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

[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

[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.

[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.

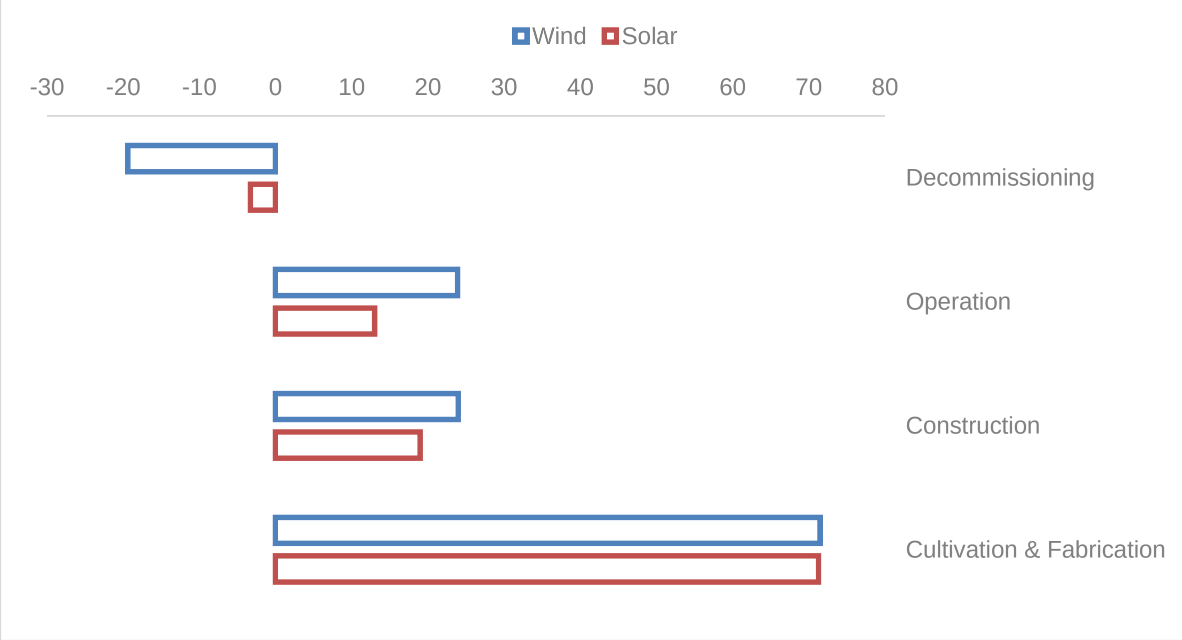
Table 2: Comparative life cycle estimates of GHG emissions per kWh of electricity – illustrative example

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).

[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)

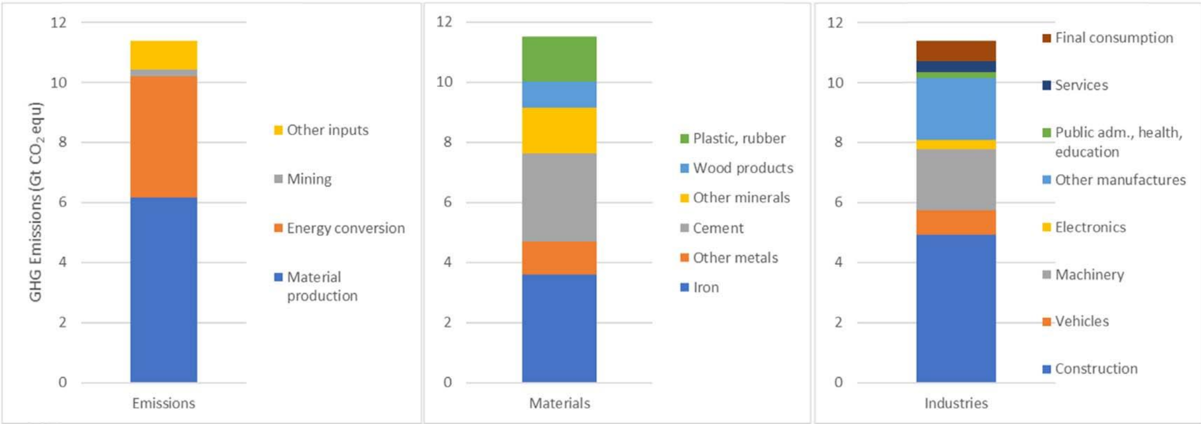
Beyond the energy sector, there is a substantial body of literature on how different material efficiency strategies can be applied at each stage of the supply value chains of energy-intensive, hard-to-abate sectors (see Figure 4), including those strategies that:

- 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]

[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

[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

[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.