and upgrading, and remarketing goods and components (Stahel, 2013).

Table 4: Mapping circular economy metrics from organizations onto existing government policy incentives – a framework

Component of circular economy (1)	Objective (2)	Organization-specific metrics (3)	Existing government policy incentives (4)	Select country examples (5)
Efficiency	Reducing the use of energy and materials in production and use phases.	▪ *Materials price variation.* ▪ *Material supply chain risks.* ▪ *Standard material recovery rates.* ▪ *Mass of material inflows defined as 'critical' or 'scarce' as % of the total mass of linear inflows.* ▪ *Value (revenue) a company generates per unit of linear inflow.* ▪ *Energy usage & CO$_2$ emissions; Water usage.*	▪ *Energy efficiency trading schemes.* ▪ *Performance-based standards.* ▪ *Carbon pricing.* ▪ *Cap-and-trade schemes.*	India's Perform–Achieve–Trade (PAT) scheme – a cap-and-trade certificates system – covers individual industry plants that cross a threshold of energy consumption. Specific energy consumption (SEC) reduction to be attained within a particular PAT cycle.
Substitution	Reducing the use of materials that are hazardous or difficult to recycle in products and production processes.	▪ *Renewables as % of energy consumption.* ▪ *Monitoring/reducing the mass of material inflows defined as 'critical' or 'scarce' as a percentage of the total mass of linear inflows.* ▪ *Monitoring material toxicity.* ▪ *Energy usage & CO$_2$ emissions, Water usage.*	▪ *Carbon pricing.* ▪ *Cap-and-trade schemes.* ▪ *Renewable purchase obligations.* ▪ *Renewable support schemes.*	EU Emissions Trading Scheme (ETS) – EU carbon markets saved cumulative emissions of about 1.2 billion tons CO$_2$ from 2008–16, or roughly 3.8% relative to total EU emissions – with the major impact in power generation (Bayer and Aklin, 2020).
Durability	Lengthening products' useful life.	▪ *Material potential and actual recovery (see above).*	▪ *Depreciation accounting.* ▪ *VAT rates.*	Sweden and Luxembourg apply lower VAT rates to the repair of certain goods in the economy to prolong their use.

Component of circular economy (1)	Objective (2)	Organization-specific metrics (3)	Existing government policy incentives (4)	Select country examples (5)
Ecodesign	Designing products that are easier to maintain, repair, upgrade, remanufacture, or recycle.	▪ *'Recovery potential' (can be improved through optimizing design).*	▪ *Performance Based Standards.* ▪ *VAT rates.*	EU Ecodesign Working Plan: 28 ecodesign regulations; 16 energy labelling delegated regulations in support of material efficiency requirements, such as availability of spare parts, ease of repair, and facilitating end-of-life treatment.
Increased intensity of use (including consumer choice and focus on services)	Increase the intensity of use of goods by encouraging wider and better consumer choice through renting, lending, or sharing services as an alternative to owning products, while safeguarding consumer interests.	▪ *Material potential and actual recovery (can be improved through adopting new business models – e.g., product-as-a-service or buyback/take-back scheme – or collaborating with value chain partners that drive circularity).* ▪ *Share of sustainable products in portfolio.* ▪ *Customer attitude towards green products.*	▪ *Product subsidies.* ▪ *VAT rates.* ▪ *Carbon labelling programmes.* ▪ *Depreciation accounting.*	EU 'Product Environmental Footprint' Methodology. USA, Peru, Taiwan, Italy, Costa Rica, France, South Korea, Thailand, and Japan are developing or have established 'carbon footprint labelling programmes' – although these are voluntary initiatives in most countries, offered to products and organizations. France's 2019 LOM (Mobility Orientation Law) contained a package of fiscal and regulatory measures to catalyse shared mobility and Mobility-as-a-Service in the automobile sector.

Component of circular economy (1)	Objective (2)	Organization-specific metrics (3)	Existing government policy incentives (4)	Select country examples (5)
Recyclability	Incentivizing separation, collection systems that minimize the costs of recycling and reuse. Creating markets for secondary raw materials (i.e., 'recyclates'). Incentivizing and supporting waste reduction and high-quality separation by consumers.	▪ *Minimizing the use of virgin feedstock.* ▪ *Avoiding unrecoverable waste.* ▪ *Altering linear flow.* ▪ *Recycling rates & recycling efficiencies.*	▪ *Recycling standards.* ▪ *Public procurement policies.* ▪ *Taxation of waste.* ▪ *VAT rates.* ▪ *Changes in depreciation accounting.* ▪ *Renewable support schemes.*	US Sustainable Materials Management Program Strategic Plan focuses on reducing life cycle environmental impacts of materials (EPA, 2015). China's objective of reusing 72 per cent of industrial solid waste (Mathews and Tan, 2016). China's government introduced VAT incentives for the circular use of materials, such as agricultural, industrial, and domestic waste. Sweden and Luxembourg apply lower VAT rates to the repair of certain goods in the economy to prolong their use.
Industrial Symbiosis	Facilitating the clustering of activities to prevent by-products from becoming wastes.	▪ *Material potential and actual recovery (can be improved through adopting new business models – e.g., product-as-a-service or buyback/take-back scheme – or collaborating with value chain partners that drive circularity).*	▪ *Carbon border adjustment mechanisms.* ▪ *R&D support.*	Kalundborg (Denmark): an oil refinery, a power station, a gypsum board facility, and a pharmaceutical company, share ground, surface & waste-water, steam, and fuel, and also exchange a variety of by-products that become feedstocks in other processes.

Source: Based on EC (2014); EMF (2012a; 2012b; 2020); WBSCD (2020); Enel (2018)

Market-based mechanisms currently being discussed around curbing leakages through embodied emissions (for example from energy installations and the supply chain), and also potentially incentivizing *industrial symbiosis* within circular systems (in other words, the sharing of resources between industries/sectors within an economy) include carbon border adjustments. Assuming the 'border' is a national one, at the basic level, these are mechanisms which adjust the costs of imports and exports in a manner that takes account of differences in carbon prices. These mechanisms have been debated from different perspectives: one views them as a way of avoiding trade distortions and increasing the effectiveness of domestic carbon price policies; while another views them as a protectionist measure with unfair consequences for developing nations (Blazquez and Dale, 2020). Concerns have been raised by developing countries that lack carbon pricing mechanisms over the impact on the competitiveness of their exports and solutions are needed to address this. Examples of some proposed solutions include recycling a portion of the revenues into a fund that mitigates negative impacts for developing countries, and full or partial policy coordination with third countries (Falcao, 2020).

3.2 Standards and regulations

Table 4 shows that the balance of existing policy incentives currently leans towards standards and regulations, although these come with trade-offs (discussed in Section 4).[59] Standards and regulations can be used in stimulating the transition to circular economy approaches in countries which do not have fully developed markets or market mechanisms. For example, Renewable Purchase Obligations, encouraging *substitution*, were responsible for the early uptake of renewable electricity in developed and developing countries. Non-tradable performance-based standards (as opposed to prescriptive standards) could be used to incentivize *efficiency* and *ecodesign* in a circular economy (for example with regards to energy installations) – the drawback being the high transaction costs of monitoring and compliance, which require close coordination between governments and industry (IEA, 2018b), in addition to well-developed institutions.

Changes in depreciation methods may incentivize *durability* and *recyclability*, as well as a shift towards a *services-based* model; they could also aid the development of second-hand markets for products, increasing their value and preventing them from being depreciated to zero (Bock, 2017).[60] Similarly, life-cycle carbon accounting in the supply chain – for instance, to take into account the decommissioning impact of unused equipment with no residual life, and the relocation of used equipment to a different utilization setting (for example second-life batteries) or geographical area – could incentivize the same three parameters. Public procurement could be an additional way to incentivize *efficiency* and *recyclability*; government procurement of products with low embodied carbon could then also stimulate demand (for example, applying similar standards to areas of regulation such as building codes could incentivize contractors to build to low-carbon specifications (IEA, 2018b)).[61] Standards that take into account their environmental impact could also be specified for energy installations – for instance, Parrique et al. (2019) discuss the 'energy return on investment' (the ratio of the quantity of energy obtained from a resource to the quantity of energy that must be spent to extract it) as a possible metric. This is a measure of net energy output, differentiating between the costs and surplus of energy; a declining return means that an increasing portion of energy output must be allocated to obtaining

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[59] An obvious disadvantage of non-market approaches is the information asymmetry faced by policymakers while enforcing these standards or regulations.

[60] This also brings up the issue of when in the life cycle a reusable resource should be taxed. One proposal has been to impose VAT on material resources only once, and then on net margins (instead of gross margins) from its recirculation in the economy (Bock, 2017).

[61] For instance, the Netherlands instituted embodied carbon reporting in 2013. It requires whole-building LCA at the buildings permitting stage, facilitated by a national Environmental Product Declaration database and a standardized LCA method. A mandatory cap was adopted in 2018 for the 'environmental profile' of new homes and offices. The environmental profile translates multiple criteria, including embodied carbon, into a single measurable metric (IEA, 2018b).

energy, which means an increase in resource use and impacts. Several countries are developing, or have established, 'carbon footprint labelling programmes'.[62] These are voluntary initiatives in most countries and they are offered for products and organizations; net-zero carbon policies could see countries scaling up these programmes into tradeable carbon standards (Day and Sturge, 2019). 'Green' labelling and certification programmes are gaining prominence within policy frameworks; the ISO-certified voluntary 'Ecolabel' programme in the EU, and India's 'star labelling' programme for consumer appliances are examples of such schemes.

4. Barriers to implementation

From the discussion above, it is evident that circular economy strategies complement decarbonization policy, and can potentially be integrated into the latter by exploiting the synergies between metrics that are typically used to measure circularity within specific organizational contexts, and the wider set of instruments of decarbonization policy. However, in practical terms there are barriers to their implementation. We outline three main barriers below.

4.1   Government regulations

As discussed earlier in the paper, one condition for achieving circular economy is if global demand for both the volume and composition of products can be stabilized.

In contrast, prevailing government regulation is still dominantly oriented towards the linear model of economic operation and hence linear decarbonization. Most regulation aims at enabling decarbonization through least-cost methods, but without fully internalizing the costs of externalities. This means that technologies and their underlying supply chains are optimized for a linear model – that is, to minimize the cost in a predominantly 'take-make-waste' system. This has several implications.

First, in a linear paradigm, the different components of the circular economy (outlined in Column 1 of Table 4 above) tend to push in opposite directions and generate the need for undesirable trade-offs. For instance, *efficiency* trades-off with *durability* and *ecodesign*, as efficiency is a cost-driven parameter.[63] Similarly, *consumer choice* trades-off with *recyclability* – as the limits of recyclability in a linear paradigm can act as a constraint to consumer choice (for example, recycling in some hard-to-abate sectors can lead to negligible benefits or to unintended consequences such as higher energy use, as discussed in Section 2.3). The relatively higher costs of labour vis-à-vis the lower cost of bulk materials in some developed countries has led to a situation in which excess materials are used to allow a saving in labour costs (Allwood, 2014).

Second, the implementation of market-based incentives to stimulate economic incentives in one area often leads to distorted incentives and unintended adverse impacts in other areas. For example, measures imposed at the end of the value chain (such as taxes) with the intended effect of reducing wastage or emissions or other negative externalities, could distort an agent's economic incentives, impeding the creation of a closed loop. This is seen from evidence that imposing high taxes on the disposal of waste has, instead of minimizing waste, led to higher levels of illegal landfill in many countries (Matheson, 2019).[64] As discussed earlier, in a linear model, incentives to stimulate energy efficiency could create a rebound effect, leading to an increase of consumption of the same product or service, or to a reallocation of 'freed' resources to other types of carbon-emitting activity. Similar issues affect the application of regulations to the circular economy: for instance, secondary markets could be impeded by regulations that can increase the transaction costs for market participants, or which could

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[62] For instance, USA, Peru, Taiwan, Italy, Costa Rica, France, South Korea, Thailand, and Japan.

[63] For example, what is efficient design for a certain lifetime may not be robust enough for a longer duration.

[64] To this respect, it may be observed that appropriate waste disposal is lawfully enforceable. Nevertheless, this is not easily done and could entail an additional cost on society.

themselves pose a barrier to circularity by generating additional demand. Likewise, the main criticism of standards and regulations imposed under the linear, energy production-focused model, is that regulations can often be overly prescriptive, leading to negative environmental externalities.[65]

The focus on costs as the primary incentive for such policies implies that the cheapest options with regards to energy and material resources (or those that are heavily subsidized) have been deployed first. While this focus has successfully reduced emissions, it has meant that the deployment of the remaining options then becomes more complex, more technologically demanding, potentially more socially disruptive, and generally more expensive (Parrique et al., 2019).

4.2   Consumer behaviour and expectations

Decisions made by the final consumer affect the amount of energy embodied in products; they also have the potential to reduce energy demand, contributing to the conditions required for a circular economy to develop, suggesting a more intensive use of a reduced stock of products relative to the linear economy (Barrett et al., 2018). However, consumer behaviour and expectations are a major barrier to achieving this. Alternatives that are rational or optimal from an environmental and economic standpoint may not be preferred by consumers because of many factors. These include:
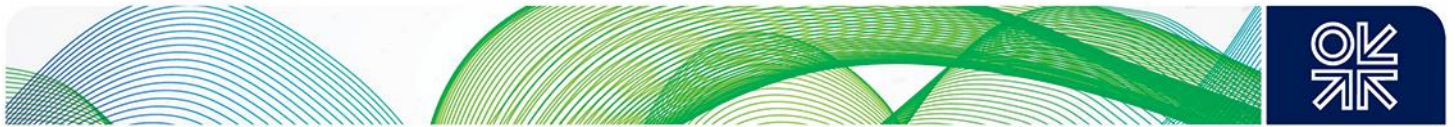
- higher upfront costs to cover externalities generated from consumption,

- simplicity (consumer understanding of various alternative options),

- timing (upfront incentives that reduce point-of-sale costs versus future incentives),

- coverage (if incentives are made available only to a subset of consumers, they may be less effective),

- certainty (over whether certain incentives will be continued or not).

For instance, taking the example of decarbonization of transport, the evidence shows that the design of EV uptake policies to decarbonize the sector faces structural barriers with regards to consumer expectations. EV sales in some countries[66] have dropped sharply when purchase incentives were withdrawn, indicating that existing economic incentives on their own may be insufficient to promote EV uptake at the desired pace – one argument is that the incentive structure in itself is inappropriately targeted. The EV supply chain is being designed around the personal passenger vehicle paradigm which fits with a linear economy, whereas a circular economy paradigm in transportation would be based around incentivizing consumers to utilize both the existing stock of EVs, as well as other shared decarbonized transport options, to full capacity.

A study on consumer engagement in the circular economy (EC, 2018) found that in choices between repair or replacement with a new product, or between replacement with a second-hand or a new product, the most important factor determining consumer behaviour was the price–quality ratio of the two options (in other words, new products were always preferred if the circular option did not offer a significant cost reduction). The second most important factor was the transaction cost (namely the difference in 'effort' required between the two options), which is also a barrier to incentivizing the circular economy. Other barriers in relation to incentivizing consumers to choose service-based consumption options include low levels of information, a lack of interest in service-based models, and 'mistrust' (EC,

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[65] For example, many specifications of concrete require a minimum cement mass content in concrete that some argue exceeds what is necessary to achieve concrete strength and durability requirements (Wassermann et al., 2009; IEA, 2018b). However, it should be noted that in some cases these margins may be included for safety reasons. Allwood (2014) states that the embodied energy of construction is, for example, underused through excess capacity, and is also underexploited – e.g., buildings which are designed to last for 100 years are replaced on average every 40 years in the UK or every 20 years in China.

[66] For example, India; the USA (California); China.

2018). Standards, regulations, and the availability of consistent product information can be a way of removing barriers relating to consumer behaviour and expectations – in effect, these methods could narrow the boundaries of consumer choice to a range that is more compatible with the required conditions for circular economy.

4.3   Business models

Another structural barrier is the absence of a dominant business model encapsulating the main components of the circular economy approach to decarbonization. Although many organizations have circular approaches integrated into their daily operations from the point of view of optimizing their internal operational efficiency and sustainability, strategic business models form an important external function – they align government policy signals with consumer behaviour and expectations. In other words, the linear economy does not lend itself to a business model that essentially says 'make less' (Gilbert et al., 2017). For instance, Allwood (2014) highlights the fact that while the optimization of individual components for specific products or services could improve material efficiency, this does not make commercial sense in the linear business model paradigm as economies of scale favour the production of standardized components – the more specialized a material is, the harder it is to recycle. The circular economy would require entirely different business models that widen out and integrate the whole supply chain.

One potential taxonomy of circular economy business models that has been proposed is based on the degree of adoption of circularity along two major dimensions:

I.   the value network, in other words, interactions with suppliers in the value chain and reorganizing internal activities around this,

II.   the customer value proposition and interface, namely the implementation of the circularity concept in proposing value to customers (Urbinati et al., 2017).

As an example of the first dimension, we draw on the ship-building industry from Gilbert et al. (2017) discussed in Section 2: circular economy conditions would require steel producers to adopt a more service-based business model – producing steel plates, and then reusing, redistributing, re-manufacturing, and reforming instead of remelting scrap to produce new steel components. From a technical and safety perspective there are key barriers that need addressing within the sector (also applicable to other sectors in a similar way): a vessel's hull would require to be designed for dismantling to improve reuse; the operation and maintenance schedule must ensure that the value of the steel is retained; and data must flow between key stakeholders on the quality of the steel. Certain commercial questions need to be ascertained and resolved – for example the retained value in the material (steel) after the product itself reaches end-of-life, and the ownership of this retained value (in this instance, for the ship-building example, whether it would be the investor, steel producer, or ship owner).

Examples of circular business models which reflect the second dimension include pay-per-use busines models, which generate value proposition and income by matching consumers with products or other assets that are not being used to full capacity (Whalen and Whalen, 2020). Examples include ride-sharing services, car-sharing services, and battery-leasing services. Another model relates to product life extension – enterprises which incorporate this into their operations do so through offering services around such areas as product refurbishment, re-trade, reuse, repair, recondition, and re-build. Fundamentally, circular economy business models imply that companies benefit from selling the service of using a product, rather than selling the product itself *and* consumers must be persuaded to prefer this option.

In the energy sector, Energy-as-a-Service (EaaS) and Heat-as-a-Service (HaaS) provide emerging examples of potential 'big' business models suited to the circular economy approach – for example, a shift from selling kilowatt-hours to selling heating as a 'service-based product' – but these are yet to

achieve significant scale. Under HaaS, customers are charged for 'warmth' rather than heat generated. Customers have a contract with an Energy Service Provider (ESP) who, in exchange for a fixed price, provides them with an outcome: a home heated to the temperature they want at the times they require it (ESC, 2019). In return for reducing their exposure to high energy bills, the ESP then takes some control over customers' heating systems. A simulated study of HaaS for UK consumers (ESC, 2019) concludes that ESPs potentially found savings of up to 3 per cent on the cost of supplying energy to its customers; this was combined with a small reduction in peak electricity demand, potentially reducing the need for network reinforcement. Barring any rebound effects, this would have implications for reducing emissions as well. In the transport sector, as customers appear not to make their choices according to the total cost of ownership (Wu et al. 2015), the promotion of Mobility-as-a-Service, or lease plans as an alternative to car ownership, could unlock commercial value propositions and drive consumer choices towards EVs.

5. Conclusion

There has been a recent acceleration of ambitions on decarbonization, with numerous countries adopting targets to achieve net-zero carbon emissions by the middle of this century. Although the predominant policy approach to decarbonization over the past two decades – the replacement of fossil fuels with renewables in power generation, and improvements in energy use efficiency – has contributed the largest proportions of offsets to CO_2 emissions from economic growth in recent years, there are two reasons why this approach may leave some sectors un-decarbonized in the context of accelerated ambitions. First, there is evidence that direct electrification may not be possible, for technical and/or economic reasons, in 'hard-to-abate' sectors outside of electricity generation. Decarbonization in these sectors will require costly rebuilds and retrofits, and the additional costs could render some products uncompetitive on world markets. And second, the predominant approach to decarbonization has disregarded the globalization of trade and supply chains and the spatial dissociation between places of extraction, production, and consumption. In the current 'linear' decarbonization model, a sole focus on the reduction of emissions from energy production is likely to be insufficient to achieve net-zero objectives, as emissions would need to decline very rapidly to offset the expansion in economic output, which is not the case at present.

In this paper, we asked what *other* solutions (beyond the predominant focus on energy production) can be used to enhance decarbonization in order to meet net-zero carbon targets? The circular economy – a traditional concept in the economics of production and management of resources – has recently risen in the agendas of policymakers as an additional way of enhancing decarbonization through non-energy means. The concept was originally adopted with the aim of improving short-to-medium-term efficiency (such as allocative and technical efficiency) in the operations of large organizations, but was later extended to include sustainability (the decoupling of financial growth from a dependence on finite material resources). There is significant scope for circular economy approaches in aiding the decarbonization of electricity generation and use, based on life cycle emissions reduction. Circular economy approaches can therefore be a strong complement to existing policies in enhancing decarbonization.

This paper then looked at the implementation of circular economy approaches. Organizations have developed their own metrics to implement circular economy approaches. However, there are some broad conditions that need to be met in order for circular economy to lead to net economic *as well as* environmental benefits, when extended to an economywide level. These include: the more intensive use of an existing stock of resources; the development of secondary markets to aid circular flows; and mechanisms/measures to prevent or mitigate unintended consequences or circular economy rebound effects. There is a strong case for the establishment of clear public policy frameworks to ensure that circular economy approaches can complement decarbonization policies, and also that these approaches, particularly when adopted at the organizational or sectoral level, do not result in net negative impacts on decarbonization at the macro level (for example from the spillover of unintended
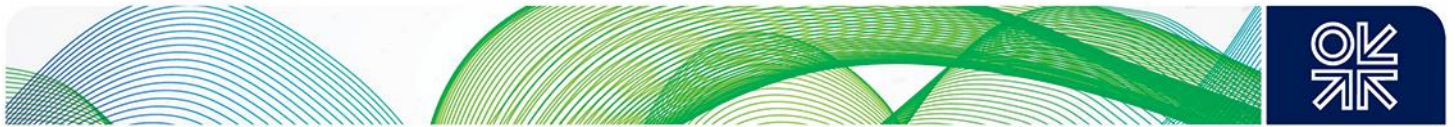
consequences, which were discussed in this paper). Such frameworks could exploit synergies between metrics that are used to measure circularity within specific organizational contexts, and the wider set of existing instruments of decarbonization policy, including market-based incentives and regulatory incentives, as set out in this paper. However, in practical terms there are barriers to their implementation, including: the fact that prevailing government regulation is still dominantly oriented towards the linear model of economic operation and hence linear decarbonization; the complexity of consumer behaviour and expectations; and the absence of a dominant business model encapsulating the main components of the circular economy approach to decarbonization.

However, circular economy approaches implemented through cohesive public policy frameworks, as described in this paper, should become an inherent and integrated part of the existing instruments of decarbonization, as they could potentially fulfil the dual functions of efficiency and decarbonization during the energy transition (namely reducing costs as well as reducing emissions). Moreover, given their original underpinning objective of improving allocative and technical efficiency, circular economy approaches will continue to be relevant even beyond a time when full decarbonization has been achieved, by playing their traditional function of improving efficiency – ultimately making the adoption of circular economy policies a 'no-regrets' strategy for governments.

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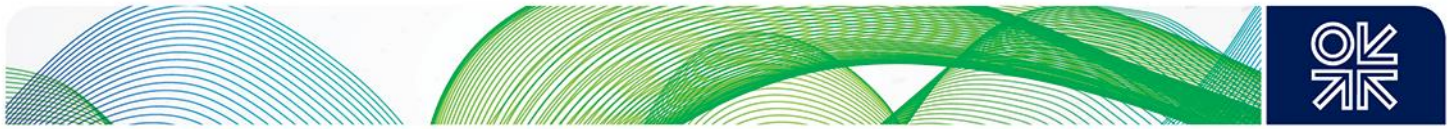
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