

How Circular is the Global Economy?

An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005

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Summary

It is increasingly recognized that the growing metabolism of society is approaching limitations both with respect to sources for resource inputs and sinks for waste and emission outflows. The circular economy (CE) is a simple, but convincing, strategy, which aims at reducing both input of virgin materials and output of wastes by closing economic and ecological loops of resource flows. This article applies a sociometabolic approach to assess the circularity of global material flows. All societal material flows globally and in the European Union (EU-27) are traced from extraction to disposal and presented for main material groups for 2005. Our estimate shows that while globally roughly 4 gigatonnes per year (Gt/yr) of waste materials are recycled, this flow is of moderate size compared to 62 Gt/yr of processed materials and outputs of 41 Gt/yr. The low degree of circularity has two main reasons: First, 44% of processed materials are used to provide energy and are thus not available for recycling. Second, socioeconomic stocks are still growing at a high rate with net additions to stocks of 17 Gt/yr. Despite having considerably higher end-of-life recycling rates in the EU, the overall degree of circularity is low for similar reasons. Our results indicate that strategies targeting the output side (end of pipe) are limited given present proportions of flows, whereas a shift to renewable energy, a significant reduction of societal stock growth, and decisive eco-design are required to advance toward a CE.

Introduction

While resource use globally is growing at high rates and has even accelerated in the last decade (Schaffartzik et al. 2014), it is becoming evident that the scale of humanity's metabolism is unsustainable and must be reduced. The material and energy resources required to extend the current metabolic pattern of the industrial countries to the rest of the world are most likely not available, nor are the capacities of global ecosystems sufficient to absorb the outflows of industrial metabolism (UNEP 2011a; WBGU 2011). In this context, the notion of a circular economy (CE), in which material flows are made up either of biological materials, which after discard are available

for ecological cycles, or of materials designed to circulate within the socioeconomic system (SES) with reuse and technical recycling as a key strategy (GEO5 2012), has gained momentum. In the debate about pathways toward a more sustainable industrial metabolism, the CE appears to be a promising strategy to meet the environmental and economic challenges of the early twenty-first century and define targets of sustainable resource use (Allwood et al. 2010; Chen and Graedel 2012; Ellen MacArthur Foundation 2013; Hislop and Hill 2011; Mathews and Tan 2011; Moriguchi 2007; Preston 2012). The CE is promoted by many governments and international organizations and is considered instrumental in the mitigation of greenhouse gas emissions (e.g., EC 2012; PRC 2008; METI 1991).

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In response to signs of resource depletion and sharp increases in both prices and related volatilities of raw material supply, promoters of the CE further argue that increasing the circularity of the physical economy is indispensable for maintaining future resource security (e.g., Hislop and Hill 2011).

A critical examination of the literature on the CE reveals a lack of precise definitions and criteria for assessing measures to improve the circularity of the economy. In this article, we refer to a simple definition used, for example, in the United Nations (UN) GEO5 report, which states that, in a CE, material flows are either made up of biological nutrients designed to re-enter the biosphere, or materials designed to circulate within the economy (reuse and recycling) (GEO5 2012).

Assessing the circularity of an economy based on these criteria, however, warrants caution¹: In particular, the inclusion of all biomass as a “circular” material flow seems problematic and implies that biomass is produced in a renewable way and that all waste flows and emissions effectively re-enter ecological cycles. When the production of biomass is associated with net carbon emissions, loss of soil nutrients, or the depletion of non-renewable water resources, as is often the case, biomass cannot be regarded as a circular flow proper. In practical terms, however, it is difficult to assess which share of the global biomass production meets the criteria required for a CE.

In principle, circularity can be advanced by different strategies. Alongside closing loops through recycling and reuse, a shift from fossil to renewable energy sources and translating efficiency gains into a reduction of the overall level of resource consumption is required. Recycling is, in practice, still the most widespread strategy employed to achieve a CE. For some materials, recycling is already very advanced (e.g., metals, paper, and glass) while for others, such as construction and demolition, waste considerable efforts are made to increase recycling rates (Graedel et al. 2011; Mugdal et al. 2011). But not in all cases does recycling lead to an effective reduction of material use: Energy requirements for recycling can be high, the lower quality of secondary material can lead to increased virgin material demand, or secondary materials may not be used to substitute virgin materials, but may instead drive the production of new low-price products (Moriguchi 2007). Thus, considering the wide variety of different CE strategies for different material flows and their interdependencies, it becomes increasingly important to establish frameworks on how to assess not only specific measures and improvements, but also their overall contributions both to closing material loops within the economy and making use of ecological material cycles.

The assessment presented in this article is an attempt to frame and substantiate the discussion by applying a systemic and sociometabolic perspective to assess the current level of circularity of the global economy. We define and quantify a set of key indicators to characterize the circularity of national economies and apply it to the global economy and the European Union (EU-27).

In the next section, we lay out the conceptual foundations of the material flow model we are using to analyze material flows and briefly describe the database and the assumptions we

made. This is followed by a presentation of the empirical results of the circularity of global economy and the EU-27 in 2005. Based on these results, we then discuss, for each of the four main material groups, the current state of circularity and the potentials and limitations for further improvement and draw some general conclusions for further progress toward a CE.

Methodological Approach

Figure 1 shows a simple model of economy-wide material flows and depicts the different flows and processes that were quantified in this study to assess the circularity of the economy. The model we use is based on the conceptual framework and the system boundaries applied in economy-wide material flow accounting (MFA) (Eurostat 2012). It defines the flow of materials from extraction and import, by processing, immediate consumption, or temporary accumulation in material stocks to recycling or final treatment before all materials finally leave the SES as waste and emissions.

Flows were estimated for the global economy and the EU-27 for the year 2005. Material flows were calculated at a detailed level of 47 material groups following the Eurostat classification of MFA (Eurostat 2012). Rather than assessing circularity for specific materials or substances, this study aims at a comprehensive picture, taking all materials into account. Results are therefore presented at the level of main material groups: biomass, fossil fuels (FFs), metals, waste rock, and industrial and construction minerals. Table 1 provides an overview of the literature and the sources used to derive the different coefficients to estimate flows or formulate assumptions.

Inputs into the economic systems comprise domestically extracted materials and imports. A fraction of inputs is exported. We define domestically processed materials (PMs) as the sum of apparent domestic consumption of materials (DMCs; extraction plus imports minus exports) and recycled materials. Data on domestic extraction, imports, and exports were derived from a global economy-wide material flow database (Schaffartzik et al. 2014). From materials processed, we distinguish three pathways of material flows of high relevance for the CE: energetic use; waste rock; and material use.

Energetic use comprises all materials that are used for energy production. This includes the combustion of energy-rich materials, such as wood, coal, oil, or gas, to provide technical energy² and applies to the largest fraction of all fossil materials (except for a small share used in material applications, such as plastics or bitumen) and a comparatively small fraction of biomass (e.g., fuel wood and biofuels³). We also consider agricultural biomass used to feed humans or livestock to provide metabolic energy in the catabolic processes in the human body and livestock as energetic use.⁴ All fossil and biomass materials used to provide energy are converted into gaseous emissions (mainly carbon dioxide [CO₂]) and other residues (combustion residues and excreta) and become domestic processed output (DPO; see below). None of these residues can be recycled within the economy in the sense that they can be used again for the original purpose. To a limited degree, cascade utilization is possible,

for example, when dung is used as fuel or to produce biogas or when ash is used in chemical processes. In the MFA system, excrta or biowaste used as fertilizer is not considered as recycling within the SES in MFA, but as an output that (potentially) enters ecological material cycles within the biosphere.

Waste rock (from metal ore processing) is a flow of considerable size, which goes straight from processed materials to DPO. MFA reports metal extraction in terms of gross ore and metal content. While the extracted metal is further used within the economic process, waste rock and tailings are discarded. This flow is a major waste flow, which, with few exceptions, does not qualify for recycling.⁵

Material use comprises of all other materials, that is, all metals and nonmetallic minerals and the fractions of biomass and fossil energy carriers not used for energy generation. Material input data from the detailed global material flow database were allocated to energetic or material use according to their material properties. For material flows where the resolution of the global material flow database did not allow for this distinction to be made, we used additional data from production statistics, for example, FAO (2013) for wood products and Plastics Europe (2012) and IEA (2013) for petroleum products.

The material use fraction is further split into two pathways based on average product lifetime: We distinguish between materials that are used within 1 year (throughput materials) and materials that remain in the SES for a longer period of time, that is, they add to stocks of artefacts (stock-building materials). Throughput materials become end-of-life (EOL) waste within a year, and the largest part of this fraction is potentially available for recycling after use. Typically, these are consumer goods, such as packaging, newspapers, batteries, plastic bags, and so on. In contrast to these consumables, by far the largest amount of materials is used to build up and maintain long-life stocks of buildings, infrastructures, and other long-life goods, which remain in the socioeconomic system as in-use stocks for more than a year. This flow is denoted as “addition to stocks” and is not immediately available for recycling, but remains in use for a period of 1 year to several decades until it is discarded and becomes EOL waste. Based on a literature survey and data from production statistics (e.g., for plastics and paper), we made material-specific assumptions to estimate the stock building fraction of a material (stocking rate), for example, for construction wood, paper, plastics, iron, aluminium, and other metals (see table 1).

Annual Discard of Stock Building Materials

Several studies indicate that economies still increase their physical stocks (Hashimoto et al. 2007; Pauliuk and Müller 2014; Wiedenhofer et al. 2015; Fishman et al. 2014), while, at the same time, a considerable amount of stocks that reach their EOL time each year are discarded or demolished. To estimate the annual amount of discarded stocks, we used data from stocks and flow literature that is available for specific materials, such as iron or construction minerals, on the global and/or regional level. For materials where this type of information was not

available (e.g., wood, plastics, and tin), we applied a simple so-called delayed model, which states that outflow from a stock at a given time t equals the inflow from year t minus the average lifetime of the stocks in years (Voet et al. 2002):

$$\text{Outflow}(t) = \text{Inflow}(t - \text{life time})$$

We estimated lifetimes based on literature and used the corresponding historic inflow data from the global material flow database (Schaffartzik et al. 2014).

End-of-Life Waste: We assume that all discarded stocks become EOL waste at the end of their lifetime. We do not distinguish between in-use stocks and hibernating stocks, that is, stocks that are not demolished, but remain in place unused (Hashimoto et al. 2009; Wallsten et al. 2013). The amount of EOL waste equals the amount of materials potentially available for recycling, reuse, or downcycling.

Recycling is defined as any recovery operation by which EOL waste is reprocessed into products, materials, or substances that can serve the original or comparable purposes (EP&C 2008). We estimate the amount of recycled materials on the basis of statistical data and recycling rates published in the scientific literature (see table 1). In this context, downcycling also plays an important role, which can be defined as the reprocessing of EOL waste into products of inferior quality, compared to the primary material, for example, concrete being crushed into aggregate. In practical terms, data on recycling flows often do not allow us to distinguish between re- and downcycling. We assume that, in particular, the recycling flow of construction minerals includes a considerable amount of downcycling. Case studies suggest that construction and demolition waste is often used in applications with reduced quality demands such as backfilling. Given that there is a lack of data, downcycling is subsumed under recycling in this study. We therefore overestimate the recycling flow proper.

DPO comprises all wastes and emissions that leave the SES. In order to be able to close the material balance, we do not account for DPO in their actual form as suggested by MFA guidelines (e.g., as CO₂) (Eurostat 2012), but, for reasons of simplicity, we exclude changes in mass flows resulting from oxidation or changes in moisture content.⁶

To assess the circularity of an economy based on the material flows shown in figure 1, we propose a set of key indicators:

- a) Material size: PMs (gigatonnes [Gt] and tonnes per capita [t/cap])
- b) Stock growth: Net addition to stocks as share of PMs (%)
- c) Degree of circularity within the economy: recycling as share of PMs (%)
- d) Biodegradable flows: biomass as share of PMs (%)
- e) Throughput: DPO as share of PMs (%)

It is further important to note that an assessment of the CE needs to take the issue of spatial and temporal scales into account. It is not straightforward over which period of time and at what spatial scale circularity should be optimized, but this is

Table 1 Sources for data and assumptions used to calculate material flows shown in figure 1 by main material groups

Main material group	Domestic extraction	Trade flows	Allocation to material or energetic use	Additions to stocks	Demolition and discard of stocks	Recycling
Biomass			Primary crops and crop residues: assumptions based on FAO commodity balances and Krausmann and colleagues (2008) Wood: FAO (2013)	According to use According to use	Estimates based on assumption of lifetime delay model, see Van der Voet and colleagues (2002) Estimates based on own assumptions re. lifetimes	n.a. FAO (2013)
Fossil fuel carriers			Crude petroleum: Plastics Europe (2012) Natural gas: Wood and Cowie (2004)	According to use	Estimates based on own assumptions regarding lifetimes	Estimates based on Plastics Europe
Metals (content)	All: Schaffartzik and colleagues (2014)		n.a. n.a. n.a.	Iron: Wang and colleagues (2007) Aluminium: Cullen and Allwood (2013); Bertram and colleagues (2009) Other metals: Allwood and colleagues (2010)	Wang and colleagues (2007)	Hislop and Hill (2011); UNEP (2011b)
Waste rock			n.a.	n.a.	n.a.	n.a.
Industrial minerals			n.a.	Authors' assumptions	Authors' assumptions	Authors' assumptions
Construction minerals			n.a.	Estimates based on Wiedenhofer and colleagues (2015); Fishman and colleagues (2014); Kapur and colleagues (2009)		Monier and colleagues (2011); Mugal and colleagues (2011)

Note: n.a. = not applicable

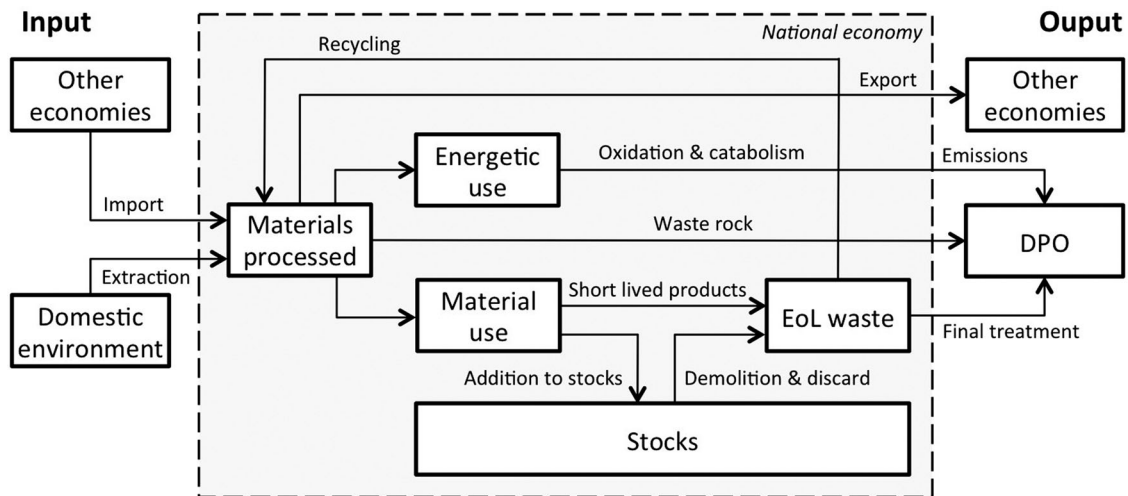


Figure 1 General model of economy-wide material flows from resource inputs imports and extraction to outputs of wastes and emissions and exports. All flows shown in the model have been quantified to assess the key characteristics of the circular economy. EoL waste = end-of-life waste; DPO = domestic processed output.

rarely discussed. We have chosen to assess circularity for a specific year (2005) and at a global scale. The observation period of 1 year has been chosen for practical reasons (MFA system boundaries and data availability), but it allows to capture the interplay of long-living stocks and annual flows and their impact on circularity only to a limited extent. The global scale chosen in this article provides a very comprehensive picture, but, ultimately, a multiscale perspective is required. It is important to observe and improve the CE at various levels, and the objectives for the CE may differ for different materials at different scales.

Robustness of the Estimate

The estimate of the different material flows entails considerable uncertainties. For some material groups, such as many metals, fossil energy carriers, and biomass, a broad knowledge of the material system and solid data exist. For some flows and some materials, the data situation is less satisfying and the level of uncertainty is considerable, in particular for recycling rates and flows of construction minerals. In a review, Monier and colleagues (2011 15) conclude, for example, that the available data and estimates of construction and demolition waste for the EU-27 vary by a factor 2. To estimate the different material flows, we used the best available information based on a broad literature survey. In general, we used assumptions that rather overestimate the degree of circularity of the economy. This refers, in particular, to the assumed rates for discard and recycling, which are at the upper limit. Further, the inclusion of all biomass as a circular material flow, regardless of the way this biomass is produced or how biomass wastes are discarded, overestimates the actual degree of circularity.

Although the level of uncertainty for specific materials may indeed be considerable, we assume that, for the overall aim of the article, which is to provide a rough, but comprehensive,

assessment of the global economies circularity at the level of main material groups, the reliability of the data and our estimates is sufficient.

Current State of the Global Economy's Circularity

Based on a quantification of the different material flows shown in figure 1, we can make a rough assessment of the degree of circularity of the global economy at the turn of the twenty-first century. Figure 2 presents the size of the material flows in the year 2005 for the global economy and the EU-27 in the form of a Sankey diagram. In 2005, 58 gigatonnes per year (Gt/yr) of extracted raw materials entered the global economy. Together with 4 Gt/yr of recycled material, this added up to a total of 62 Gt/yr of processed materials (see table 2). Forty-four percent of all processed materials (28 Gt/yr) were used to provide energy through combustion or catabolic processes in humans and livestock and were converted into gaseous emissions or solid wastes leaving the SES as DPO. Another 6% of the processed material left the SES as waste rock or tailings from ore processing. This leaves 30 Gt/yr having entered the production process for material use. Of these, 4 Gt/yr were used in goods with a lifetime shorter than 1 year and 26 Gt/yr (or 43% of all processed materials) were added to stocks of buildings, infrastructures, and other goods with a lifetime longer than a year. This large flow of additions to stocks was accompanied by 9 Gt/yr of discarded stocks, which results in a total of 17 Gt/yr of net additions to stocks in 2005. According to our estimate, the total EoL waste flow from material use sums up to 13 Gt/yr. This amount of materials, which corresponds to one fifth of all material inputs, was potentially available for recycling and reuse in 2005. We estimate that roughly one third of this waste flow (4 Gt/yr) was actually recycled or downcycled, and the

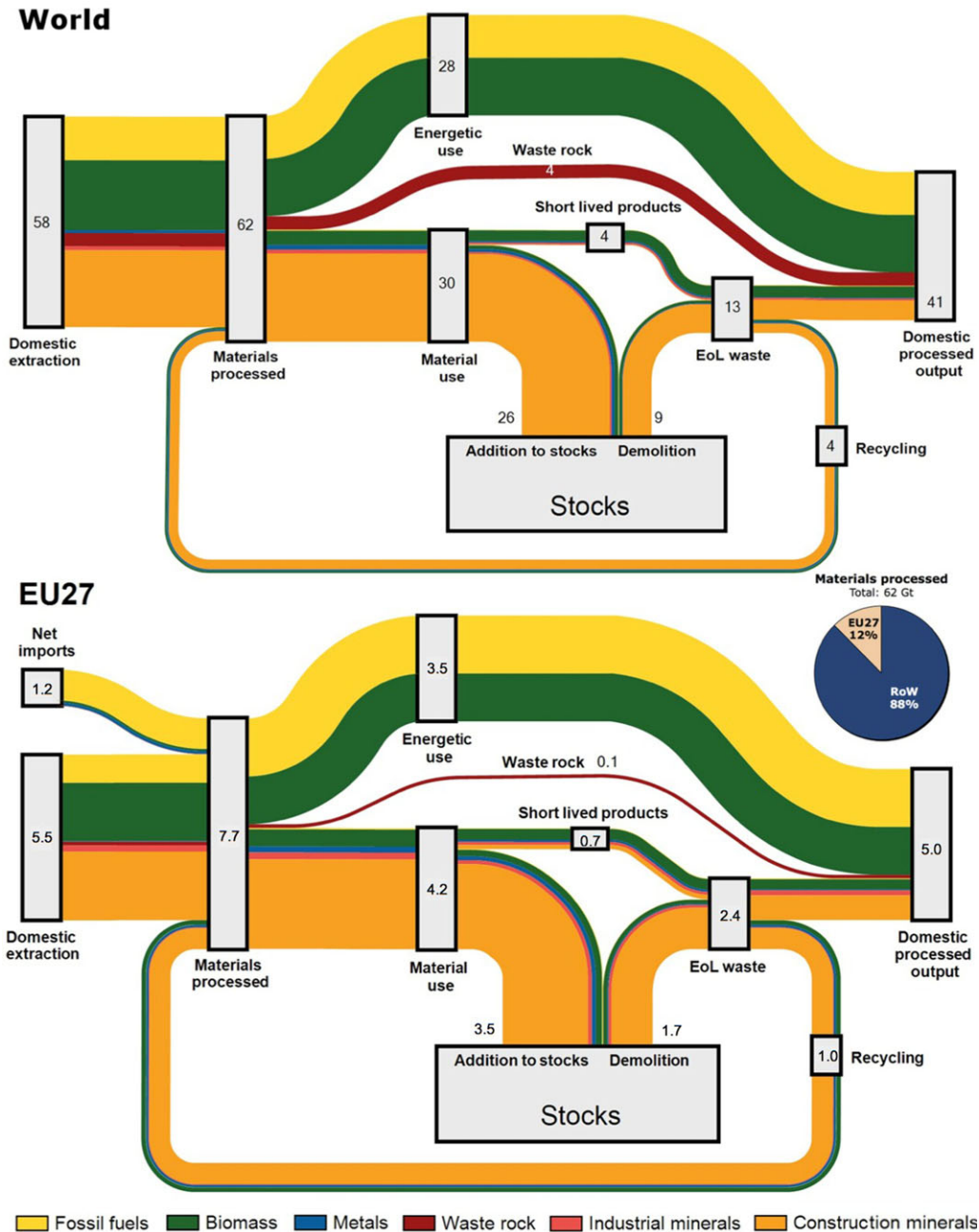


Figure 2 Sankey diagram of material flows through the global economy (world) and the EU-27 in 2005. Numbers show the size of flows in Gt/yr. For a definition of flows, see the article text. EU = European Union; EoL waste = end-of-life waste; Gt/yr = gigatonnes per year; RoW = rest of the world.

remainder was disposed to the environment directly or after treatment in waste plants and left the SES as gaseous, liquid, or solid outputs. A considerable fraction of this flow may also have remained in place as unused (hibernating) stocks (Hashimoto et al. 2009; Pauliuk et al. 2013; Wallsten et al. 2013). When related to the total material input (processed materials), the aggregate recycling rate shrinks to 6%.

From such a system-wide metabolic perspective, the degree of circularity of the global economy measured as the share of actually recycled materials in total processed materials appears

to be very low, at 6%. The vast majority of all processed materials (66%) left the global economy as wastes and emissions and a large fraction (27%) were net additions to stocks of buildings, infrastructures, and other long-life goods. These materials become available for recycling only after longer periods of time, often after decades. Materials used for energy provision dominate the inputs (44% of all processed materials). This large material flow does not qualify as recycling proper within the economy at all. However, if we follow the common definition of the CE, biomass is considered a cyclical flow owing to the fact that all

Table 2 Circular economy indicators for the world and the EU-27 in 2005 (see figure 1 and the article text for definitions; per capita values are shown in figure S2 in the supporting information on the Web). Indicators above the horizontal dividing line are the proposed set of key indicators. The indicator below the line signifies a potential and others provide more detailed information

Indicator	Unit	World	EU-27
PM	Gt	61.9	7.7
	t/cap	9.6	15.8
Net addition to stocks as share of PM	%	28%	22%
Recycling within the economy as share of PM	%	6%	13%
Biomass as share of PM	%	32%	28%
Domestic processed output as share of PM	%	66%	66%
Flows either biodegradable or recycled in economy as share of PM	%	37%	38%
Fossil energy carriers as share of PM	%	19%	26%
Material for energetic use as share of PM	%	44%	46%
Material for material use as share of PM	%	50%	54%
Waste rock as share of PM	%	6%	1.5%
Short-lived products as share of PM	%	7%	9%
EOL waste as share of PM	%	21%	31%
Recycling as share of EOL waste (overall recycling rate)	%	28%	41%

Note: PM = processed material; EOL = end of life; Gt = gigatonnes; t/cap = tones per capita; EU = European Union.

biomass waste products re-enter the biosphere and are available for ecological cycles (CO₂, plant nutrients, and manure) and new biomass production. Hence, combining economy-internal technical cycles and economy-external ecological cycles by including all biomass yields a level of circularity of 37% globally. Considering that global biomass production is associated with deforestation, net CO₂ emissions, and soil degradation or that a considerable fraction of plant nutrients is lost to global sinks (Cordell et al. 2009; Rosegrant et al. 2009; Vermeulen et al. 2012), the actual degree of circularity of biomass is much lower. Thus, the overall level of circularity of 37% rather stands for a maximum current level and considerably overestimates the circularity of the global economy.

The EU-27 is among the regions taking the lead with respect to policies of sustainable development and sustainable resource use, but is also a major consumer of resources and producer of emissions. In 2005, the EU-27 accounted for 7.5% of the global population, but used 12.4% of the globally extracted materials. The highly industrialized region had approximately 30% of global gross domestic product (GDP) which, in capita terms, was in average US\$28,600 in 2005 (in constant 2005 prices; UN 2014), approximately 200% above the global average. Average material use per capita amounted to 15.8 t/cap/yr and was 64% above the global average. The EU-27 is further a net importer of materials, which amount to roughly 20% of its DMC (Schaffartzik et al. 2014). The high import rate also indicates that a considerable amount of waste production associated with European consumption may occur elsewhere in the world (Wiedmann et al. 2013; Bruckner et al. 2012) for example, the comparatively small flow of waste rock is owing to the high import of processed metals). Figure 2 shows the size of the different material flows in the EU-27. Of the total amount of processed materials of 7.7 Gt/yr, roughly 54% went into material use, of which additions to stocks accounted for 80%. In the EU, a larger share of stocks reached EOL, compared to the global

average, and the flow of discarded stocks amounted to 50% of additions (compared of 33% globally). Nevertheless, per capita net additions to stocks in the EU were, at 3.4 t/cap/yr, still much higher than the global average of 2.7 t/cap/yr (see figure S2 in the supporting information available on the Journal's website). Recycling in the EU is advanced. A total of 2.0 t/cap/yr of materials were recycled in the EU in 2005, which corresponds to 41% of EOL waste, compared to a global average of 0.6 t/cap/yr or 28% of EOL (figure S2 in the supporting information on the Web). The aggregate recycling rate (recycled material as share of processed material) was, at 12.6%, roughly twice as high as the global average. But, in spite of a higher recycling rate, DPO is large and amounted to 10.4 t/cap/yr or 66% of processed materials, as compared to 6.3 t/cap/yr in the global average. Including all biomass flows as circular flows results in a degree of circularity of 39%. But, also for the EU-27, biomass production cannot be regarded as fully circular, as discussed above. Whereas the overall degree of circularity of the EU economy is surprisingly similar as the global value, owing to the fact that the lower share of biomass in the EU's metabolism is balanced by higher recycling rates, also the size of the flows needs to be taken into account: The flows that are in a material loop within the economy or that are biodegradable, as the definition of the CE demands, amount to 6.8 t/cap/yr in the EU-27 and 3.5 t/cap in the global economy. But also the noncircular flows are much larger in the EU-27, at 6.4 t/cap/yr, as compared to 3.4 t/cap/yr globally, which indicates the significance of downscaling the overall size of social metabolism, in particular, in industrial countries in addition to advancing the degree of circularity.

Challenges for a Global Circular Economy

In 2005, the global economy processed 62 Gt/yr of materials. Twenty-eight percent of these materials were net additions to stocks of built structures and long-life goods, indicating that

global in-use material stocks are growing at a high rate. At the same time, the degree of circularity measured as the share of recycled material in total processed materials was very low, at only 6%. The EU-27, a group of highly industrialized countries with relatively progressive environmental policies, processed 7.7 Gt of materials in 2005. Twenty-two percent of these flows are net additions to stocks, indicating that relative stock growth in the EU was lower than the global average. The estimate of recycling flows amounts to 13% of processed material. Whereas the degree of circularity within the economy in the EU is twice as high as the global average, the renewable biomass flows are, at 28% of the processed materials, relatively lower than the global average of 32%. Thus, the metabolism of the EU countries is also characterized by material throughput, and the distance to closed material loops appears to be surprisingly high. In this section, we discuss some of the factors responsible for the low degree of global circularity as well as the potentials and limitations of different options for furthering advance circularity by the four main material groups.

Fossil Energy Carriers

Of the 12 Gt of fossil energy carriers extracted globally in 2005, roughly 98% were used to produce energy. The energy contained in fossil energy carriers is released by combustion and in a highly irreversible manner. With the exception of plastics and a few other material applications, recycling is not an option for the group of fossil materials. For this reason, the share of recycled fossil materials in all processed fossil materials was only 0.26% (EU-27: 0.38%) and lower than for any other material group except for waste rock (see table S1 in the supporting information on the Web, circularity within the economy). Recycling potentials are limited to the small fraction of fossil materials used as raw material. Owing to source and sink problems related to FFs, a transition toward a new energy system will be required, with effects on the circularity of the economy. Whereas some of the energy solutions discussed might conserve the present linearity of the energy system, others have the potential to significantly improve circularity: Carbon capture and storage is one example that contributes to conserving or even reinforcing the economy's linearity. This technology increases the input for material and energy required by fossil-powered plants per unit of energy output and therefore reduces the efficiency of energy production (Herzog 2011). In contrast, a rising share of energy generated by solar, wind, geothermal, and tidal power plants in the total energy mix could improve circularity. These technologies are less material intensive in terms of material input per unit of energy output than the fossil energy system and thus can reduce both inputs and outputs of materials (Raugei et al. 2012). If we assume that 50% of the fossil energy carriers used in 2005 globally were to be substituted by solar, wind, and geothermal power generation,⁷ according to our calculations this would reduce the size of processed materials by 10% and DPO by 15%.

Recycling is an option for part of the 2% of all fossil energy carriers that are used globally as material, mainly in

the production of plastic, bitumen, and lubricants. Important recycling pathways exist for plastic and bitumen (see asphalt under nonmetallic minerals). Global recycling rates for plastic are estimated at 17% (22% in the EU) (Plastics Europe 2012), but these rates overestimate proper recycling given that, in most cases, plastic is, in fact, downcycled to replace products of lower quality (e.g., food packaging to plastic bags or flower pots) (Mugdal et al. 2011). For present recycling, the variety of different synthetic materials is a major barrier for increased material recycling. Reducing the consumption of plastics seems to be a more promising option, in particular in packaging, where 40%, and in building and construction, where 21% of all plastics are used. Concerning material properties for both uses, an almost complete substitution by biogenic materials, which are degradable in ecological cycles, is technically feasible. However, the land requirements for some substitutes are large and pose limits for actual substitution (Dornburg et al. 2003; Lauk et al. 2012).

In addition to recycling, the cascading use of fly ash and slag, which accrue as waste product in the combustion of coal and wastes, in the production of concrete can reduce material flows and contribute to circularity. Though there are no reliable data for the current use of fly ash in cement production, experts argue that a shift to concrete mixtures containing more than 50% fly ash by mass of the cementitious material can reduce the water and energy demand of production as well as improve the workability and durability of concrete (Wang 2004). Such strategies, however, also perpetuate the use of FF carriers.

Biomass

Global biomass extraction amounts to 19 Gt/yr and the degree of circularity for this material group within the economy is low, at only 3% (7% in the EU-27). Almost 80% of all biomass is used energetically in the form of food, feed, and fuel. Similar to fossil energy carriers, for this fraction of biomass, recycling within the economic system is not feasible. However, if biomass is produced sustainably, that is, without damaging soil or water resources and without depleting ecological carbon stocks (Jordan et al. 2007), it can be considered renewable and the emitted CO₂ as well as waste flows such as excreta can largely be recycled into new primary biomass within ecological cycles. These processes can be supported by human activity, for example, when nutrient-rich excreta of humans and livestock or ash are used to fertilize agricultural ecosystems. This not only helps to close loops of essential plant nutrients, but it also contributes to a reduction of the input of industrial fertilizer based on nonrenewable mineral resources and further increases the circularity of the economy.

Additionally, there seem to be large potentials to reduce the amount of biomass inputs required to produce sufficient food for the global population. Reducing food wastes is one possible strategy, given that approximately 20% to 30% of all food is wasted along the way from harvest to consumption (Gustavsson et al. 2011). A second, even more powerful pathway involves changing dietary patterns toward a lower share of animal products, which could drastically⁸ reduce the material intensity of

food supply (Wirsenius 2003; Krausmann et al. 2008). Cascade utilization of by-products, residues, and excreta also has a high potential to improve overall resource efficiency (Ma et al. 2010).

Roughly one fifth of all biomass is used as raw material; wood accounts for the largest fraction of this flow: Approximately 12% of biomass (approximately 4% of globally processed materials) is wood used for construction, for other durable wood products such as furniture and for paper production. In Europe, approximately 44% of the materially used wood was recovered; of this, 64% were recycled or downcycled, 2% were reused, and 34% were used for energy generation in 2005 (Merl et al. 2007). Seventeen percent of the wood is used for paper production. Paper has a long recycling tradition with current recycling rates of 40% to 50%, both globally and in the EU-27. Whereas collection of waste paper and subsequent recycling or alternative uses have almost reached their limits, there is great potential for improvement in the prevention of paper flows, in particular, where use is inefficient (e.g., newspapers, unsolicited bulk mail, and office paper use) (Roberts 2007).

Metals

Ores account for approximately 4.5 Gt/yr or 8% of global material extraction. The actual metal content of these ores is only approximately 0.8 Gt; the remainder are tailings and processing slags of little further use. Of the pure metal, approximately two thirds are added to stocks. For many “base metals” (e.g., copper, zinc, and so on), EOL recycling rates are slightly above 50%, and only for two metals they are significantly higher: iron, with a recycling rate of approximately 90%, and lead (Graedel et al. 2011; UNEP 2011b). Lead is an exception owing to the fact that the biggest share of lead is used for just one product group: vehicle batteries, of which approximately 90% to 95% are collected and recycled. On the other end of the spectrum, there is a wide range of metals and metalloids with recycling rates below 1% (e.g., lithium and thallium). Whereas aggregate EOL recycling rates of metals are high both in the EU (76%) and globally (71%), the high flow of net additions to stock for metals keeps the degree of circularity for this material group much lower, at 40% and 36%, respectively.

There are promising strategies to make more efficient use of metals such as increasing lifetimes, more-intense uses, repair and resale, product upgrades, modularity and remanufacturing, component reuse, and using less material to provide the same service (Allwood et al. 2011). Although these strategies seem to have great potential, quantitative assessments are difficult to make and are largely lacking (Mugdal et al. 2011).

In terms of recycling, metals can theoretically be recycled infinitely. However, there are significant challenges to metal recycling (Reck and Graedel 2012; Graedel et al. 2011): At the beginning of the twenty-first century, humanity is using almost the entire spectrum of available metals. Many of these metals are used in very small quantities (nanomaterial technologies and microelectronics), in complex alloys, or in composite materials, and individual products can contain dozens of different metals.

All of these factors decrease the recyclability of metal products, because the separation of metals becomes more demanding and costly and pure recycled metals are increasingly difficult to obtain. This is aggravated by the fact that recycling technologies (shredding, crushing, or magnetic sorting) are often crude and far less advanced than production technologies.

In general, metal recycling contributes not only to a reduction in the demand for virgin ores, but also has a positive effect on energy requirements. The processing steps from ore extraction to pure metal entail moving and processing huge quantities of raw material and consume large amounts of energy, both of which can be reduced through recycling. Metals are approximately 5% of the total EOL waste streams. If a product design that favors recycling is applied and if economic incentives are in place, there is a high potential to close material loops for metals to a high degree, provided that net additions to stocks are also reduced. Additionally, this could substantially reduce carbon emissions related to steel production, which amounted to 25% of global industrial carbon emissions in 2006 (Allwood et al. 2011). Increasing the recycling rate for steel from 71% to 91% would, for example, reduce the overall global sum of extracted materials by 1.3% (equals the reduction of pure metal and waste rock extraction as well as associated fossil energy carriers use) and DPO by 1.7%, compared to the present situation.

Nonmetallic Minerals

Nonmetallic minerals are the largest fraction of global material extraction and their consumption is growing at very high rates (Krausmann et al. 2009). Of the 22 Gt extracted in 2005, bulk minerals, such as sand, gravel, stone, or clay, account for roughly 95% and are subsumed under the category of construction minerals. According to our calculations, global EOL recycling rates for this material group are 33% globally and 46% in the EU-27. Similar to metals, net additions to stock are very high for nonmetallic minerals, and the overall degree of circularity is much lower, at only 11% and 23%, respectively (see table S1 in the supporting information on the Web). Proper recycling flows are even lower than that, owing to the fact that recycling statistics for construction minerals include large amounts of downcycled materials (e.g., construction and demolishing waste used as backfilling material). For asphalt (a mixture of gravel and bitumen) in situ recycling is already quite high, but quantitative assessments at the global level or for world regions are lacking. The National Asphalt Pavement Association (NAPA) assumes asphalt pavement recycling rates of over 99% for the United States (NAPA 2013). For industrialized countries in general, we assume a range from 80% to 90% (see also US DOT 1993).

Key strategies for reducing material inputs and improving circularity of this group are to stabilize or even reduce the size of stocks and extend the service lifetime of existing structures. Additionally, further closing loops for construction minerals is possible, but requires recycling-friendly design of buildings and infrastructures and regional flow management to keep transport distances short. While, in principle, nearly all types of

construction materials can be recycled, recycling is not always the most sustainable option for this material group. Negative environmental and resource effects for some materials are considerable (e.g., cement recycling), and also transport intensity is a limiting factor (Blengini and Garbarino 2010). Chong and Hermreck (2010), for example, point out that saturation of local markets for recycled construction materials can become a critical factor, given that an increase in the distance between project sites and recycling facilities might counteract the benefits of recycling. The study concludes that further increases in recycling activities depend on the existence of a market for recycled materials, regional recycling capacities, total energy used to recycle, and the knowledge of the workers and designers of options for using recycled materials in construction projects. Another limitation concerns underground stocks of built structures. These are large stocks, but difficult to access, and the costs of recycling are high (Tanikawa and Hashimoto 2009). Often, underground stocks are simply abandoned and remain in the ground as so-called hibernating stocks.

The small fraction of nonmetallic minerals used for other applications than construction is a very heterogeneous group. For some of these materials (e.g., salt), recycling potentials are very low; but examples of materials with a long tradition of recycling and high recycling rates (such as glass) are also in this group. Nonmetallic mineral inputs for the production of glass account for less than 0.5%⁹ of global extraction. Recycling rates in industrialized countries range from 40% to 70%. Glass can be remelted and used in new glass products without loss of physical property or quality.¹⁰ However, according to the priorities of the CE, reuse would be more favorable than recycling. Another example is phosphate, which currently moves mainly in a linear direction from mines to distant locations for crop production, processing, and consumption. There is a high potential for improving phosphorus use efficiency, and as a result of phosphorus scarcity it will need to be recovered from waste streams from human and animal excreta to food and crop wastes (Cordell et al. 2011; Schröder et al. 2011).

Conclusions

The sociometabolic approach shows that, currently, only 6% of all materials processed by the global economy are recycled and contribute to closing the loop. If all biomass is considered a circular flow regardless of production conditions, the degree of circularity increases to 37%. The rates for the EU-27 are only slightly above the global averages. This indicates that both the global economy and that of the EU-27 are still far away from a CE. Against the background of an average growth rate in global material consumption of approximately 3.6% in the last decade (1950–2010) (Schaffartzik et al. 2014), the CE is not in sight at present. Several lessons can be learned from our systemic assessment, from a metabolic perspective, for policies aiming at the implementation of a CE.

Recycling is one of several important elements of a CE; yet, although it has the potential to increase circularity for some materials, circularity cannot be achieved on the basis of

recycling alone. We identify two structural barriers for improving the circularity of the economy through recycling: A very large fraction of the materials we use still accumulates as in-use stocks. While a certain trend of stock stabilization in industrial countries can be observed, globally stocks are growing at high rates and might continue to do so. As long as additions to stocks grow at such high rates,¹¹ even high EOL recycling rates will make a limited contribution to overall circularity. A second barrier is the large amount of materials used for energy generation. For these materials, and, in particular, for fossil energy carriers, closing the loop is not possible and a high share of these materials keeps the degree of circularity low. Whereas sustainably produced biomass that is recycled within the biosphere can be an important component of a CE, reducing the consumption of fossil energy carriers is necessary to further raise the degree of circularity of the economy. The energy transition from fossil to renewable energy resources is therefore an important prerequisite for moving toward circularity. Reducing barriers for recycling materials used as raw materials is another important cornerstone. Although EOL recycling rates for some materials are already high, considerable improvements seem possible. This requires the consistent eco-friendly design of products (including buildings and infrastructures) that increases lifetimes, provides the same service with less material requirement, and facilitates repair and resale, product upgrades, modularity and remanufacturing, component reuse, and, finally, also EOL recycling. Achieving a reversal of the trend of global growth in resource consumption into a dynamic of reduction, or at least a steady-state physical economy, remains the greatest challenge of all.

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Notes

1. Further, it must be noted that circularity should not be regarded as equating to ecological sustainability: Also, the use of materials that run in cycles can have negative impacts on ecosystems and biodiversity.
2. Material used for nuclear fission in power plants is not considered in our assessment.
3. Fuel wood and biofuels account for roughly 10% of all globally processed biomass (FAO 2013; Krausmann et al. 2008; Goldemberg et al. 2014).
4. While food and feed not only provide nutritional energy for humans and livestock, but are required to building up body mass (i.e., stocks), the fraction of food/feed that accumulates in body mass is very small. On the basis of population growth, we estimate that global net additions to population stock correspond to less than 0.1% of total food supply (per year). We therefore neglect the “material use” component of food in our assessment and consider all food and feed as “energetic use.”

5. Waste rock may be used, for example, as backfilling material. Owing to lack of data, this flow has not been considered in this assessment. Waste rock may also eventually become a resource again, if rising metal prices and technological development make the exploitation of remaining metal content feasible. Given that waste rock becomes DPO in the MFA system, this would be considered as extraction and not as recycling.
 6. Processing and consumption change the moisture content of biomass and combustion adds atmospheric oxygen to fuels. To close the mass balance between material inputs and outputs, economy-wide MFA considers water flows resulting from changing moisture content and oxygen inputs resulting from combustion as so-called balancing items. For reasons of simplicity, we do not consider balancing items in this assessment. This means that changes in the mass of flows resulting from oxygen uptake or changes in moisture content are not taken into account.
 7. Such an energy scenario is discussed and considered feasible, for example, by Jacobson and Delucchi (2011). In our calculations, we neglected the fact that also renewable energy technologies require inputs of mineral materials, for example, for infrastructure, turbines, or dams and the implications of these material flows for circularity.
 8. Approximately 60% of all harvested biomass is used to feed livestock, which converts plant biomass into meat, milk, and other livestock products at a low efficiency (Krausmann et al. 2008). A change in dietary patterns toward a lower share of animal products and within animal products toward meat from monogastrics, which have a much higher feed-use efficiency than ruminants, would significantly improve the biomass efficiency of the food system (see Herrero et al. 2013; Wirsenius et al. 2010).
 9. According to the World Silica Sand Market report (Freedonia Group 2012), extraction will increase to 278 million metric tons in 2016, compared to approximately 175 million tons for 2004.
 10. Colored glass cannot be turned into clear glass products, but can be recycled into other colored glass products.
 11. At the global level, additions to stocks in the material category of construction minerals grew by 4% annually during the period 1990–2005 (respectively by 0.8% in the EU-27).
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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides further material flow calculations with regard to the main material categories (table S1), a breakdown of processed materials into main material groups (figure S1), and a comparison of main material flows (figure S2) for the world and the EU-27.