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Global Circular Economy Scenario in a Multiregional Input−Output Framework

Kirsten S. Wiebe,[*,†,‡,¶,||] Marek Harsdorff,[§] Guillermo Montt,[§] Moana S. Simas,[†] and Richard Wood[†]

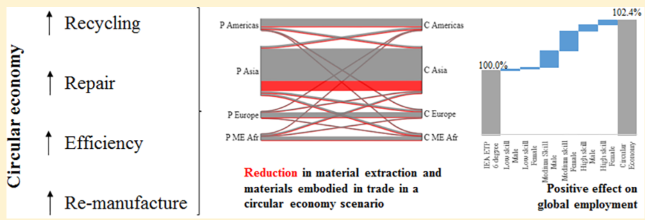
[†]Industrial Ecology Programme, Norwegian University of Science and Technology, Trondheim 7491, Norway

[‡]SINTEF Industri, Trondheim 7456, Norway

[§]International Labor Office, Geneva 1202, Switzerland

Supporting Information

ABSTRACT: In a resource-constrained world of an estimated 10 billion people in 2050 with the same material aspirations of today's high-income nations, there is no question: The future economy will need to be circular. From a policy perspective, the question is whether averting catastrophic environmental impacts through an accelerated transition to a global circular economy can also deliver sustained growth and jobs. The adoption of circular economy measures will have a range of effects on both domestic and foreign supply chains. Multiregional input−output (MRIO) analysis models the interdependencies between industries and within and between countries as well as between intermediate and final goods producers and consumers. It provides a useful toolbox for assessing social, environmental, and economy-wide impacts of the adoption of the circular economy. We project the MRIO database EXIOBASE to 2030 on the basis of the exogenously given parameters of the International Energy Agency's Energy Technology Perspective (IEA ETP) 6-degree scenario. We compare this business-as-usual (BAU) scenario and an alternative circular economy scenario. The circular economy scenario considers more recycling, reducing (material efficiency increase), repair, and reuse in relation to the BAU scenario. The adoption of circular economy measures has diverse impacts on the economy and environmental pressures. Global material extraction is reduced by about 10% compared to the baseline, while the impact on employment is small but positive. In particular, the shift from resource extracting sectors to the service sector will provide more opportunities for high-skilled and female workers.



INTRODUCTION

Assuming that the ever-increasing world population would rely on similar systems of production and services, housing, mobility, food, energy, and water supply, as compared to today, up to 180 billion tons of materials will be required, almost three times today's amounts.[1] It is unclear if those quantities of materials are available and even more importantly if there are large enough sinks that exist for associated waste disposal without a catastrophic impact on human well-being.[2]

The circular economy is an attempt to break the dependency of the fulfillment of services for human needs with the reliance on material extraction. Moving away from the current linear mode of production (synthetically referred to as an "extract-produce-use-discard" model), the circular economy promotes the design of durable goods that can be easily repaired, with components that can be reused, remanufactured, and recycled. The circular economy relies more on the service sector and the rental of goods when compared to the ownership of goods in a linear economy.[3] At the same time and in addition to the environmental debate, interest in the employment effects of a circular economy has led the policy debate notably in the EU. It is taking place among broader concerns about the future of work and unemployment, total factor productivity, and wage stagnation. The circular economy is framed as a means to weave together opportunities related to employment and wage stabilization and innovation as well as productivity together with environmental objectives.[4] The European Commission Strategy and Action Plan cite the need to foster growth and employment creation and to do so in a way that meets environmental constraints, through resource efficiency, innovation, and capturing the value of wastes as secondary raw materials. The European Parliament provided estimates of up to 3 million new jobs by 2030.[5] In China, the concept of ecological civilization, to which the circular economy is a key element, has been promoted as the long-term vision of increased productivity, well-being, and sustainable development.[6,7] However, the employment gains are disputed, and how many jobs will emerge in the EU, China, and other countries embarking on the circular economy remains unclear.

When products are recycled, repaired, or reused, employment is generated, and when waste from one process is used as an input into others, efficiency and productivity gains are achieved (Porter Hypothesis).[8] The circular economy keeps products, components, and materials at a high level of utility and value through maximizing the product's life, promoting

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reuse, refurbishment, and remanufacture, and the recyclability of inputs and components.[3] The concept of a circular economy is easily understood in the context of China. As the world's largest manufacturer and processor of natural resources, China sees some of the worst effects of unchecked resource extraction, waste, and pollution while struggling to achieve its growth targets. First proposed by scholars in China in 1998, a circular economy strategy, which featured prominently in the 12th and 13th Five-Year Plans, was adopted in 2002 by the central government as a new form of development that eases the conflict between rapid economic growth and the limited quantities of raw materials and energy.[9] In 2009, China's Circular Economy Promotion Law came into force to mandate the resource utilization rate and resource recovery in production, circulation, and consumption. China's policies toward the circular economy became more comprehensive over time, led by different government agencies and the use of different policy instruments. Today, the government and subsidy led policy approach, however, starts to show limitations in terms of capturing the whole production life cycle and use of market-based policy design.[10] Japan's law,[11] passed already in 2000, treats materials as circular goods and covers products' entire lifespans. Manufacturers are legally required to run disassembly plants and recover materials, turning product disposal into an asset as companies have an incentive to reuse materials. Today, for example, across Japan, 98% of metals are recovered.[12] In South Korea, a circular economy approach was initially developed through the 15-year National Eco-Industrial Park Program. Extending in scope and size and involving around 600 firms, in its third phase which ends in 2019, a national network that integrates industrial complexes and urban areas should be established.[13]

The circular economy has also been adopted at the level of individual firms. Renault, the French automaker, ensures that 85% of a new vehicle is recyclable when it reaches end of life and that 36% of that new vehicle's mass is made from recyclable materials.[14] The same is true for other enterprises, like Xerox, which instead of selling printers is now selling the printing service, offering clients the latest technology while still owning the printers. In owning the machines, Xerox is able to design future models based on components currently in use.[15]

Given the international linkages across industries and material flows,[16,17] international consumption patterns affect local production patterns and material use. Indeed, the adoption of circular economy principles in Europe could not only result in employment effects domestically but also affect labor markets in other regions.

Simply put, the circular economy is likely to reduce the extraction of primary materials, reformulate the waste management sector, and strengthen the recycling of goods and the service sector.[18] The transition to a circular economy encompasses economy-wide changes affecting a large variety of economic sectors and actors. An account of the impact of the adoption of the circular economy ought to take into account not only the effects on the industries directly affected but also those linked, upstream and downstream and within and between countries, to these industries. Multiregional input−output (MRIO) analysis provides a useful toolbox for assessing these economy-wide changes. In comparison to other material flow accounting approaches,[19] MRIO analysis has the advantage of tracking the transformation of products at each step along the supply chain and thus capturing material flows across increasingly fragmented international supply chains. In addition, MRIO data is consistent with the System of National Accounts and thus makes it relatively easy to capture impacts on employment and value creation. As a negative, MRIO data is often reported at more aggregate product groups than most material flow data and, thus, are susceptible to aggregation errors.[20] A number of input−output (IO) approaches have been used to study circular economy research: they can be grouped into four groups. The first group simply looked at resource efficiency (i.e., material footprints) implicitly but not explicitly including secondary production (i.e., the distinction between goods produced with virgin raw material versus those produced with recycled material or scrap).[16,21−23] Second was those that have looked at waste flows through the economy.[24−26] The best example of an IO framework used to track waste and waste treatment is provided by the Waste Input−Output model of Nakamura and Kondo.[27] Their framework has been used extensively in the Japanese case.[28,29] A third group of IO studies looked specifically at the material content of production, synonymous with how materials are tracked through the economy in the Waste Input−Output model.[30,31] Such studies can better link into understanding potentials for reuse and have been postulated as a more pragmatic way to implement either consumer or trade policy to tackle embodied emissions. A number of these studies have taken a scenario-based perspective.[32−34] A fourth group of studies using IO to understand the circular economy focused on the value creation aspects of the circular economy, with the advantage of IO approaches being the integration of value added and employment alongside material and energy in a single framework.[35]

However, compared to the use of IO frameworks for studying environmental issues, the application of IO in circular economy research is relatively rare due to the high industry aggregation. This might be due to the limited availability of mining and processing of raw materials data and waste and waste treatment accounts in official statistics, especially at the global level.[36] The recent work on the EXIOBASE database has gone someway into solving this issue. Starting with the CREEA research project (www.creea.eu) and continued with the DESIRE project (www.fp7desire.eu), a physical layering approach was introduced in EXIOBASE to estimate mass balances across physical inputs and outputs in dry matter terms. A part of this work involved the specific estimation of processes for handling waste and secondary products distinguished by material type.

In this work, we build on the EXIOBASE data set, utilizing the explicit handling of secondary production to model in a scenario context three broad policy initiatives. Taking a comparative scenario-based approach until 2030, we estimate the material, employment, and value creation impacts of the policy initiatives. With this work, we aim to show the direct and indirect effects of the technological change that comes about with a more circular economy, but we refrain for now to show the induced effects in the economy.

■ MATERIALS AND METHODS

In contrast to previous studies[34,37−39] that pay specific attention to the details of future metal demand based on specific low-carbon technologies/technology scenarios, this paper focuses on the economy-wide effects of a general group of circular economy measures and the implications these have for material extraction and employment around the globe. This section shortly introduces the multiregional input−output

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Table 1. Business-as-Usual (BAU) and Circular Economy Scenario Specifications

	BAU−IEA ETP 6 degree scenario	circular economy scenario		
		recycling	reducing	repair, reuse, and service
investment (gross fixed capital formation)	renewable energy technologies	assumption that production capacity grows commensurate to recycling levels and becomes available	savings from material efficiency allocated to R&D	reduction of final demand by 1% per year for all machinery products; reallocation to services such that motor vehicle savings are allocated to repair services and other savings to retail trade and renting services
input coefficients of technology production	machinery and equipment, electrical machinery and apparatus			
input coefficients of technology use	relative changes of electricity use	change in market shares from primary to secondary material producing industries (linear to a cap of 65%)	annual decrease of 1% in the use coefficients of both primary and secondary materials	
market shares of materials production	shares of electricity types and development of energy efficiency according to IEA ETP 6-degree scenario			

framework EXIOBASE, which underlies the analysis, summarizes the methodology used for extrapolating the system into the future, and describes the implementation of the circular economy scenario.

Using EXIOBASE To Model Production from Secondary Materials. For the MRIO EXIOBASE,[40] physical data in line with the framework provided by the System of integrated Environmental-Economic Accounting (SEEA) in order to ensure international consistency have been used in the compilation of the waste industries in the supply-and-use tables.[41] The physical data is used to estimate the relative share of primary and secondary production (under the assumption that they produce an equivalent end product from different inputs). This results in the differentiation between primary production and secondary production for 13 sectors: wood material, pulp, paper, plastic, glass, steel, precious metals, aluminum, lead zinc and tin, copper, other nonferrous metals, bottles, and construction material (see the list in Section 1 of the Supporting Information and details on the data and the construction process in refs 40 and 41). In the monetary supply-and-use framework, the corresponding waste products are treated as a service of handling of the waste product and have a zero value as it is assumed the price of the waste material is zero. However, the corresponding industries differentiate the production of materials both from original resources and from recycled materials. In the EXIOBASE construction, life-cycle inventory data was used to disaggregate the inputs into the primary vs the secondary industry (for example, the energy use into primary or secondary aluminum production). This was done at the coefficient level for the 13 sectors identified above, using generic (not country specific) life-cycle inventory data. The most important coefficients are different in the database between the two forms of production and at least include energy inputs and the main material content inputs; see ref 42 for a proper description of the data used in this part of the disaggregation in EXIOBASE. Estimates of the market share of primary versus secondary production are taken from available statistics.[42] It is assumed that the output of the primary and secondary production in terms of processed material is equivalent. In essence, the setup is very similar to the original waste IO model,[27] with specific processes set up to handle the treatment of waste, with their own input coefficient and emissions. One contrast is the implementation in a supply-and-use framework, which allows for a more formal specification of allocation between waste products and industries. The physical layering of EXIOBASE imposes a mass balance on the physical inputs and outputs at the product and industry level. Total mass of all relevant flows in the economy is estimated in dry matter units. The physical inputs into the economic supply chains and the emissions and other physical wastes from the economy are derived directly from the physical mass balances and complement the monetary IO data as environmental extensions. This allows for the estimation of emissions and other waste in physical terms and, if desired, the supply chain modeling in mixed units. In this work, we use the monetary layer of the EXIOBASE data set for the supply chain modeling, which ensures all supply chain data is kept in line with statistical data provided in country specific supply-and-use tables. This also ensures the modeling of monetary balances that have a large impact on value added and labor indicators.

EXIOBASE provides data for 44 countries and 5 rest of the world regions. It covers a range of environmental extensions and has 200 unique product groups and 163 industries. For full details, see Stadler et al.[43] To facilitate comparison of results from regions at different stages of development, we present results at the regional level. Each region is built upon data from individual countries and the rest of the region as a whole. The number of individual countries modeled within each region differs, with higher individual country detail for Europe (30), major economies in Asia and the Pacific (9), the Americas (4), and Africa (1) and only regional-level data available for the Middle East. We use indicators from EXIOBASE for material requirements,[44] employment per gender and skill levels (6 types of labor, male and female in high-, medium-, and low-skilled work),[45] and value creation (simply value added by sector). Material data includes all biogenic and nonbiogenic extractions from nature to the economy, whereas employment is measured in person-year equivalents.

Projecting EXIOBASE to 2030. To analyze the direct and indirect impacts that a transition to a more circular economy might have on the economy and the environment, we use the business-as-usual (BAU) scenario from Wiebe et al.[46] and implement an alternative circular economy scenario up to 2030. The BAU scenario is based on the International Energy Agency's Energy Technology Perspective (IEA ETP) 6-degree scenario.[47] The IEA scenario was chosen as BAU because of its no-policy-change projection of world GDP up to 2030 at country and sector levels, which have no direct relation to the circular economy scenario. As such, it can be seen as an independent no-policy-change scenario of the world economy, while still foreseeing major ongoing changes in the energy industry. The MRIO EXIOBASE is extrapolated into the future on the basis of the exogenously given parameters of the IEA ETP scenario and shortly summarized in the Supporting

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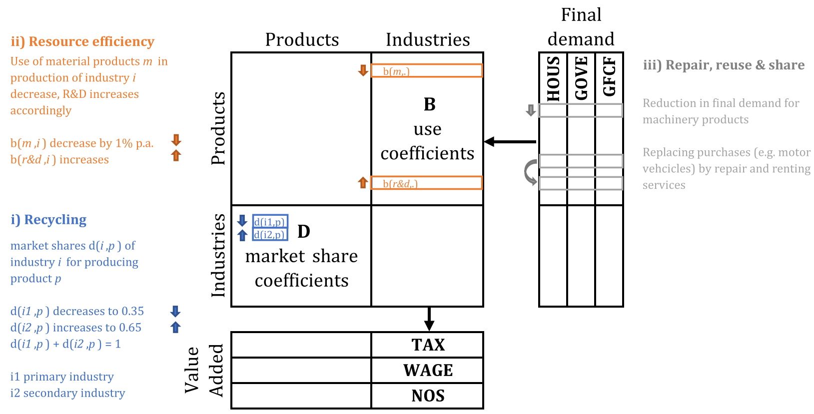

Figure 1. Changes in the SUT system for the three key aspects of the circular economy. The schematic representation of the SUT is adapted from ref 46. Copyright 2018 The Authors.

Information and explained in detail in the Supporting Information of Wiebe et al.[46]

Overall, the approach taken here is a typical IO scenario analysis, with all its virtues and drawbacks as, for example, described by Duchin.[36]

"What-If" Scenario Specifications. The BAU scenario is compared to a scenario which adopts three key aspects of the circular economy: (i) recycling, (ii) reduction in material consumption (i.e., higher material efficiency), and (iii) repair, reuse, and service. This scenario design touches three of the four tenets of the circular economy (the fourth being product design). All three have important sectoral implications in the extraction, manufacture, and waste management sectors. The scenarios are built on the major provisions of the Chinese, Japanese, and European circular economy legislation highlighted above and the approaches used by Scott et al.[48] to model increases in material productivity in the UK economy and identified by Aguilar-Hernandez et al.[49] There are clearly many more complex scenarios that could be modeled, and further research should aim for a more comprehensive assessment of different options compared to the two stylized extremes we present here.

The alternative scenario changes different parts of the supply-and-use tables, as summarized in Table 1 and described in more detail below. Figure 1 gives an overview on the parts changed in the table related to the three key aspects of the circular economy.

Rather than considering waste generation, as, e.g., in the supply-and-use approach to waste modeling in Lenzen and Reynolds,[24] here, we take advantage of the supply-and-use framework using the fact that one product, e.g., steel, can be produced by different industries: the industry that uses the primary resources and the industry that uses the recycled material. For the scenario, we exogenously choose the level of production of metals and other materials from recycled products relative to the production from primary resources such as metal ores, rather than using, e.g., the rectangular choice-of-technology (RCOT) model.[50] The RCOT model would endogenously determine the speed of the shift toward secondary material industry. As we aim to estimate the indirect supply chain effects of a strong increase in recycling activities, we chose to set the level of the desired outcome of circular economy policies exogenously.

The scenario is applied to the 43 countries and 5 rest of the world regions in EXIOBASE and implemented in relation to the BAU scenario. We have not fully endogenized capital investments in the model but assume that past investment patterns are sufficient to provide adequate capacity for waste treatment. A drawback of this approach is that investment patterns do not differ between the BAU and the alternative scenario (apart from the energy sector as defined by the IEA), as detailed information on the differences in the investment structure between the technologies is not available for implementation in an IO framework. Nonetheless, the modeling approach is general enough to incorporate more details in this respect once data becomes available, so it becomes possible to improve the current approach of the comparative static analysis to a more dynamic model.[36] A further assumption is that the products produced from the complementary technologies (that have as *inputs* primary *or* secondary materials) are equivalent and, thus, perfect substitutes. The entire system is constructed and projected in constant prices. We report price differences between the scenario due to more efficient use of material inputs (see Supplmentary Information) but do not model subsequent price effects (e.g., that may lead to changing demand). The goal of this research is not to forecast trends in the world economy; rather, we are interested in the differences in physical and socio-economic outcomes (nature inputs and employment outcomes) when certain technological and structural changes in the economy occur. We apply standard input−output analysis using the exogenously determined changes in final demand and the multiplier matrix based on the Leontief demand model.[51,52] As such, we are analyzing direct and indirect effects but do not model induced effects.[52] For determining the impacts on employment and material extraction, the usual input multiplier matrix is multiplied with the respective stressors, i.e., employed persons (in thousands) per unit of output or materials (in tons) per unit of output.

We compare the consumption- and production-based material and employment implications of the adoption of circular economy principles to understand how consumption-based decisions in one region affect environmental and socio-economic outcomes in another.

Recycling. The recycling component of the scenario is based on the circular economy principle that waste is a resource. Elements in waste can be reprocessed to replace inputs from primary industries. Paper, metals, plastics, and glass are routinely separated and recycled. In their Circular Economy Strategy, the EU has set the target of recycling 65% of

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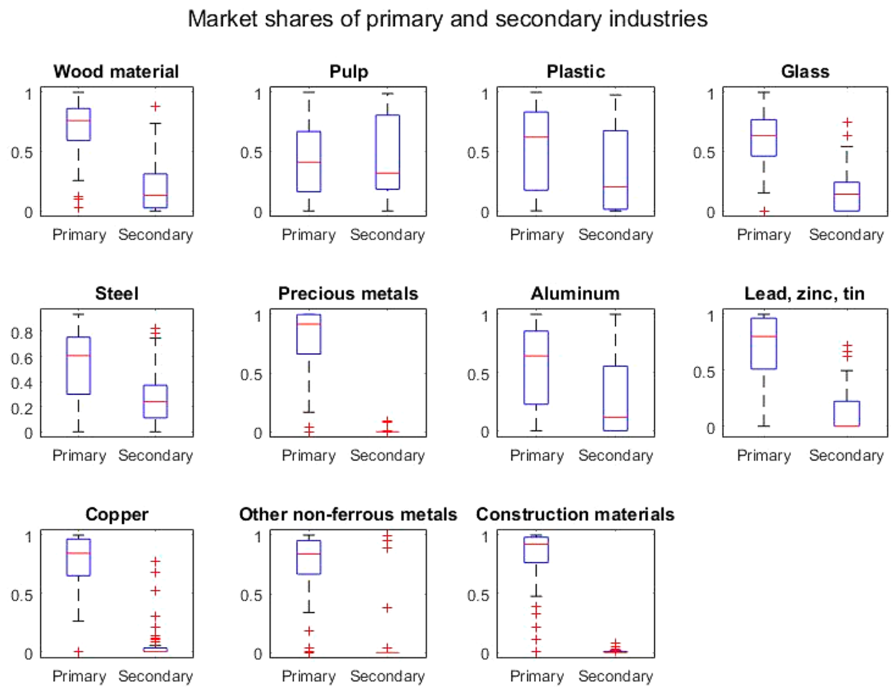

Figure 2. Distribution of different market shares of primary and secondary industries across countries in 2014.

municipal waste by 2030. Translating this target directly into the supply-and-use framework is unfortunately not possible. In EXIOBASE, growth in recycling can be reflected by the replacement of intermediate goods from extractive industries (e.g., manufacture of basic iron and steel or manufacture of glass and glass products) by intermediate goods from recycling industries (e.g., reprocessing of secondary steel into new steel or reprocessing of secondary glass into new glass). We assume the price of the products produced from recycled materials to be the same as the one of products produced from raw materials. The final output of the industries is assumed to be the same (for example, steel produced from iron ore or from scrap is the same steel). The difference lies in how the production is distributed between the primary and secondary industries. Eleven primary industries in EXIOBASE can be replaced by recycling, as shown in Figure 2. By changing the market shares in the supply matrix from the manufacture from raw materials to the reprocessing of materials, we assume that the products are produced more and more by the industries that use waste materials (secondary industry) rather than by the industries that use the primary materials (primary industry). We linearly increase the market shares of the secondary industries in every country from their current share (displayed in Figure 2) to 65% in 2030, if the current share is not already higher. This number has been chosen to mirror the current situation, where the primary industries have an average median of about 65%. This will reduce the demand for primary material extraction.

Figure 2 displays the cross-country distribution of the market shares for the 11 selected industries in 2014. The boxplots show the distribution of the market shares of the primary and secondary industries across countries. The median is the red line in the middle; e.g., the median market share for primary wood is about 75%. In half of the countries, the market share of primary wood in total wood products is higher than 78%. The blue box contains 50% of the observations, 25% below and 25% above the median. That means that, for half the countries, the market share of primary wood is between 60% and 85%. The black lines indicate the spread of the lowest/highest 25%, and the red crosses are outliers. From these, it is obvious that there are some materials with very high recycling rates in some countries, such as pulp, plastic, steel, and aluminum. For other materials, however, less than half the countries are having any secondary material production, such as precious metals, lead, zinc and tin, copper, other nonferrous metal, and construction materials.

In summary, the alternative scenario assumes a linear growth in the secondary industries (recycling, reprocessing) reaching a market share of 65% in 2030 in all countries. This growth is accompanied by equivalent decreases in the primary manufacture of these goods, which in turn, reduces the demand for the corresponding material extraction. That means that only 35% of the respective processed material is produced from raw materials; 65% is produced on the basis of recycled material. The scenario does not take into account the reprocessing of other forms of waste (e.g., organic waste) as other inputs (e.g., compost).

Reducing Material Inputs. A second element of the circular economy relates to a higher durability of goods. The durability of goods can involve more materials used per good but lower material use overall. In the case of beer, the use of reusable bottles may bring about 20% cost reductions. Though each individual bottle would require a 34% increase in glass used, the fact that each bottle is reused up to 30 times reduces the overall material used. The same applies to garments that require more resistant fibers but fewer overall as they last longer.[53] In this sense, durability is equivalent to pointing to a higher material efficiency. The scenario thus assumes that material efficiency gains in the circular economy scenario grow faster than in the BAU scenario, by assuming a 1% annual growth. This additional growth could have important consequences. For example, buildings in the European Union account for 42% of the final energy consumption, about 35% of greenhouse gas emissions, and more than 50% of all extracted

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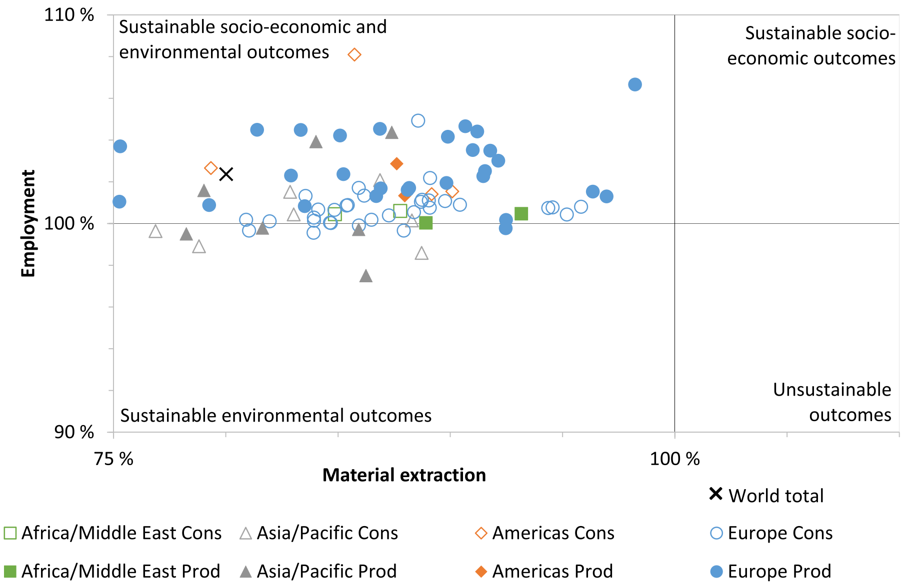

Figure 3. Comparing relative effects of consumption- and production-based outcomes to the baseline in 2030: Each country/region is represented by two markers in this figure: the solid, which represents the differences between the scenarios in material extraction and employment from the production side, and the outlined marker, which shows the differences from the consumption perspective, i.e., how much material and labor are embodied in the final consumption of that country. The different world regions are highlighted in different shapes/colors, even though no significant differences between the world regions are observed.

material, and thus, the use of better construction materials and the use of these buildings could lead to reductions in the EU's energy and material demand.[54] In EXIOBASE, this is modeled by decreasing the use coefficients of primary and secondary materials in the manufacturing industries. The savings from lower material use are reallocated to research and development (R&D). This modeling is not exact, meaning that there could be a time lag between the R&D investments and material efficiency improvements. This lack of endogenous dynamics is a drawback of the current approach and will need to be improved. Theoretical models for this exist (see, e.g., refs 52, 55, and 56), but empirical implementation is challenging and is still lacking.

Through interindustry relations in the IO framework, a lower use of materials in the manufacturing industries translates to lower intermediate demand for materials from the primary and secondary material processing industries. This in turn lowers the demand for products from the material extraction industries, which leads to lower material extraction from nature.

Repair, Reuse, and Share. The circular economy emphasizes the repair and reusability of goods. Goods are repaired and reused at a higher frequency not discarded and replaced. The circular economy also emphasizes use in terms of a service industry in opposition to use in terms of ownership. The circular economy thus embraces the sharing economy.[57] For example, for Europe McKinsey calculates the feasibility to grow resource productivity by up to 3% annually looking at the systems for three human needs (mobility, food, and built environment). This would generate a primary resource and nonresource and externality benefit to a total of around €1.8 trillion versus today. This would translate into an increase in gross domestic product of as much as 7 percentage points relative to the current development scenario, with additional positive impacts on employment.[58] To be on the conservative side and to account for lower implementation capacity in emerging and developing countries, per year, we shift 1% of final demand for all machinery products to repair and reuse in EXIOBASE. The fall in the final demand for motor vehicles is compensated by a corresponding increase in repair services (repair). The fall in the final demand for all other machinery is compensated by an increase in retail trade and renting service (reuse and share). Implementing these changes exogenously into the model, i.e., using expert knowledge for scenario specification, has a long history in IO analysis.[36,59]

■ RESULTS

The adoption of the circular economy leads to a significantly lower global material extraction when compared to the BAU scenario. Global results range from a decrease of about 27% in metal extraction to 8% in fossil fuel extraction and use, 8% in forestry products, and about 7% in nonmetallic minerals. These changes result from the increased demand for reprocessed products as opposed to those stemming from primary extraction in addition to the obvious effect of increased material efficiency, which reduces material use. These results are in line with feasibility assessments from McKinsey and studies by the International Resource Panel.[58] Results differ by region, with material extraction falling the most in the Americas and not changing at all for certain industries in Europe. As compared to McKinsey's European assessment, this is not surprising when taking a global perspective. In the EU, over the last two decades, manufacturing shifted to Asia with much lower material efficiency in producing countries but significantly increasing material efficiency in EU importing countries.[2]

Given the linkages between material extraction with other industries and the sectoral distribution across regions, the adoption of the circular economy has diverse impacts on employment and environmental pressures. Worldwide, about 10% less material is extracted, while slightly more people are employed (marked with an × in Figure 3). In the circular economy scenario, practically all countries/regions have a

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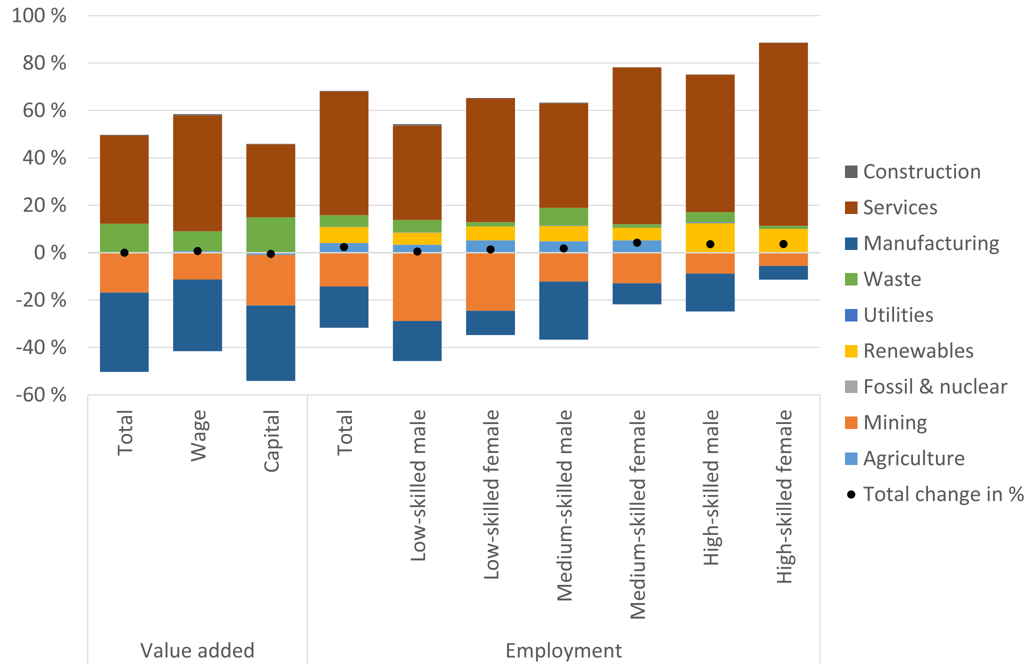

Figure 4. Sectoral contribution to total difference between scenarios: value added and employment.

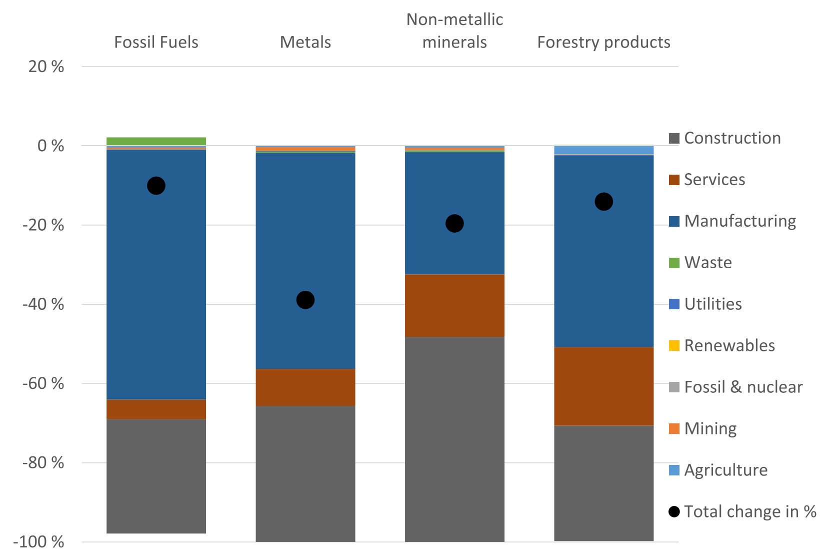

Figure 5. Sectoral contribution to total difference between scenarios: material extraction due to final demand for products.

predicted material extraction lower than 100% of the BAU scenario. In most countries, the adoption of the circular economy promotes employment, as the majority of observations lie above the employment predicted by the BAU scenario (100%). All points in the top-left panel of Figure 3 are considered sustainable outcomes of the circular economy scenario: employment increases, while fewer materials are used. The top-right quadrant of the Figure 3 indicates employment and material use increases, which is interpreted as "sustainable socio-economic outcomes", while a reduction in both indicators reflects "sustainable environmental outcomes" (lower-left quadrant). A reduction in employment and an increase in material use would reflect unsustainable outcomes (lower-right quadrant).

Figure 3 also decomposes findings according to the materials used in production (territorial material use, solid markers) or those embedded in consumption (material footprint, outlined markers). The production perspective indicates what happens within the country due to changes in the production, e.g., the direct and indirect domestic impacts on employment of the increasing share of the recycling industries. The consumption perspective shows the change in the outcomes induced through the countries' final demand domestically and internationally. For a further illustration of the difference in production and consumption-based measures of material use, see, e.g., refs 16 and 44.

Consumption-based impacts affect multiple countries through international trade, while sustainable production patters are mainly determined through domestic action. Hence, even if the domestic technology is improved significantly, through the consumption of a mix of products produced with domestic and foreign technologies, the sustainability of consumption may not increase as much, but also the opposite is true: even if there is no technological

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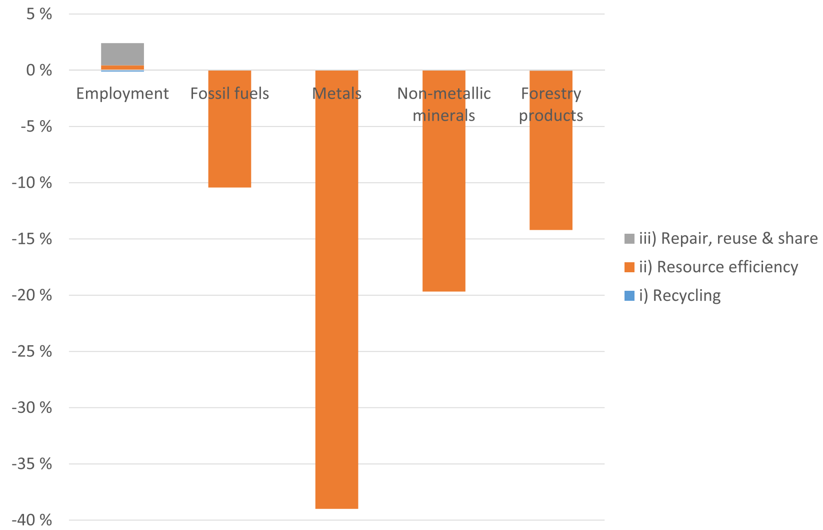

Figure 6. Contribution of the three key aspects of the circular economy to the results.

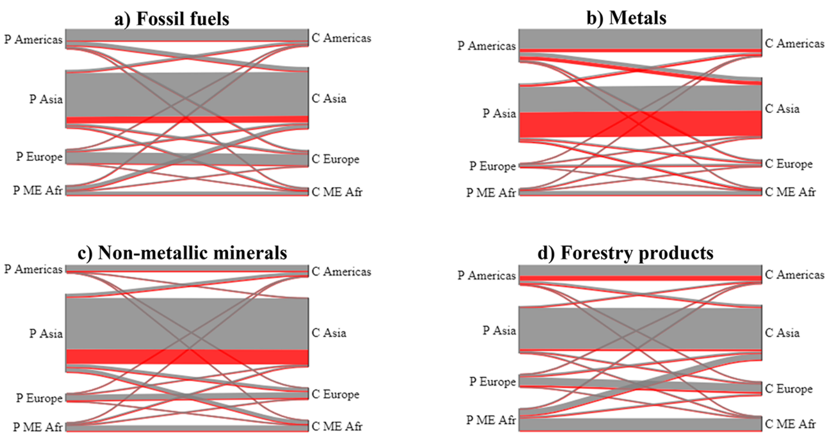

Figure 7. Reduction in trade in embedded materials.

change domestically, the country's consumption may become more sustainable through the import of goods produced abroad adopting circular economy principles.

While Figure 3 shows that employment outcomes are similar or slightly higher in the circular economy when compared to the BAU scenario, Figure 4 outlines how this general average masks important reallocation across industry sectors. Value added shifts from the capital intense industries mining and manufacturing to more labor-intensive service industries. In line with that, employment is expected to decline in mining and manufacturing, and these sectoral employment losses will be compensated by growth in the renewables and service sectors. As shown in Section 2 of the Supporting Information, the employment intensity of the secondary industries is not necessarily higher than that of the primary industries. That means that the positive effects on employment are mostly indirect effects through the upstream value chain and the increase in the demand for repair and renting services. On average, the aggregate demand for employment by skill level and gender will not change substantially. However, the circular economy will shift the demand from mining and manufacturing to service and renewables with slightly higher skill levels. While there are possible negative outcomes for low-skilled workers, the shift to a circular economy could contribute to higher labor force participation of women and accelerate the demand for skills upgrading in the workforce. This follows the increased demand in services and goods and services from the waste management and renewable energy industries (Figure 5). For both material and socio-economic indicators, industries in the waste management sector (see Section 1 in the Supporting Information for a list of these industries) have a positive effect on the overall change. This is due to the increased market shares of industries reprocessing secondary materials. The small positive impacts on material extraction due to demand for production from these secondary industries are more than offset by significant reductions in material extraction for the primary material processing industries.

Figure 5 shows the material implication of these changes. Adopting a circular economy results in lower demand for fossil fuels, metals, nonmetallic minerals, and forestry products. The reduced economic activity in utilities, production of fossil fuel-based electricity, and mining in the circular economy scenario, vis à vis the business-as-usual scenario, results in a substantially lower material footprint worldwide. Almost all of the decrease in material use stems from increased resource efficiency, while the positive employment impact is dominated by increased repair, reuse, and share; see Figure 6.

Given the economic linkages across borders, consumption of goods in one region impacts the production of goods and the material extraction in other regions.[16,60] Considering this

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perspective is important because the development in one region in the world can increase pressures in other regions, depending on the scarcity of resources.[61] For all world regions, both production and consumption of materials are lower in the circular economy than in the BAU scenario.

Figure 7 maps[62] the material flows between regions, as they are produced (P) in one region (left) and consumed (C) in another region (right). The red parts mark the reduction in material flows that results from the adoption of the circular economy. That is, the size of the gray parts display the flows in the circular economy scenario, while the total (gray + red) indicates the material flows in the baseline scenario. Some parts of the lower material extraction are due to consumption abroad as noted by the red share of the flows between the different regions in Figure 7. Most of the reduction, however, is due to decreased intraregional use, i.e., the red flows between production P (on the left) and consumption C (on the right) of the same region.

The top-left panel in Figure 7 shows that a large share of the fossil fuel materials extracted in the Americas can be traced to the consumption of these materials embodied in goods and services consumed in Asia and, to a lower extent, Europe and Africa and the Middle East. In the scenario of the circular economy, the reductions in fossil fuel demand result in a decline of extraction in the Americas but also in lower fossil fuel induced by the consumption of Asia and the Pacific and Europe. For the Middle East and Africa, most of the reduction in fossil fuel production however stems from reduced demand in the other regions not from reduced demand within the Middle East and Africa.

For all other materials, the adoption of the circular economy in Europe and Asia has an important impact in the material extraction of Africa and the Middle East as well. The reduction in global metal extraction is dominated by the reduced intraregional flows in Asia and the Pacific (reducing both consumption and production by almost 40%), while the reduction in global extraction of forestry products is dominated by the reduction in intraregional flows in the Americas. A large part of Africa's forestry products is embodied in Asian consumption. Europe has consistently higher consumption of embodied materials than extraction of materials but overall the smallest share in the world, especially regarding metals, where consumption is expected to be cut by more than 20% compared to the BAU scenario.

■ DISCUSSION

Increasing rates of recycling, reducing material inputs, and promoting repair, reuse, and sharing are three principle strategies to achieve increased rates of resource efficiency while not negatively affecting economic development or employment. In this work, we model these three strategies at the global level to give a first insight into some of the indirect global supply chain cobenefits (or costs) of these strategies. While many policy and behavioral barriers must be overcome to realize the potential benefits of circular economy measures, our analysis provides an insight into the potential effects that these measures will have, considering the indirect reliance on materials and employment and being value added. The use of a global multiregional input−output model allows us to give insight into the potential direct and indirect impacts on global trade flows and spillover effects compared to the situation we have today.

Overall, we find that there is a small positive effect on employment, no significant effect on being value added, other than a shift from capital intensive to labor intensive industries, and a strong decrease in material extraction. The latter is what the scenario was built to achieve, while the two former results reflect the direct and indirect economic effects through changes in global supply chains. The positive effect on employment must be analyzed in detail, as the number of employees needed in both manufacturing and mining industries is expected to decrease. This is strongest for the employment of low- and medium-skilled male workers. The number of employees needed in the service sector is expected to strongly increase, with the highest increase in demand for jobs that are currently occupied by medium- and high-skilled female workers. These results clearly show that a retraining of workers is necessary to supply the labor market with a skilled workforce that is ready to take on the challenges of a circular economy. This is particularly important for the workforce in Asian economies, where a large number of low-skilled jobs in manufacturing are located.

From the theoretical perspective, the approach is on the simpler side of input−output-based scenario analysis, but according to our knowledge, this is among the first high-resolution MRIO-based scenario calculations. There are two main aspects that we would highlight in advancing the research agenda. First, the increased resolution of input−output databases and the increased data quality on tracking material flows through the economy will allow for more refined and precise estimates, especially around the actual potential for the circular economy measures. Further development of Waste Input−Output approaches (globally), the further integration of technological detail from life-cycle inventory work to input−output models, and expanded coverage of life-cycle inventory work (especially related to nonmaterial inputs and regional detail) are areas that need more work. One key component of understanding the potential success of the measures is to have a better understanding of stocks, as is common in material-flow analysis research (e.g., refs 63 and 64). Rather than parametrizing the success of measures (as is done here), a next step for future research is endogenizing the potential, through the use of dynamic input−output methods. These consider induced effects in the economy by endogenizing technological change and required investment.[50,55,56,65−67] This will give additional insights into the temporal dynamics, the links between possible secondary production, the capital and investments required for the production, and the material stocks becoming available for reuse. Detailed data on consumption of fixed capital (CFC) for MRIO systems has recently become available, and first analyses show the importance of capital for the accounting of CO_2 emissions.[68−70] For materials, including capital is even more important. As a way forward, we envision the estimation of a capital requirement matrix from the CFC and related data.

The second aspect of this research that we would like to highlight resolves around the better understanding of economic development in the global south, where a significant share of material extraction occurs. Our study (and the underlying MRIO database of EXIOBASE) has only basic coverage of both economic structure in the global south and the development pathways that they are expected to follow. Given the employment effects in the global south, its rapid development, and the generally increased quantities of materials embodied in trade from the regions, having a better

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understanding of the technology, the industrial structure, and the development pathways in these regions may have a strong impact on understanding the dynamics of global supply demand relationships. In particular, further statistical work in these regions will enhance the opportunity for global models such as EXIOBASE to provide more accurate representation.

The circular economy is an attempt to achieve both economic and employment growth while minimizing resource use. Whether this can be realized remains to be seen, but here, we attempt to model some of the macro-economic impacts of policy measures relevant for the circular economy. The model is a forward-looking what-if scenario analysis, and we consider three different aspects of a circular economy: higher recycling, more efficient use of materials, and repair and sharing of final goods. We model and analyze the structural changes in both the final and intermediate demand that are necessary to achieve a more circular economy.

Utilizing the what-if scenarios, our results show that the adoption of the circular economy can lead to a significantly lower global material extraction compared to a baseline. Global results range from a decrease of about 27% in metal extraction to 8% in fossil fuel extraction and use, 8% in forestry products, and about 7% in nonmetallic minerals. At the same time, we see a small increase in employment, as demand causes a shift in the need for employment from resource extracting sectors to the service sector. In particular, this will provide more opportunities for high-skilled and female employment, while demanding specific attention to alleviate negative impacts from reduced demand for low-skilled workers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b01208.

> List of waste industries in EXIOBASE; information on how to project EXIOBASE to 2030; figure of compensation of employees shares; description of price changes based on the Leontief price model (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: kirsten.wiebe@sintef.no.

ORCID

Kirsten S. Wiebe: 0000-0003-3105-4194

Richard Wood: 0000-0002-7906-3324

Present Address

¶K.S.W.: SINTEF Industri, Department of Sustainable Energy Technologies.

Author Contributions

‖K.S.W. implemented the model, designed by all authors. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

BAU	business-as-usual (scenario)
C	Cons, Consumer
IEA ETP	International Energy Agency's Energy Technology Perspectives (publication)
IO	input−output
MRIO	multiregional input−output
P	Prod, Producer
R&D	research and development

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