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The Macroeconomics of the Circular Economy Transition

A CRITICAL REVIEW OF MODELLING APPROACHES

Andrew McCarthy, Rob Dellink,
Ruben Bibas

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THE MACROECONOMICS OF THE CIRCULAR ECONOMY TRANSITION: A CRITICAL REVIEW OF MODELLING APPROACHES - ENVIRONMENT WORKING PAPER No. 130

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ABSTRACT

This paper reviews the existing literature on modelling the macroeconomic consequences of the transition to a circular economy. It provides insights into the current state of the art on modelling policies to improve resource efficiency and the transition to a circular economy by examining 24 modelling-based assessments of a circular economy transition. Four key conclusions emerge from this literature. First, most models find that a transition to a more circular economy – with an associated reduction in resource extraction and waste generation – could have an insignificant or even positive impact on aggregate macroeconomic outcomes. Second, all models highlight the potential re-allocation effects – both between sectors and regions – that the introduction of circular economy enabling policies could have. Third, certain types of macroeconomic model are more appropriate for assessing the transition than others, notably due to their accounting of interactions between sectors and macroeconomic feedbacks. Fourth, of the assumptions that are fed into these models – those concerning future rates of productivity growth, the substitutability between different material types, and future consumption patterns – are key determinants of model outcomes.

Keywords: Circular economy, resource efficiency, natural resources, raw materials, general equilibrium model.

JEL Classification: C68, O13, Q53.

RÉSUMÉ

Ce rapport passe en revue les travaux existants sur la modélisation des conséquences macroéconomiques de la transition vers une économie circulaire. Quatre conclusions clefs émergent de l’examen de 24 études, qui constituent l’état de l’art de la modélisation des politiques d’efficacité des ressources et de transition vers une économie circulaire. Premièrement, la transition vers une économie plus circulaire, en l’associant avec une réduction de l’extraction de ressources and de la production de déchets, aurait pour la plupart des modèles un impact macroéconomique négligeable voire positif. Deuxièmement, tous les modèles soulignent les potentiels effets de réaffectation entre secteurs et entre régions que l’introduction de ces politiques pourrait engendrer. Troisièmement, certains types de modèles macroéconomiques sont plus appropriés à l’évaluation de la transition que d’autres, en particulier du fait de leur prise en compte des interactions entre secteurs et des rétroactions macroéconomiques. Quatrièmement, les hypothèses intégrées par ces modèles concernant l’évolution future des taux de croissance de la productivité, de la substituabilité entre différents matériaux, et des modes de consommations sont des déterminants majeurs des résultats des modèles.

Mots clés : économie circulaire, efficacité des ressources, ressources naturelles, matières premières, modèle d’équilibre général.

Classification JEL: C68, O13, Q53.

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EXECUTIVE SUMMARY

Natural resources, and the materials derived from them, represent the physical basis for economic growth. Recent decades have witnessed an unprecedented growth in demand for resources. This has sparked increased interest from policymakers in a transition to a more circular economy. Three main reasons are often highlighted for promoting a circular economy transition. First, reduced extraction, processing, and disposal of natural resources may have significant environmental synergies; more efficient resource use could represent an important tool for achieving climate and other environmental goals. Second, the reduced reliance on critical resource and material inputs and improved security of materials access that result from expanded domestic secondary material supply is important; supply risks associated with future geopolitical shocks could be mitigated in importing countries. Third, the activities that will drive any circular economy transition could also become significant drivers of job creation and economic growth. New opportunities will emerge in various sectors, including secondary material production, repair and remanufacture, the services sector, and the sharing economy.

The focus of this paper is to review the literature on the third point, i.e. the macroeconomic implications of the transition to a more circular economy and increased efficiency in the use of material resources. Addressing this issue is complex. Any such transition will involve multiple interactions between different sectors and countries, and will take place in parallel with other trends like digitalisation and automation. Ex ante, economy-wide quantitative models appear to be best suited to analysing this transition as they capture the major drivers of the economic consequences. Furthermore, there is insufficient ex-post data on the consequences of circular economy enabling policies for a robust empirical assessment. As such, the analysis in this paper is restricted to studies that have used macroeconomic models. However, in this context, such models are also only recently emerging; 15 of the 24 studies considered are either currently in progress or were published since 2015.

There is no single commonly accepted definition of the term “circular economy”, but different definitions share the basic concept of decoupling of natural resource extraction and use from economic output, i.e. increased resource efficiency as outcome. One core view of the circular economy is that it can be defined relative to a traditional linear economic system, i.e. one that focuses on closing resource loops. A second, slightly broader, view of the circular economy stresses the importance of slower material flows, either within an economy with some degree of material circularity, or within one that is more linear. The third, and broadest, view of the circular economy is that it involves a more efficient use of natural resources, materials, and products within an existing linear system. This broad view of the circular economy affects potentially all economic activities, not only those that have a high material use profile, and is the one applied in most modelling assessments and in this review.

Four key conclusions emerge from the existing literature. First, most economic models find these shifts will have an insignificant or even positive impact on aggregate macroeconomic outcomes. In other words, the current literature indicates that a transition to a (broadly defined) circular economy – with the associated reductions in resource extraction and waste generation – could take place with potentially significant positive (or at least without negative) consequences for economic growth or overall employment. Second, all models highlight the potential re-allocation effects that the introduction of circular economy enabling policies could have. The competitiveness of material intensive sectors – natural resource extraction and certain types of manufacturing – will probably decline; workers, regions, and

countries specialising in these activities may be made worse off in any circular economy transition. Other sectors – waste management and recycling, remanufacturing and repair, and services more generally – will probably expand as their output becomes relatively affordable. Third, dynamic multi-region models are well suited to capturing the transition in the economy, as well as the socioeconomic trends and trade impacts that will accompany any transition. In contrast, (static) single region models may be better suited to representing material circularity in more detail. Fourth, three key sets of assumptions that drive modelling outcomes, and the quality of the policy advice that emerges from them, are identified: (i) assumptions on future efficiency improvements (e.g. future rates of material productivity growth, cost of the underlying drivers, and role of policies), (ii) assumptions on the degree of substitutability between primary and secondary materials, both for different materials, and in different applications, and (iii) assumptions on the changes in the future structure of the economy and consumption patterns, and to what extent will these take place in the absence of policy drivers.

LIST OF ABBREVIATIONS

CES	Constant elasticity of substitution
CGE	Computerised general equilibrium
DMC	Domestic material consumption
EEMRIO	Environmentally extended multi-region input output
EPR	Extended producer responsibility
ME	Macro-econometric
MRIO	Multi-region input output
REE	Rare earth element
RMC	Raw material consumption
SAM	Social accounting matrix
SSP	Shared socioeconomic pathways

1. INTRODUCTION

1.1 Context

Natural resources, and the materials derived from them, represent the physical basis for economic growth. Land, water, and a variety of mineral-based fertilisers are critical inputs in our food production system. Coal, oil, and natural gas, despite receiving a diminishing share of new energy investment, continue to dominate the energy mix in many countries. Iron transformed into steel, and non-metallic minerals transformed into cement, are central to infrastructure development. Bauxite transformed into aluminium is important to the transport sector, while the group of rare earth elements are vital inputs across a range of low carbon technologies.

Recent decades have witnessed an unprecedented growth in demand for resources. This has been driven by the rapid industrialisation of emerging economies and continued high levels of material consumption in developed countries. As a result, the weight of materials consumed worldwide has more than doubled since 1980, and increased ten-fold since 1900. In 2013, global extraction of minerals, fossil fuels, and biomass reached 84 billion tonnes (SERI, 2017), or around 30 kilograms per person per day. There is also considerable variation across regions; material consumption in developed countries tends to be several times higher than that in developing ones (Wiedmann et al., 2015).[1]

By 2050, the world population is expected to increase from about 7 billion to more than 9 billion, and the per capita income of the world's population to roughly triple (OECD, 2012). This will substantially increase demand for natural resources, especially if global production and consumption patterns converge with those of OECD countries. Robust projections of future global resource consumption are scarce (OECD, 2012; OECD, 2016a), however UNEP's International Resource Panel (UNEP, 2017) has projected that total resource use may more than double by 2050 if existing trends continue. Unless the efficiency with which resources are used is significantly improved, this is likely to lead to increasing input costs and, for some resources, a growing risk of supply shortages (e.g. Coulomb et al. 2015).

Business as usual resource use will also increase the environmental impacts that are associated with harvesting resources, processing and using them, and disposing of the resulting waste. Areas of particular concern include the local environmental damages and greenhouse gas emissions associated with material extraction and processing (e.g., Nuss and Eckelman (2014). Interestingly, not many of the studies surveyed in this paper make the environmental benefits associated with improved resource efficiency and a transition to a circular economy explicit. These benefits include the energy savings while recycling energy-intensive materials. For instance, every ton of steel scrap made into new steel, over 1,400 kg of iron ore, 740 kg of coal, and 120 kg of limestone are saved (World Steel Association, 2012). Similarly, the aluminium production from scrap requires around 10% of the energy input of primary aluminium production (IEA, 2015). Clearly, environmental impacts associated with material extraction differs widely between materials and extraction and processing technologies, and advanced extraction methods may not be more harmful than dirty recycling techniques. Nonetheless, many papers have an implicit assumption that a transition from primary to secondary materials will reduce environmental pressures. A detailed global analysis of the net environmental impacts of such a transition is however beyond the scope of the economic assessment in this paper.

1 On a raw material consumption (RMC) basis, i.e. where the materials embodied in imports are accounted for.

1.1.1 The growing interest in a transition to a more circular economy

These issues have led to increasing interest in the circular economy and improved resource efficiency in recent years (see Box 1 for an introduction to the key terminology used in this paper). At the international level, a succession of multilateral initiatives and frameworks have been introduced. An OECD Council Recommendation issued in 2008 encouraged member countries to "take appropriate actions to improve resource productivity and reduce negative environmental impacts of materials and product use". In the same year, G8 environment ministers signed the Kobe 3R Action Plan, in which countries agreed to prioritise implementation of 3Rs[2] policy in order to improve resource productivity. There have also been several important recent developments. The creation of the G7 Alliance on Resource Efficiency at Schloss Elmau in 2015, and the subsequent adoption of the Toyama Framework on Material Cycles[3], signalled increasing interest from G7 countries. The inclusion of specific goals[4] related to resource efficiency in the 2030 Agenda for Sustainable Development also represented a major landmark. Finally, the introduction of resource efficiency into the G20 agenda in 2017 was notable, particularly given the presence in that forum of various countries with large resource endowments.

Box 1. Definitions: circular economy, resource efficiency, secondary materials and decoupling

There is no single accepted definition of a circular economy. The precise meaning of a "transition to a circular economy" varies across the current literature, but tends to involve reduced demand for certain natural resources, and the materials that are derived from them. The resources usually emphasised are minerals (both metallic and non-metallic), fossil fuels, and various biotic resources such as forestry, fish, or other biomass. Relatively little attention tends to be given to other resources: land and water are the most obvious examples.

Three main mechanisms for reduced demand are often highlighted (e.g., Bocken et al., 2016). *Creating material loops* involves the substitution of secondary materials (i.e. those that have been used already in production processes and are derived from the recycling of industrial or household waste) and second-hand, repaired, or remanufactured products for their virgin or new equivalents. *Slowing material flows* involves the emergence of products which remain in the economy for longer, usually due to more durable product design. *Narrowing material flows* involves the more efficient use of natural resources, materials, and products, either through the development and diffusion of new production technologies, the increased utilisation of existing assets, or shifts in consumption behavior away from material intensive goods and services. In sum, a "transition to a circular economy" could therefore be seen as involving any process that might lead to lower rates of natural resource extraction and use. This is the definition that is used in this review (see Section 1.2.1 for further details).

Resource productivity is more easily defined. It refers to "the effectiveness with which an economy or a production process is using natural resources" OECD (2015b). Resource efficiency is generally used in a broader sense. It is used by UNEP (2017) to refer to a set of ideas including: (i) the technical efficiency of resource use, (ii) resource productivity, or the extent to which economic value is added to a given quantity of resources, and (iii) the extent to which resource extraction or use has negative impacts on the environment. In concrete terms, resource efficiency, or more precisely resource intensity, can be calculated as the ratio between the value of economic output from a particular sector or economy, and the amount of resources (typically in terms of weight) used to produce it. This is the definition used in this paper. An improvement in resource efficiency therefore describes a situation where more economic value is being produced with a particular amount of resources (or one where fewer resources are being used to produce a particular level of economic value).

Decoupling is used to describe an improvement in resource efficiency, usually at the aggregate level of an economy. Relative decoupling refers to a situation where the value of economic output and the amount of resource inputs are growing, but with the former at a higher rate than the latter. This process has been well documented at the level of the global economy during the last 30 years (OECD, 2016). Absolute decoupling refers to a situation where the value of economic output is growing while the amount of resource inputs used is shrinking. There is little evidence for absolute decoupling in any country once the materials embodied in intermediate imports are taken into account (e.g. OECD, 2016, Wiedmann et al., 2015).

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2 3Rs = reduce, reuse, recycle.

3 In which G7 countries committed to taking ambitious action on resource efficiency.

4 For example, goal 8 is to "promote inclusive and sustainable economic growth, employment and decent work for all" while goal 12 seeks to "ensure sustainable consumption and production patterns".

A circular economy transition, to the extent that it results in lower resource extraction without an associated reduction of economic output, can result in improved resource efficiency and decoupling. Whether this is possible is the main question addressed in the studies considered in this review.

There has also been tangible policy action by a number of governments. Circular economy roadmaps were introduced in the People's Republic of China (hereafter China) in 2013, in the European Union in 2015, and in Finland, France, and the Netherlands in 2016. Several of these roadmaps include specific quantitative targets on resource efficiency, recycling rates, or disposal quotas. For example, China has a stated objective of reusing 72% of industrial solid waste (Mathews and Tan, 2016) while the Netherlands is aiming for a 50% reduction in the use of virgin resource inputs by 2030 (MIE, 2016). Other countries have introduced national policy frameworks related to resource efficiency or materials management. Japan's Fundamental Law for Establishing a Sound Material-Cycle Society is supported by regulations on the management of specific waste streams, and targets a cyclical use rate of 17% by 2020 (MoE, 2013). The Sustainable Materials Management Program Strategic Plan in the United States focuses on tracking and reducing the overall amount of materials disposed of, reducing lifecycle environmental impacts of materials, and increasing socio-economic benefits from materials. It includes a national target of a 50% reduction in food waste by 2030 (US EPA, 2015).

The transition to a more circular economy, and to improved resource efficiency, is not usually considered to be a policy goal in itself. Rather, it is the economic, environmental, and social gains that might accompany such a transition that seem to be of interest for governments. Four specific sets of benefits tend to be highlighted in discussions of a circular economy transition:

- Increased demand for natural resources will increase the wastes and emissions generated in extraction, processing, consumption, and disposal activities. The resulting deterioration in environmental quality could become a bottleneck for continued improvements in living standards. In this context, policymakers see synergies between natural resource decoupling and achieving various environmental objectives. In particular, there is increasing awareness that more efficient material management can be a useful tool for meeting national level climate commitments. Around 50% of industrial CO_2 emissions can be attributed to the production and processing of five basic materials (FMEAE, 2015) – steel, cement, paper, plastic, and aluminium – most of which have secondary equivalents that are considerably less energy intensive to produce.
- It is also pointed out that increased domestic secondary material production to reduce imports and production of virgin material resources can reduce supply risks associated with future geopolitical issues. This is especially relevant for metallic mineral resources which, among other things, are highly geographically concentrated, amenable to recycling, and critical inputs in an increasing number of applications. The oil shocks of the 1970s and the recent Chinese export quotas on rare earth elements (REEs) represent historic examples of such supply risks.
- It is often suggested that the activities that will drive any circular economy transition could also become significant drivers of re-industrialisation, job creation, and economic growth. New opportunities will emerge in various sectors, including secondary material production, repair and remanufacture, the services sector, and the sharing economy. Further, early adopting countries could realise additional benefits by becoming exporters of circular economy expertise and technology. In this view of the circular economy, there is a win-win proposition that is not being realised.
- International fora emphasise that large increases in demand for natural resources will be associated with a growing and increasingly affluent global population (G7, 2016; UNEP, 2017). Given the finite nature of many natural resources, it is often concluded that future resource scarcity could become a drag on long run economic growth. In this context, decoupling of

economic output from natural resource use is seen as a vital ingredient for sustainable development. From an economic perspective, it may make more sense to look at resource criticality, i.e. a combination of risk of supply disruptions and economic importance, rather than absolute scarcity (Coulomb et al., 2015).

1.1.2 The macroeconomic impacts of a circular economy transition are not well understood

The focus of this review paper is on the third point: the macroeconomic implications of a transition to a more circular economy and increased efficiency in the use of material resources. It is clear that the policies required to drive any such transition will result in structural shifts involving the decline of certain sectors and the rise of others, with a reallocation of capital and labour along the way. What is less clear is the possible magnitude of these shifts, and what their overall impact on aggregate economic outcomes might be. A recent review of the circular economy (Rizos et al., 2017) concludes that there is "little specific analysis or data on how different sectors will be affected" and "there is also a need to understand the indirect effects on the economy (e.g. impacts on the value chain and/or changes in consumption spending patterns) in order to estimate the overall impacts".

There is an emerging body of work that employs ex ante quantitative models to address these questions. Ex ante because many aspects of a circular economy transition are "out of sample"; there is no historical experience that can be drawn upon for empirical analysis.[5] Quantitative because any such transition is likely to be highly complex; it will affect many types of resources and materials, involve multiple sectors and countries, with spill-over and interaction effects between each, and take place in parallel with other emerging trends such as digitalisation and automation. These models, which are the main focus of this review, are only very recently being employed more widely; well over half of the known literature has been published since 2015. Although most assessments find that circular economy enabling policies will have a positive impact on aggregate economic outcomes, there is considerable uncertainty in a number of the underlying modelling assumptions, and therefore in the reliability of these results.

1.1.3 The objectives of this review

The primary aim of this paper is to critically review the existing assessments of the macroeconomic consequences of a transition to a circular economy, and to improved resource efficiency. It builds on an earlier OECD assessment (Dubois, 2015), which concluded that the "current quantification methodologies for the circular economy give a first estimation of the benefits but are not robust enough to serve as trustworthy policy tools". In addition to reviewing the methodologies and results of existing modelling, this paper therefore also offers a set of recommendations on how future work can better assess the efficiency and effectiveness of frequently proposed circular economy enabling policies.

A full meta-analysis of the economic implications of the transition to the circular economy is well beyond reach given the current state of the literature. Currently, the economic literature is still scarce on the topic, especially concerning macroeconomic impacts rather than sectoral impact, and therefore any statistical analysis on these results would have very large error margins and not provide very robust insights. In addition, a comprehensive meta-analysis would require detailed insights into the comparability of parameters and input data, which for many sectors and materials is incomplete, in particular at the global level. Therefore, this paper focuses on a more qualitative review of the limited number of existing studies.

[5] Although there is a small body of empirical work that assesses the employment effects of various waste management policies.

The likely impacts of a circular economy transition, when assessed in an ex ante context, depend on (i) how such a transition is defined, (ii) the structure and assumptions of the model that is used to assess it, and (iii) the policies that are implemented to enable it.[6] This paper addresses each of these issues in three sections. The remainder of this introduction outlines the scope of this review in terms of the modelling approaches and definitions of the circular economy that are considered. The second section describes existing modelling tools in terms of four key characteristics: geographic coverage, sectoral coverage, linkages with physical material flows, and the mechanisms used to simulate efficiency improvements and different types of substitution. The third section discusses the types of policies that have been implemented in existing studies, and summarises the main results in terms of macroeconomic impacts.

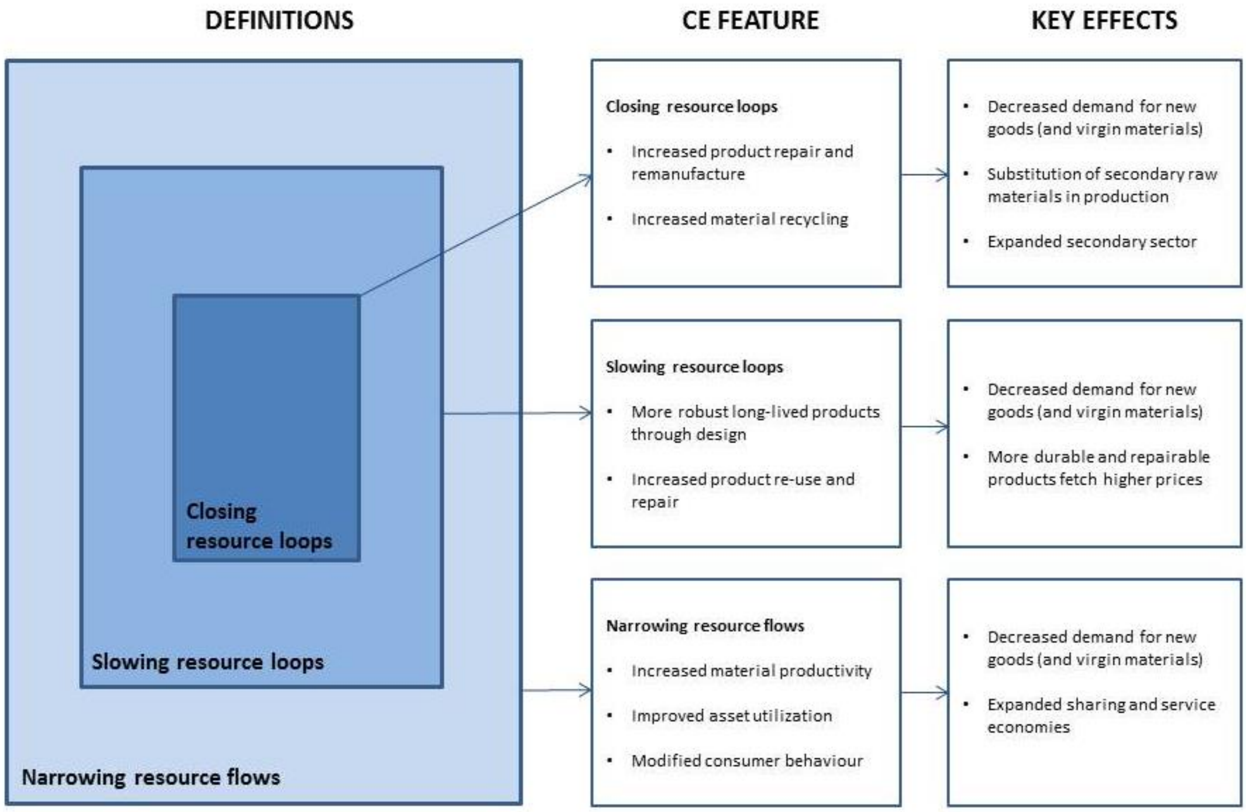
1.2 The scope of this review

1.2.1 Circular economy definitions

Recent literature reviews of the circular economy make it clear that it has no single commonly accepted definition (CIRAIG, 2015; Rizos et al., 2017). There are at least three common views (Bocken et al., 2016), each of which is summarised in Figure 1. Although each definition involves different processes and actors, they share a similar outcome: increased resource efficiency or, in other words, the decoupling of natural resource extraction and use from economic output.

6 In some cases, market forces alone have been enough to stimulate the use of secondary materials, and high recycling rates have emerged without policy intervention (see Coulomb et al., 2015 and McCarthy, 2018 forthcoming for selected metals). This is limited to a few materials, however, and a broader transition will require active policy intervention.

Figure 1. Differing definitions of the circular economy



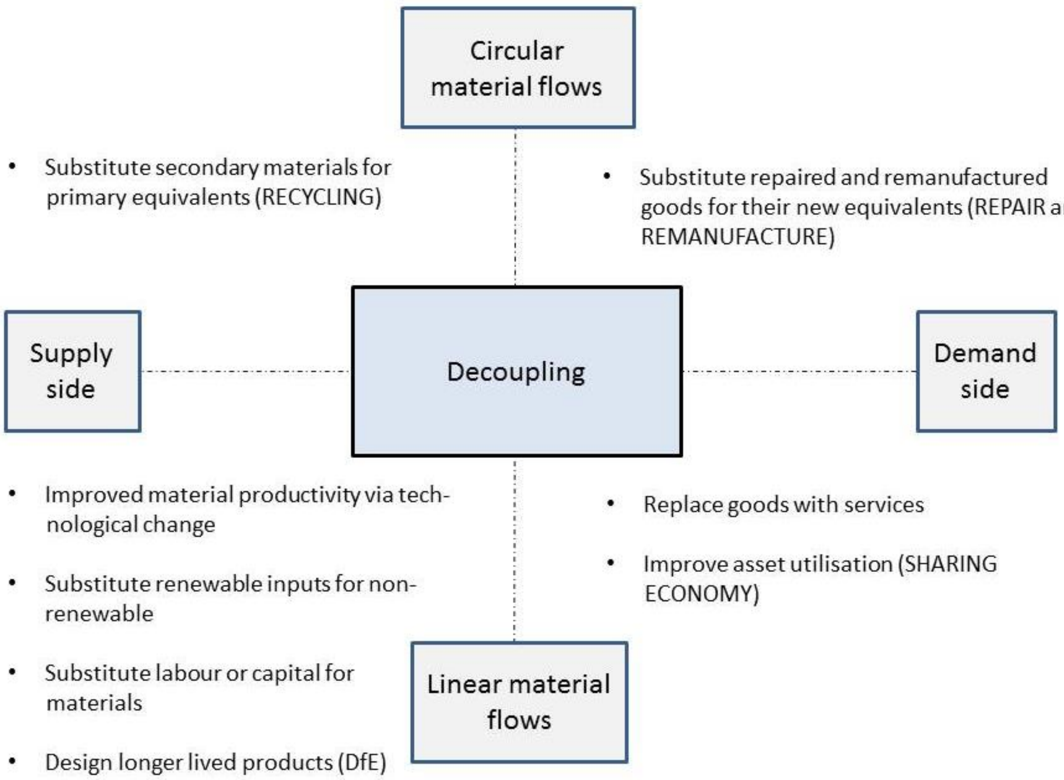
One core view (closing resource loops in Figure 1) of the circular economy is that it can be defined relative to a traditional linear economic system, i.e. one where natural resources are extracted, transformed into materials and products, and eventually disposed of in incineration or landfill facilities. Higher rates of material circularity, achieved through concepts such as "closing material loops" or "using waste as a resource", are central to this vision. Substitution of recycled materials for those derived from virgin resources, remanufactured goods for their traditional equivalents, and used products for new ones are seen as the key processes. The main sectors of the economy likely to be involved are therefore: waste management services, other services (e.g., repair), secondary material manufacturing (e.g., recycling), and other manufacturing (e.g., remanufacturing).

A second, slightly broader, view of the circular economy (slowing resource loops in Figure 1) stresses the importance of slower material flows, either within an economy with some degree of material circularity, or within one that is more linear. Product design is typically highlighted as playing an important role; products that are designed to be robust and more easily repairable will last longer and slow the introduction of new natural resources into the economy. Addressing firm incentives for designing productions with planned obsolescence in mind is seen as a key driver. The main sectors likely to be involved are therefore various kinds of manufacturing.

The third, and broadest, view of the circular economy (narrowing resource flows in Figure 1) is that it involves a more efficient use of natural resources, materials, and products within an existing linear system. The development and diffusion of resource efficient technologies is central to this view, as is a postulated shift in consumption patterns towards less material intensive goods and services. There is also an idea in the literature that there is significant "structural" waste in current consumption patterns. Oft-cited examples include a perceived under-utilisation of assets such as office space and private vehicles, and the high rates of food waste in many countries. Key drivers that are often highlighted in this view of the circular economy include investment in R&D and resource-saving technology, an increased awareness in the external effects of consumption decisions, and the continued emergence of the sharing economy. A much broader group of sectors are likely to be affected than those in the core view of the circular economy, as this broad view of the circular economy affects potentially all economic activities, not only those that have a high material use profile.

This divergence in definitions found in the general circular economy literature is also represented in the modelling literature considered in this review. Although most modelling assessments to date have applied the broadest definition (narrowing resource flows), there are also a number of models that attempt to introduce material circularity. This review therefore includes publications on the circular economy strictly defined (closing resource loops), and those on resource efficiency more generally (slowing resource loops and narrowing resource flows). We consider the circular economy as any process that enables the decoupling of economic output from virgin resource extraction. Figure 2 summarises the set of available mechanisms in this respect.

Figure 2. Decoupling mechanisms: material circularity vs material efficiency in production vs consumption



Note: Technological change can also facilitate more circular material flows when it results in improved secondary production technologies.

1.2.2 Modelling approaches

As discussed above, because many aspects of a circular economy transition are "out of sample", empirical approaches relying on historic experience have not been widely utilised. Rather, most modelling studies have used ex ante simulations to assess the likely macroeconomic consequences of any such transition. There are two main variants.

The first approach, termed accounting modelling (after Dubois, 2015), involves the development of scenarios regarding material circularity or technological progress in one or several sectors (e.g., Bastein et al., 2013; Ellen McArthur Foundation, 2013; Stegeman, 2015, and SITRA, 2015). Scenarios are based on expert opinion, and are typically described in terms of higher future recycling, remanufacturing, repair, or re-use rates. These changes are modelled autonomously; that is, they are not driven by the implementation of a particular policy. The resulting economic benefits, either in terms of the cost savings achieved through reduced material use, or in terms of job creation, are then estimated. In some cases, the changes in final demand and in production of the directly affected sectors are used to calculate indirect effects throughout the rest of the economy using input-output tables. This procedure gives some insight into impact of the supply shock in other (third party) sectors but, because there is no price mechanism, these impacts don't fully reflect economic feedback processes.

The second approach involves the use of economy-wide quantitative models: computable general equilibrium (CGE) and macro-econometric (ME) models.[7] Despite making different assumptions about agent behaviour, these models share two distinct advantages with respect to accounting models. First, they both explicitly represent the role that prices play in determining supply and demand for products, commodities, and ultimately, natural resources. This is important in the context of resource efficiency; increased output from secondary material sectors may reduce demand for natural resources, but this is likely to be partially offset by the lower prices that this entails. Second, multi-sectoral models, including all CGE and some ME models, are based on an underlying social accounting matrix (SAM) that accounts for economic flows throughout the entire economy. As such, these models can identify the potential interactions and spill-overs of a policy on sectors and agents other than the ones initially affected.

This review is restricted to studies that use CGE or ME models to assess the macroeconomic impacts of circular economy and resource efficiency enabling policies. The complexity of the envisaged circular economy transition, the fact that it will affect large parts of the economy, and the likelihood of rebound effects mean that such models are the most suitable for such an analysis. Although accounting models can provide detailed insight into the likely costs and benefits of increased material or product circularity, they tend to do so for specific products, and without feedbacks associated with changing prices.

7 Gradually, other types of models are also emerging, such as agent-based models and DSGEs. The literature on applying these to resource efficiency is so scarce, however, that they are excluded from this review.

2. MODELLING THE TRANSITION TO A CIRCULAR ECONOMY: FOUR KEY DIMENSIONS

The studies that are considered in this review are presented in Table 1. The majority of this work has been undertaken during the last few years, probably in response to growing interest in the circular economy. It is also clear that this research area is still in its infancy; while there is now a considerable body of expertise in integrated economic-energy modelling, incorporating material flows into such models raises an entirely new set of issues. (Pollitt et al., 2010) assessed sixty of the most widely used macroeconomic models, and found that around half had a strong energy focus, while "consumption of material inputs is largely unexplored within a dynamic macroeconomic framework". This section describes four aspects of the CGE and ME models that have been used to assess a circular economy transition: their geographic, sectoral, and material coverage, and the economic mechanisms that they include.

Table 1. The studies and models considered in this review

Modelling Group	Key Paper	Model Name	# Regions	# Sectors	# Materials	Circularity?
GWS - SERI	Bockermann et al. (2005)	PANTA RHEI	1	59	4 (p)	N
Hitotsubashi	Okushima and Yamashita (2005)	ODIN-WR	1	25	10 (s)	Y
NIES	Masui (2005)	AIM	1	41	18 (s)	Y
KEI Korea	Kang et al. (2006)	AIM-INCGE	1	32	19 (s)	Y
IAMC China	Unpublished	AIM-IPAC	?		?	N
Wuppertal Institute	Distelkamp et al. (2010)	PANTA RHEI	1	59	4 (p)	N
TNO	TNO (2012)	EXIOMOD	27	15	?	N
UCL	Ekins et al. (2012)	E3ME	30	42	19 (p)	N
Cambridge Econometrics	Cambridge Econometrics (2014)	E3ME	34	43	19 (p)	N
French Ministry of Environment	Godzinski (2015)	Vulcain	1	5	2 (s)	Y
NERA	Tuladhar et al. (2015)	NewERA	5	17	0 (p) (s)	N
Ellen McArthur	Bohringer and Rutherford (2015)	?	5	16	0 (p) (s)	N
World Bank	Bouzaher et al. (2015)	?	1	12	1 (s)	N
NIER Sweden	Soderman et al. (2016)	EMEC	1	26	34 (s)	N
Ex'Tax	Groothuis et al. (2016	E3ME	28	43	19 (p)	N
CSIRO	Schandl et al. (2016)	GIAM	13	21	?	N
ERC	Hartley et al. (2016)	SAGE	1	49	13 (s)	Y
DYNAMIX	Bosello et al. (2016)	ICES	19	20	?	N
		MEMO	1	10	?	N
		MEWA	1	18	?	N
SIMRESS	Unpublished	GINFORS	39	27	7 (p)	N
POLFREE	Meyer et al. (2016)	GINFORS	39	27	7 (p)	N
	Hu et al. (2016)	EXIOMOD	26	36	5 (p)	N
UCL	Winning et al. (2017)	ENGAGE Materia	17	35	1, 1 (p) (s)	Y
UNEP IRP	UNEP (2017)	GTEM	28	21	10 (p)	N
WIFO	Sommer and Kratena (2017)	WIFO DYNK	1	62	4 (s)	Y

Note: (p) = linkages with primary materials, (s) = linkages with secondary materials.

2.1 The geographic coverage in existing studies

The level of disaggregation of countries and regions in the modelling analysis is particularly important in the context of this paper; the highly uneven distribution of natural resources across countries means that circular economy enabling policies will probably have quite different impacts in resource-rich and resource-poor countries. Models with lower geographic disaggregation will tend to group country types together, resulting in biases in the modelling outcomes. These differentiated impacts make the linkage to international trade crucial to an accurate assessment of a transition to a circular economy.

Another important consideration relates to how trade linkages are represented. In some models, economic activity in each region is linked to that in all other regions through bilateral trade flows. This is the case in some multi-regional models (EXIOMOD and GINFORS for example) that explicitly represent bilateral international trade. In the context of this paper, this is useful to the extent that intermediate and final goods from different regions have differing resource intensities; resource efficiency in a particular country will partially depend on where its imports originate from.

The models considered in this review can be divided into those that consider a single, usually national level, economy and those that link multiple economies through trade (Figure 3). Geographic coverage in multi-regional models ranges between 5 (e.g. Tuladhar et al. 2015) and 39 regions (e.g. Meyer et al. 2016). The multi-region models have a more explicit focus on the circular economy and, more specifically, on the broadest (narrowing resource flows) definition of it. This is largely a function of data constraints; modelling material circularity in a multi-regional context would require harmonised cross-country economic data for waste management, recycling, and secondary production sectors that is largely unavailable.[8]

The single-region assessments of resource efficiency or circular economy policies considered in this review have been undertaken for many OECD countries, including Japan, Korea, Sweden, Germany and France (Table 1). It is notable that no single-region assessments have been undertaken for countries with large extractive sectors. Representation of trade flows in single-region models is usually limited to sectoral trade balances in the SAM; bilateral trade flows are generally lacking. In addition, the concepts of resource efficiency and the circular economy don't necessarily appear explicitly; these models have often been developed with a more specific focus on waste management and energy policies.[9] This means that they have well developed linkages between economic and physical material flows in the post-consumption part of the economy; material circularity is relatively well represented. Clearly, this is facilitated by the availability of detailed data describing economic and physical waste flows in at the country level.

2.2 The sectoral coverage in existing studies

The sectoral coverage of the models considered in this review varies widely, both in terms of the number of sectors included, and the number of sectors that are directly relevant for the circular economy. The SAMs underlying most models typically have between 15 and 40 sectors, although some have as many as 164 (EXIOBASE), albeit with greater uncertainty regarding the accuracy of the data.[10] Single-region models generally have greater sectoral disaggregation than multi-regional models (Figure 3). This section

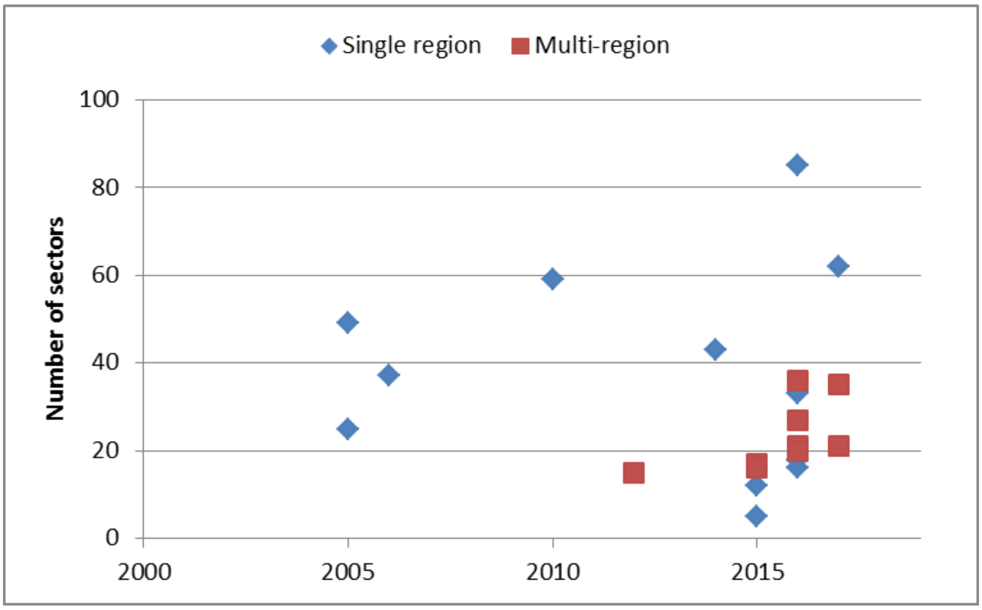
8 The EXIOBASE (version 3.0) dataset that is currently in development is one exception to this.

9 An early example of a national CGE model for waste management is Bartelings et al. (2004).

10 The national accounts data provided by most countries does not have this degree of disaggregation. Separating a particular economic activity from its parent sector therefore typically requires making various assumptions and the use of other data sources.

addresses the level of sectoral disaggregation in parts of the economy directly relevant for a circular economy transition: upstream resource extraction, material transformation and manufacturing, waste management and recycling, and several service sectors. However, disaggregation of the sectors that are not directly involved in provision or handling of materials is also important; one of the main mechanisms for reducing material use is shifting the economy away from sectors that are relatively material intensive to sectors that are less so.

Figure 3. The models considered in this review by regional and sectoral coverage



Note: The horizontal axis of this chart reflects an article's publication date of rather than the date of model development.

2.2.1 Extractive sectors

Disaggregation of upstream extractive activities, preferably by resource type, is important for modelling the circular economy. It allows economic instruments to be applied to specific extractive activities (e.g., fossil fuel, mineral, fisheries, or forestry extraction etc.), and therefore to better grasp the economic effects of these instruments further downstream. As discussed in Section 2.3.1, greater sectoral disaggregation also allows more realistic linkages to be established between economic flows and their physical equivalents.

All models considered in this review include at least one upstream extractive sector, and many differentiate between mineral extraction and different types of fossil fuel or biomass extraction. EXIOBASE has the most disaggregated upstream production structure, differentiating between forestry, fisheries, 11 agricultural sectors, 4 fossil fuel sectors, and 11 mining sectors. The GTAP series of databases, upon which a number of the models assessed here are based, also has disaggregated agricultural and fossil fuel sectors, but does not currently distinguish between extraction of metallic and non-metallic minerals. Further disaggregation of extractive sectors is possible[11], but can be highly time-consuming due to the data collection required.

[11] For example, Winning et al. (2017) disaggregate the GTAP sector 'Other Mining' into three separate sectors: iron ore mining, non-ferrous mining, and other mining.

2.2.2 Transformation sectors

Transformation sectors – those that refine raw materials into processed commodities such as paper, timber, refined fuels, processed metals etc. are important for an analysis of the circular economy. The SAMs underlying most models have a good disaggregation in this area, generally distinguishing between five or six of the major material classes. The main issue in the context of this review is that, for a given material, there is generally no distinction between facilities that use virgin natural resources, and those that use secondary raw materials.

While that is largely irrelevant for materials that are not recyclable (e.g., fossil fuels) or that are mostly recycled within the sector they are used in (construction minerals), it is critical for materials like metals, plastics, and paper where secondary production typically utilises a specific technology. If detailed data on the alternative technologies is available, representing these specific secondary production technologies is usually done through modelling different production technologies within one sector, effectively modelling two different 'sub-sectors' that provide the same output, but using different combinations of inputs. Enabling policies such as recycling standards or subsidies for secondary production are difficult to model unless technologies using secondary materials are explicitly represented.

Only two of the multi-region CGE models considered in this review introduce secondary production sectors. The ENGAGE-Material model, currently being developed at University College London (Winning et al. 2017), splits steel production into two additional sectors; one that (primarily) uses virgin mineral ores as input and one that uses secondary metal scrap. The EXIOBASE SAM makes the same distinction for six metals, although this version of it is yet to be utilised in the EXIOMOD CGE model. While it is possible to explicitly represent the specification of alternative material use technologies and their evolution over time, the implied need of disaggregating technologies and modelling sector specificities and dynamics constrains the modeller to very few materials (usually metals). There seems to be a clear trade-off between a comprehensive but not explicit representation of all materials and a detailed sectoral representation, but necessarily restricted to very few materials.

In addition, there are at least five single-region CGE studies that introduce some sort of secondary production, albeit in slightly different ways. Okushima and Yamashita (2005) follow the approach used in ENGAGE-Material and EXIOBASE, explicitly separating out secondary production in seven transformation sectors, including ferrous and non-ferrous metals, food, paper and pulp, and ceramic, stone and clay. Masui (2005), Kang et al. (2006), and Godzinski (2015) take a slightly different approach. They introduce a waste management sector that produces a disposal service along with multiple secondary commodities[12]. These then substitute with primary raw materials in downstream manufacturing sectors[13]. Hartley et al. (2016) also introduce secondary production, but do so by monetising the recyclable content of 13 individual waste streams and using this value as an exogenous supply shock for resource availability in the model. Again, this illustrates that the analysis may be deeper for country-level studies (more available data sources as well as technology and policy details), but this depth comes at the expense of linking the materials use with international trade flows and macroeconomic dynamics.

12 For example, Masui (2005) and Kang et al. (2005) introduce a waste management sector for industrial and municipal waste respectively (with the former defined as waste generated in production activities and the latter as that generated in household and business activities). These sectors produce 18 commodities which then become substitutes for the equivalent primary commodities in 12 downstream sectors.

13 See section 2.4.3 for further description on how this substitution is modelled.

2.2.3 Waste management and recycling sectors

Waste management and material recovery activities are poorly represented in the multi-regional quantitative models that have been used to assess a circular economy transition[14]. This has hindered the modelling of a number of relevant enabling policies, including landfill taxes, disposal bans, and recycling quotas. In many cases, waste related activities are included within a generic service sector that produces everything from insurance, health, education, and financial services (e.g. ICES and MEMO II models: Bosello et al. 2016). Some studies distinguish between a waste management activity (comprising collection and disposal), and a recycling activity (comprising material sorting and secondary production). However, both are usually aggregated with an array of other activities; waste management with other public services and recycling with other types of manufacturing. The EXIOBASE SAM has perhaps the best representation of waste related activities, with individual sectors for waste collection, incineration, disposal, metal recycling and non-metal recycling, but the quality of the underlying data is unclear. The MEWA model used in the DYNAMIX project also introduces a dedicated recycling sector, although it is unclear what the output of this sector is, and how substitutable this output is with that from extractive sectors.

Several of the single-region CGE models discussed in Section 2.1 do introduce specific waste management sectors into the SAM (Masui, 2005; Kang et al., 2006; Godzinski, 2015). This sector utilises the solid waste generated by production and consumption activities[15] to produce two outputs: a disposal service (in some cases split between landfilling and incineration), and one or more secondary raw materials. As discussed above, these then substitute with primary raw materials in downstream manufacturing sectors.

2.2.4 Product-life extending activities

Remanufacturing, repair, and trade of second hand goods are clearly also relevant for a circular economy transition. However, these are not well represented in the models considered here. Currently, remanufacturing is mostly undertaken by original product manufacturers. In the SAM, the value of remanufacturing output in a particular sector is therefore aggregated with the value of traditionally manufactured output. Separating these two components to allow substitution between them is likely to be prohibitively difficult. Output from repair services is aggregated with a range of other services in most SAMs. For example, GTAP 8 groups this with a number of other activities including all retail sales and hotels and restaurants. EXIOBASE provides better disaggregation – the sale, maintenance, and repair of vehicles is separated from all other retail trade – however, this is still insufficient to model impacts on the repair sector. These activities are at the core of many soft policies to decrease material use. Since their accounting in data and representation in models is difficult, the results of most studies have to be handled carefully.

14 For example, in the GTAP database, waste management is aggregated with other (government) services, such as education, health and defence.

15 Masui (2005) and Kang et al. (2006) introduce pollution as a factor of production; it represents a transfer from the representative firm in each sector to the waste management sector. In Godzinski (2015), consumers demand a waste disposal service in addition to a generic consumption good. This sets up a transfer from consumers to the waste management sector.

2.3 Material coverage and linking of economic and physical flows

2.3.1 Primary materials: upstream linking

A central objective of the studies considered in this review is to assess the impact that circular economy enabling policies may have on natural resource extraction rates. Among other things, this will depend on the changes in relative prices that these policies stimulate, and the reaction of firms and households to the new set of prices. As such, any model of the macroeconomic consequences of a circular economy transition needs to include some accounting of economic flows.

Given that different sectors are likely to expand and contract to different extents during a transition to a circular economy, and that individual sectors have differing material intensities, these economic flows also need to be linked with their physical equivalents. Changes in sectoral economic output can then be translated into aggregate resource extraction terms.

The range of resources or materials that can be considered is constrained only by the availability of physical extraction data. Distinguishing between a larger number of materials is important because of differences in: (i) physical abundance – some materials are more scarce than others, (ii) environmental impacts – extraction, processing, and use of some materials can produce differentially large damages, (iii) historic decoupling rates – there has been relatively rapid historic decoupling for particular materials, and (iv) potential future decoupling mechanisms – material circularity, for example, is only relevant for some materials. In practice, limited sectoral disaggregation of economic value flows can hinder the accuracy with which physical and value flows can be linked (see below). For this reason, most models consider between five and ten materials, although models with more disaggregated SAMs have considered as many as eighty (e.g., Hu et al., 2016).

Economic and physical flows have traditionally been linked using a so-called production approach.[16] This typically involves assigning Domestic Material Consumption[17] (DMC) to the domestic sector where it first enters the economic system. Sector specific material intensities can then be estimated by distributing this extraction through the economic system on the basis of economic value flows represented in the SAM. The main limitation of this approach is that it does not account for the materials embedded in traded goods and services. This can lead to potentially misleading results. For example, countries without domestic resource extraction or processing sectors can appear to consume very few materials, even though there may be significant volumes embedded in imports. The recent development of environmentally extended multi-regional input-output (EEMRIO) tables largely addresses this issue (see Giljum et al., 2014; Wiedmann et al., 2015; Wood et al., 2015). This approach uses bilateral trade data to link intermediate goods and services imported in one country back to their country of origin and, in turn, to the resources that were used in their manufacture. By including the bundle of material resources embodied in intermediate inputs and finished goods in the analysis, this approach allows the calculation of DMC, but also the embedded materials in imports, as reflected in Raw Materials Consumption (RMC). Ideally, the information on DMC and RMC is presented next to each other to provide full insights into overall material use. The distinction between DMC and RMC is also very helpful in the analysis of international trade consequences of the transition to a circular economy.

16 For fossil fuels, there is relatively ample data available, and data on volume flows can be directly linked to the respective economic activities.

17 DMC is the physical quantity of domestic extraction of a given resource plus the difference between any equivalent imports and exports.

There are two main sources of error in mapping physical material flows according to their associated economic equivalents. The first relates to an implicit assumption about the homogeneity of the output of each sector represented in the SAM. In practice, many SAMs are highly aggregated; a given production sector groups multiple products that end up in numerous supply chains. The distribution of material extraction throughout the economy on the basis of value flows could therefore lead to a contestable allocation of materials (e.g. Schaffartzik et al., 2014). For example, if, as in several of the models considered in this review, metallic and non-metallic mining are grouped into a single extractive sector in the SAM, then domestic extraction of construction minerals will find its way into the same supply chain as iron, copper, aluminium, and other metal ores[18]. This issue is often cited as a key motivation for the development of highly disaggregated MRIOs such as EXIOBASE (Giljum et al., 2016). This type of error is especially valid for models that take a "supply-side" approach to materials accounting, i.e. for models that link material use to the extracting sector and then follow the flows through the economy based on where the extraction sector outputs go. The alternative is to link materials to the demand for the outputs of the extraction sector (the "demand-side" approach). In this set-up, one can make ad-hoc, but logical, assumptions on the differences in materials content coming from one aggregated extraction sector; for instance, the materials flowing into metals processing would comprise metals, whereas the inputs from extraction to the construction sector would comprise building materials (essentially non-metallic minerals)[19].

The second source error relates to an assumption about the homogeneity of prices for a given output. It is not uncommon for different economic activities to pay different prices for the same product. One example relates to corn for food versus corn for feedstock. In this situation, distributing material flows on the basis of aggregated value flows that consist of multiple sub-products with different qualities and prices may also result in biased sectoral material intensities. To the extent that price differentials stem from differentiation in tax rates, net-of-taxes value flows can be used and are not biased.

2.3.2 Downstream linking

Linking economic and physical flows further downstream is also important, particularly for modelling material circularity. As discussed in Section 2.1, there are a handful of (mostly single-region) studies that introduce secondary production, and thereby allow for substitution between the outputs of primary and secondary material sectors. An important consideration in this context is the representation of supply of secondary materials. Output from secondary sectors is in reality constrained by the availability of waste; it isn't possible, or even desirable, to prematurely recycle the in-use stock of capital and consumer goods in order to increase the availability of secondary materials. This is distinct to the situation for primary materials where, at least in the medium term, additional demand can be satisfied through the expansion of upstream extractive capacity.

This issue has been overlooked in existing work. For example, the POLFREE project introduced a standard of 70% recycled content[20] for all metals (Meyer et al. 2016). Given that the current recycled content in global steel, aluminium, and copper supply is currently around 20% (McCarthy, 2018

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18 The same issue also exists in more disaggregated SAMs. For example, non-ferrous metals such as copper, aluminium, and the suite of rare earth elements follow quite distinct supply chains. That said, in many cases, these resources are assigned to a single economic sector: either undifferentiated mining or non-ferrous metal processing.

19 Furthermore, the iron used in construction effectively comes from the steel sector, rather than being taken directly from iron ore mining.

20 In this context, recycled content refers to the proportion of total metal supply that originates from secondary facilities.

forthcoming), this would require a massive increase in secondary output, even in a relatively optimistic scenario where total metal production remains constant. Whether there would be sufficient scrap available to support this expansion is quite unclear.

Addressing this issue requires linking the economic flows in waste management and secondary production sectors with their physical equivalents. Six of the studies considered in this review, do this to some extent (Okushima and Yamashita, 2005; Masui, 2005'; Kang et al. 2006; Godzinski, 2015; Hartley et al., 2016; Soderman et al., 2016). It is notable that each of these models is both single-region and static; linking downstream economic and physical flows in a multi-regional dynamic context would likely be prohibitively difficult. For one, this would require internally consistent data on waste generation and recycling rates across different materials and countries; no such dataset is currently available. Further, for dynamic models, this would necessitate the existence of a stock-flow model that describes the evolution of waste generation as a function of historic capital investment and contemporary consumption[21].

2.4 Decoupling mechanisms in existing studies

There are three key mechanisms that can result in decoupling of economic output from natural resource use. Technological change leading to improved material productivity or, "producing more with less" as this is more commonly referred to, allows a particular activity to produce additional economic value without increasing material inputs (or substituting from materials inputs to other inputs). Slowing resource loops with the introduction of more durable goods can have a similar effect; products that are designed to last longer will slow the introduction of new materials to economy without necessarily decreasing its size in value terms, at least if the higher quality of more durable goods translates into higher prices. Substitution – either between natural resource inputs and other factors of production, primary and secondary materials, new and remanufactured goods, or differentially materially intensive goods and services – can also have the same result. In the case that different materials are substitutes in production (for example between different building materials in the construction sector), different mechanisms need to be considered in conjunction, especially by looking at whether technological change affects the relative productivity of one material versus the other. This section discusses the extent to which each of these three mechanisms is incorporated into existing models.

2.4.1 Representing technological change

Almost all existing models of a circular economy transition model technological change exogenously[22]. Technological change consists of two distinct items: (i) innovation of new technologies that were not previously available to any producer, and (ii) diffusion of existing technologies to new users. The former improves the frontier of materials efficient production, while the latter reduces the gap between the average production techniques used and the frontier.

Material saving *innovations* tend to appear as exogenous "manna from heaven", rather than resulting endogenously from particular policy changes. In practice, this entails making autonomous changes to certain production function parameters, either in specific sectors or across the supply side of the economy. This approach is well summarised in Tuladhar et al. (2015), which states that "production functions typically contain parameters that govern the overall efficiency of production …" and "… increasing the parameter for overall productivity implies that the same amount of output can be produced with a

21 Fraunhofer ISI are developing such a model for copper flows in Germany.

22 Two models – the MEMO II and MEWA models used in the DYNAMIX project – do incorporate a mechanism allowing for endogenous technical change, but these are highly stylised models and not large-scale CGE or ME models.

proportionally smaller utilisation of every input". The implication is that innovation is costless, and will somehow materialise as a by-product of the policy implementation.

Implementing innovation exogenously is not a problem for no-new-policies baseline projections, and is strongly preferable to modelling approaches that ignore technological change completely. Baseline technology projections will reflect the most plausible consequences of existing trends and existing policies, in the absence of new policies. It is more problematic, however, for policy scenarios. Models that incorporate exogenous innovation ultimately make some assumption about the achievable rate of additional material productivity growth that is triggered at no net cost by the policies that are implemented. Such an approach denies the effort required to achieve the associated innovation. Beliefs about the rate of 'free' productivity growth triggered by the circular economy enabling policies differ widely across the studies considered in this review; whether or not they are realistic is discussed in more detail in Section 3.2.1.

One rationale for assuming zero costs for innovation stems from the idea that the most cost-effective new technologies will deliver benefits that outweigh the costs; this feature is prominent for example in the McKinsey marginal abatement cost curves for greenhouse gases (McKinsey, 2009). Thus, all new technologies that have a benefit-cost ratio larger than one can be implemented without net costs. Caveats to this reasoning are however significant. First, it ignores that an up-front cost to develop the innovative technology must be borne, possibly by an economic agent that is not the same as the one that reaps the future benefits. Future benefits may also not always be tangible or transferable. Secondly, negative-cost options as identified in the literature often miss important hidden costs or other barriers to implementation that prevent the uptake of the technology.

A related issue concerns the linkages between the assumed efficiency gains and their underlying drivers. It is well established that R&D activity is an important long run determinant of technological change and that, in turn, R&D expenditure is determined largely by market incentives and various aspects of the regulatory environment. Further, the diffusion of a given innovative technology, once it has emerged, will generally not be instantaneous, whether due to lack of knowledge on the potential new technology, or property rights that restrict diffusion, or other reasons. Most of the models considered in this review do not appear to represent these mechanisms adequately; productivity improvements emerge from nowhere and diffuse throughout the economy at no apparent cost.

Apart from induced innovation, virtually all models capture technology choice and diffusion of new technologies in some way. In most cases, technology choice boils down to changing the combination of inputs in production, i.e. substitution (see Section 2.4.3). Essentially, firms can respond to increasing prices for a given factor by investing in existing technologies that use that factor more efficiently, potentially at higher overall costs, or at least at higher overall costs at the initial set of relative prices. However, in some cases, diffusion of new technologies is represented as a pure efficiency improvement, i.e. the reduction of one input of production per unit of output, without increased use of other inputs and represents a cost reduction. Ideally, all available technologies should be fully specified. But given a lack of detailed data on technologies that are not yet mainstream, and in some cases the wide range of technology options that exist, many models simplify technology choice to a continuous function of changing shares of different input factors, especially a substitution between resource use and capital, as described below. That said, regional cost curves describing material "abatement" possibilities that have a firm basis in data are still lacking, and there is currently very little information available on this subject.[23]

[23] Specification of such material efficiency cost curves could build upon existing cost curves for emissions and energy efficiency.

2.4.2 Representing longer lived products

The emergence of longer lived, more durable products is often highlighted as a key element of a circular economy transition. Products that are designed to last longer will remain in use for longer, thereby slowing the introduction of new materials into the economy[24]. This process is not explicitly represented in the studies considered here; CGE and ME models are based on representations of economic flows, they include very little stock accounting[25]. In practice, slower material loops could be modelled in two ways. First, one could exogenously decrease demand for the hypothetical longer lived product; in this setting, a new, more robustly designed product that lasts twice as long leads to a reduction in the annual demand for the product and thus lowers total sales value by half. This would thus result in decreased revenue in the affected sector, which may not be an accurate representation of reality. It may be that products with longer lifetimes fetch higher prices; this would, at least partially, negate lower sales volumes. The second approach is therefore that the longevity improvement is entirely captured in the price of the product; i.e. the new product with a lifetime that is twice as large sells for double the price and total sales of the product remains the same. In this case, the total demand in value terms is unaffected by the slower material loops, and the policy has no noticeable direct effect on the economy, although there will be indirect effects caused by the reduced demand for materials. It is clear that both approaches are caricatures of reality; robust approaches that have a more realistic representation are, however, not yet available.

2.4.3 Representing substitution

Dynamic analysis of materials use and economic activity requires an assessment of the evolution of production technologies over time. The simplest (and crudest) approach is to use a fixed Social Accounting Matrix and vary only the levels of production; this Leontief approach is common in input-output analysis. Dynamic CGE models in contrast specify substitution elasticities to accommodate shifts in input requirements over time. Three distinct supply-side substitution possibilities are relevant in the context of a circular economy transition. These are: (i) substitution between a particular material and other production inputs such as capital and labour, (ii) between different types of materials, and (iii) between primary materials (derived from natural resources) and secondary materials (derived from waste). In addition, opportunities for substitution also exist on the demand side of the economy. Depending on relative prices of consumption goods, households will have incentives to substitute away from material intensive goods and services, either to other goods and services that effectively fulfil the same consumption use (e.g. changing transportation modes to go on holidays) or to other consumption uses (e.g. reducing the number of holidays in favour of local activities). The modelled effects of changes in relative resource and material prices, resulting from the introduction of economic instruments for example, depends considerably on how these possibilities are represented in a given model.

The models considered in this review generally do not represent the physical flows of materials as an explicit factor of production, but only represent the value flows from extraction sectors to use sectors.[26] Material inputs into the economy therefore originate in various extractive sectors, and usually substitute with other intermediate goods and services according to a constant elasticity of substitution (CES)

24 This may also have potentially negative environmental effects. For example, extending the in-use period of a particular product may not be desirable in situations where the energy (or other material) efficiency of new equivalents is rapidly increasing.

25 Developing physical accounts of materials stocks is a necessary first step before stock accounting can be integrated in economic models; such developments are still in their infancy, however.

26 For example, the steel sector is modelled to use "metallic mineral mining products" in production, but not iron ore. This is in contrast to some resources – fossil fuels in energy production and land in agriculture for example – that are usually captured with explicit volume indicators.

production function that reflects a stylised summary of production technology choices that firms have. Output in each sector is then typically produced by combining the resulting intermediate goods and services composite with a value added plus energy composite. The position of the extraction inputs in the production sectors needs to be specified with care, as this reflects the ease with which firms can substitute away from material use by switching to other inputs. With the exception of some materials – fossil fuels in energy production and feed inputs in livestock production for example – most models have not adequately differentiated inputs from the extraction sectors to realistically represent material substitution possibilities. Further, many models implicitly assume no substitution possibilities at all (i.e. all intermediate inputs are required in fixed proportions in production in a CES function with the substitution elasticity equal to zero). This may resemble a plausible lack of substitution possibilities, or a lack of data to specify more differentiated production processes.

2.4.3.1 Substitution between materials and capital and labour

In the type of model described in the previous paragraph, there is limited scope for substitution between materials and capital and labour; value added is combined with intermediates (of which materials are a part), often in fixed proportions. One way to address this involves modifying the nesting structure of the production function to allow particular materials to explicitly substitute for capital or labour.[27] This approach is common in the energy modelling literature where an energy bundle is allowed to substitute for capital, usually with an elasticity of substitution around 0.5. Similarly, at least the more advanced models tend to represent fertiliser inputs in agriculture in a dedicated nesting structure. One obvious issue in the resources context is the identification of the best nesting structure (i.e. what are the direct substitutes?), and of the equivalent elasticity parameter. Very little research has addressed this issue.

2.4.3.2 Substitution between different materials

A set-up with a detailed and flexible production function provides some scope for substitution between different materials. For example, to the extent that timber and cement production are differentiated in the SAM, the construction sector could effectively substitute between the two. Similarly, there may be scope for substitutability between plastics and metals in certain manufacturing sectors. This may be important in situations where varying tax rates are applied to different materials on the basis that their production results in differential environmental damage. Capturing such substitution possibilities is often hampered by a lack of detail in the representation of different sectoral inputs; any material use that concerns switches between materials that are represented in the economic model as coming from the same sector, e.g. different non-metallic minerals used in construction, is not reflected in a change in the economic flows in the model, and requires either an ad-hoc adjustment of the different material uses within the sector or a further disaggregation of the sector involved. Furthermore, there is again very little data describing the degree of substitutability between materials in different applications, and most models assume fixed input coefficients at this level, implying that such substitution possibilities are ignored.

2.4.3.3 Substitution between primary and secondary materials

Three main approaches have been used to represent substitution between primary and secondary materials. The first involves representing available alternative technologies explicitly, producing the same output as the current technology, but with different input combinations. This is the approach used in some models for representing steel production, differentiating between primary iron ore and secondary scrap.

[27] More advanced models include a sector-specific generic “natural resource” input in production that can substitute with other production inputs.

This approach gives a lot of control over specifying the differences between the production processes, but requires detailed information on these differences.

The second approach involves making exogenous changes to the production functions of selected material intensive sectors such that the substitutability between primary materials and own sector output increases. For example, Meyer et al (2016) state that the "technical coefficients are adjusted for the manufacturing of metals, non-metallic minerals and paper. Less input is needed from the mining or forestry sector and more input is needed from the own sector". The underlying idea is that this mechanism simulates higher recycling rates by allowing manufacturers to substitute their output (future waste in other words) for materials derived from natural resources. While at first glance unintuitive, it can provide an accurate representation of materials re-use and recycling within a sector. One difficulty involves the attribution of value to implicit waste flows.

The third approach involves the separation of one or more dedicated waste management or secondary material production sectors in the underlying SAM (see Sections 2.2.2 and 2.2.3, and Table 2). These produce secondary raw materials[28] which then substitute for their primary equivalents in downstream manufacturing sectors. Different assumptions have been made about the ease of this substitution (Table 2); some studies assume a fixed proportions production technology (Masui, 2005; Kang et al. 2006) whereas others allow an elasticity of substitution as high as 2 or 3 (Godzinski, 2015). In reality, the actual ease of substitution between primary and secondary materials will differ considerably as a function of the material considered and the application in which it is used. More research is therefore needed to find plausible values of this elasticity for different materials in different sectors; uncertainty analysis represents a logical way forward in the meanwhile. An additional consideration in this approach relates to the representation of secondary material supply; this may serve to constrain the potential expansion of the secondary sector (see Section 2.3.2 for additional discussion).

Table 2. Elasticities of substitution between primary and secondary material in existing modelling

Study	Model	Year	Type	ES (prim-sec)
Masui (2005); Kang et al. (2006)	AIM	2005	Secondary sectors introduced	0
Okushima and Yamashita (2005)	ODIN-WR	2005	Secondary sectors introduced	0.3
Distelkamp et al. (2010) and Meyer et al. (2016)	PANTA RHEI GINFORS	2010	Exogenous technology modification, favouring own sector inputs	1
Godzinski (2015)	Godzinski	2015	Secondary sectors introduced	2 (aluminium) 3 (steel)
Winning et al. (2017)	ENGAGE-Materials	2017	Secondary sectors introduced	0.1 - 0.3 (steel)

Note: Masui (2005), Kang et al. (2006), Okushima and Yamashita (2005), Distelkamp et al. (2010), and Meyer et al. (2016) use the same elasticity of substitution across the entire range of secondary materials that they consider.

2.4.3.5 Demand side substitution between different goods and services

All the models considered in this review allow for demand side substitution that can be stimulated by changes in relative prices resulting from circular economy policies. Consumers are able to substitute away from material intensive goods and services as they become relatively expensive. For example, consumption of services – travel, education, entertainment – could increasingly substitute for consumption of goods – vehicles, clothing, household electronics – if material taxes were to increase significantly. Clearly, the

28 And in some cases a waste disposal service.

model parameter describing the responsiveness of consumers to price changes is critical; the overall cost of a circular economy transition will be considerably higher if consumers do not consider that viable substitution possibilities are available (or if these are not fully represented in the model).

2.4.3.4 Demand side substitution between goods and services that fulfil the same use

Circular economy policies can also trigger demand side substitution between goods and services that effectively fulfil the same use. Examples include: (i) shifting transport modes – public transport may become increasingly competitive with private transport, (ii) the digitalisation of entertainment – literature and music can be consumed online without ownership of the physical products (books, records, or CDs) themselves, and (iii) the so-called sharing economy – under-utilised accommodation, office space, and vehicles can be leased rather than owned. The overall impact of both digitalisation and the sharing economy on material extraction and use remains unclear. Digitalisation may decrease demand for some materials, but demand for others – the metals used in computer servers for example – may increase. Similarly, the sharing economy may increase the utilisation of certain goods without necessarily reducing demand for materials – if shorter product lifetimes result in faster turnover for example. These demand substitution possibilities are not always well represented in existing models. In particular, the sharing economy, with its focus on long-lived under-utilised assets and consumer to consumer transactions, does not fit well with the structure of most macroeconomic models. One possible approach is to autonomously reduce demand for new goods, although it is not always clear that the sharing economy will have such an effect.

3. ASSESSING THE ASSUMPTIONS AND RESULTS OF EXISTING STUDIES

3.1 Business as usual projections

Assessing the impacts of circular economy and resource efficiency enabling policies requires some sort of counterfactual scenario: how will patterns of economic activity and material use evolve under a business as usual scenario? In the models considered in this review[29], this information is contained in baseline scenarios that reflect certain assumptions about future population growth, productivity growth, consumption patterns, and the relationship between economic output and material use. Each baseline reflects a different “storyline” about the possible evolution of the main drivers of economic and resource flows across countries and sectors. Policy scenarios are then constructed as a set of specific assumptions on certain elements of the system, e.g. the introduction of a tax on the input of specific inputs in production and using the model to then find the associated changes in the economic system and related material use. The consequences of modelled scenarios involving the implementation of circular economy enabling policies can then be determined through a comparison of the policy scenario with to the appropriate baseline.

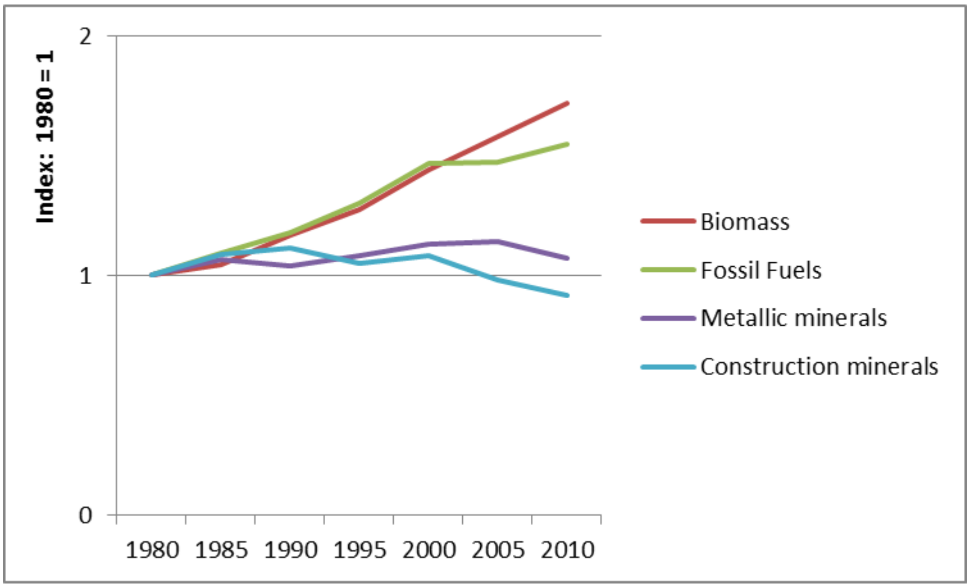
Two issues require particular attention in the context of baseline development for models of a circular economy transition. First, many discussions on the circular economy emphasise the importance of wide ranging structural changes in production and consumption patterns. To some extent, these are already taking place; one example relates to the recent emergence of peer to peer sharing platforms. These are changing the way that individuals consume, with potentially significant impacts for both the distribution of income and the flow of materials. This, along with other structural shifts – an increasing preference for services and experiences relative to goods for example – are important considerations in the context of what a business as usual scenario might look like. There is uncertainty in how these trends will play out, and this provides some rationale for the development of multiple visions of future “states of the world”. Most existing models of the circular economy introduce a single baseline, and the underlying assumptions regarding sectoral shifts are not always made explicit.

The second issue relates to what rate of decoupling between economic output and material use, both at the sectoral and at the macro level, should be incorporated into baseline scenarios. History provides some insight here, at least on the macro level. Today, the global economy generates around 30% more economic value per unit of resource use than it did in 1980 (OECD, 2015b). This equates to an average decoupling rate of around 0.8% per annum (p.a.), but with considerable variation across materials and across time. Average decoupling rates between 1980 and 2010 were fastest for biomass (1.8% p.a.) and fossil fuels (1.5% p.a.), slower for metallic minerals (0.2% p.a.), and non-existent for industrial minerals (-0.3% p.a.). Decoupling rates also appear to have slowed during recent years; they were notably slower for fossil fuel resources between 2000 and 2010, while recoupling actually took place for both metallic and construction and industrial minerals during this period (Figure 4). These data are not always consistent with baseline assumptions in existing models; several assume business as usual decoupling rates of 1.5% to 2% p.a. across the economy (Meyer et al., 2016 and Hu et al., 2016), others assume no decoupling at all (UNEP, 2017).

29 Only the dynamic models; static models generally take the counterfactual scenario to be represented by economic and physical flows recorded in the base year of the SAM, although in a few cases a projection of the SAM for a future year is used as basis for the analysis.

The underlying rate of material productivity growth incorporated in baseline scenarios will result in some decoupling as transformation and manufacturing sectors use resource inputs more efficiently, and as the share of different sectoral economic activities changes over time and across regions. In other words, a shift in economic activity from very resource-efficient production sectors in one region to more materials-intensive production in another region will, reduce the average global materials intensity of the economy. The question is whether this change in economic activity should then translate into decoupling on a "one to one" basis. In other words, are there factors other than changes in the economic system that could lead to changes in the relationship between economic output and natural resource use? One possible example relates to recycling rates; an increase in the proportion of secondary materials in overall material inputs[30] will, all else equal, generate more decoupling than that associated with economic efficiency alone. Increased product utilisation associated with continued expansion of the sharing economy could have a similar effect[31]. Again, existing studies do not always explicitly discuss the assumptions that are made for these issues.

Figure 4. Evolution of material productivity at the global level for major material categories



Note: Material productivity = economic output per unit of materials extraction. Source: OECD (2015b) and SERI (2017).

3.2 Policy coverage

The modelled macroeconomic impacts of a transition to a more circular economy depend on the modelling framework used for the assessment, and on the type of policies that are implemented to enable the transition. Existing modelling focusses heavily on three main policy areas (Table 3): policies that drive technological change and efficiency improvements, policies that drive various kinds of substitution through

30 Perhaps due, for example, to fluctuating waste supply associated with the decommissioning of the evolving infrastructure stock.

31 Again, historic data provides some insight. Multi-factor productivity growth at the global level averaged around 1% between 1990 and 2015 (OECD, 2015c). Decoupling rates for energy and biomass were faster than that, while those for metallic and construction minerals were considerably slower. That either implies differential rates of productivity growth across sectors, or the existence of other processes not captured in productivity calculations.

changes in the relative prices of natural resources, and policies (usually relating to the introduction of product information requirements and public education schemes) that drive changes in consumption patterns.

There is a clear divergence between the measures that are commonly modelled, and those that are emphasised by policy makers interested in promoting a circular economy transition. In terms of the latter, policies such as disposal bans, recycling quantity standards, extended producer responsibility (EPR) schemes, eco-design standards, and green public procurement are often cited (e.g., see EU Circular Economy Action Plan). Implementing the latter policies in a CGE or ME framework can be challenging. Some of them are so-called “soft” policies; their impact on prices are difficult to establish. Modelling the effects of others would require the introduction of waste management or recycling sectors, which, as discussed in Section 2.2, can be hampered by data issues. In contrast, technological change and resource taxes have been assessed in energy models for many years; they can be relatively quickly adapted to models of the circular economy.

Table 3. Summary of policy coverage in selected studies[32]

		Masui (2005)	Distelkamp et al. (2010)	Ekins et al. (2012)	Cambridge Economics (2014)	Godzinski (2015)	Schandl et al. (2016)	Soderman et al. (2016)	UNEP (2017)	Bosello et al. (2016)	Hu et al. (2016)	Meyer et al. (2016)
Economic Instruments	Landfill taxation					■		■				
	Carbon tax			■			■					
	Per-unit waste disposal tariff							■				
	Material consumption tax		■	■	■	■		■	■	■	■	■
	Differentiated VAT rate		■					■				
	Targeted subsidies					■						■
Information Based	Labelling: % raw material inputs	■							■			
	Labelling: recyclability/repairability	■							■			
	Public education programs	■							■	■	■	■
	Collaborative platforms											
	Certification scheme: secondary inputs											
Eco Design	EPR											
	Ecodesign requirement: durability										■	
	Ecodesign requirement: repairability										■	
	Ecodesign requirement: recyclability		■								■	
Other Regulation	Recycling rate standard (on EOL-RR)		■			■					■	■
	Final disposal quota	■				■					■	■
	Reform of end of waste rules											
	Waste shipments: proper enforcement											
	Sharing Economy regulatory framework											
Public Provision	Green public procurement											
	Targeted public R&D	■	■		■		■	■	■	■	■	■
	Services e.g., separated collection											

32 Only two of the studies shown in the table implement a carbon tax. This does not reflect any perception that carbon taxes are unimportant for a circular economy transition. Rather, some studies have chosen to focus on other instruments given the rich literature on carbon taxes in climate change literature.

3.2.1 Innovation, investment, and technological change

Technological change is the most frequently modelled "policy" in existing models. It also seems to be the factor that drives modelling outcomes to the greatest extent; studies that assume high rates of productivity growth induced by the circular economy transition also tend to be those that find the largest positive GDP changes in a circular economy transition.

As highlighted in Section 2.4.1, almost all models considered in this review implement productivity improvements from innovation exogenously; they appear as "manna from heaven" rather than resulting endogenously from certain changes in policy. This is problematic for two main reasons. First, the reality of the modelled outcomes is clearly questionable if they are based on naive assumptions about the rate and cost of productivity gains. Second, this approach only provides limited insights for policymakers: productivity gains clearly result in faster output growth, but what policies are required to realise the emergence and dispersion of innovation in the first place?

In practice, exogenous technological change is implemented through the modification of certain parameters of the production function, either in particularly material intensive sectors, or universally across the supply side of the economy, while endogenous technology choice is implemented through allowing supply-side substitution possibilities.[33] In a number of studies, scenarios involving technological changes resulting in improvements in material productivity of 2% p.a. above baseline are specified (Table 4). This is more than twice the rate of aggregate decoupling that was observed at the global level between 1980 and 2010, and has led some authors to criticise this work on the basis that such changes would be largely unprecedented (e.g., Lenzen et al., 2016).

The potentially available improvements in resource productivity used in the modelling literature appear to originate from two main sources. In several projects, bottom up estimates of sector specific efficiency gains are undertaken as a complement to macroeconomic modelling (e.g., TNO, 2012; Pfaff and Sartorius, 2015; DYNAMIX, 2016). These usually involve detailed assessments of specific alternative technologies, and therefore remain quite rare. In other cases, estimates of potentially available productivity gains are either assumed, or taken from third party studies. This often involves borrowing from the energy literature where the possibilities and constraints to efficiency gains are much better documented than for other materials. One frequently cited publication in this context is Factor 5 (Von Weizsacker et al., 2009), which outlines innovations that would lead to five-fold improvements in energy productivity in the construction, steel, cement, agriculture, and transport sectors. It is unclear whether such estimates have any relevance for other resources; energy productivity has historically grown significantly more rapidly than that for metallic or construction minerals. Furthermore, the incentives to improve efficiency in use may also be lower for materials that can be reused or recycled than for materials that can only be used once.

In addition to questions about the achievable rate of material productivity gains are uncertainties about the associated costs. The treatment of the R&D and capital investment costs required for the invention and dispersion of material saving innovations is unclear in most studies. In many cases, the

33 The rationale for making autonomous changes to production functions varies across studies. In some cases, this approach is taken simply because representing other decoupling mechanisms can be difficult in a macroeconomic framework (e.g. Bohringer and Rutherford, 2015; Tuladhar et al., 2015). Other studies provide some underlying "storyline" for productivity improvements. One example involves addressing information failures; Distelkamp et al. (2010) state that "producers do not use the best practice technology concerning resource consumption because they do not know all the alternatives they have". Another explanation involves the adoption of material efficient technologies that are supposedly, at worst, cost neutral (e.g. TNO, 2012 and UNEP, 2017). The underlying assumption is that firms would naturally adopt such technologies if existing barriers were removed.

absence of the policies required to drive technological change mean that there are no costs at all. This is acknowledged explicitly in several cases. UNEP (2017) state that their "modelling has not fully accounted for costs related to either resource efficiency policies or the innovation that will undoubtedly be required to achieve the increases in resource efficiency assumed by the modelling". Similarly, CGE modelling undertaken for the Ellen McArthur Foundation (Bohringer and Rutherford, 2015) states that "exogenous productivity gains, …, towards a circular economy are not traded off against the resource inputs to facilitate the specific technological change nor the opportunity cost of choosing a different technological future". Finally, Schandl (2016) state that, "the material efficiency measures have been derived purely following the logic of a physical economy and in the absence of economic considerations such as the level of investment and changes in price".

Table 4. Assumptions regarding average material productivity improvements in selected studies

	Material	Annual decoupling rates	
		Baseline	Scenario
Historically observed rates	All	**0.8%**	N/A
	Biomass	1.8%	
	Fossil fuels	1.5%	
	C&I minerals	-0.3%	
	Metal minerals	0.2%	
Cambridge Econometrics (2014)	All	0.9%	2-3%
	Biomass	0.9%	?
	Fossil Fuels	?	?
	C&I minerals	-0.2%	?
	Metal minerals	0.3%	?
Bohringer and Rutherford (2015)	All	~2%	2%
Schandl et al. (2016)	All	1.5%	2-3%
Wu et al. (2016)	All	2.0%	0.7%
UNEP (2017)	All	-0.04%	0.7%

Note: Historic rates are at the global level and derived from SERI material extraction data and OECD GDP data. Scenario decoupling rates are above and beyond those contained in baselines.

There are a small number of studies that do attempt to cost exogenous material saving technological change. Assumed improvements in material productivity are paid for through the diversion of public resources to: (i) R&D activity (MEWA: Bosello et al., 2016), (ii) consulting services for firms (e.g., Distelkamp et al., 2010; Meyer et al., 2016), or (iii) investments in resource efficient capital stock (Cambridge Econometrics, 2014). That said, it is apparent that the cost curves describing material "abatement" possibilities are not at all well constrained. Cambridge Econometrics (2014) use data from the energy literature as a starting point; EUR 31.4bn of annual investment is required to achieve each 1% reduction in energy consumption in the EU. This implies that investments scale up linearly, with no decline in the marginal productivity of additional units of investment. Other studies borrow data from detailed engineering models in specific sectors. Meyer et al. (2016) highlights work undertaken in the German manufacturing sector (Fischer et al., 2004 and Little et al., 2005); a 10 to 20% permanent improvement in material efficiency is possible at a cost equivalent of one year of the resulting resource savings. Bosello et al. (2016) generate a cumulative 10% improvement in material efficiency between 2010 and 2050 with additional annual public R&D investment equivalent to 0.4% of GDP.

3.2.2 Material taxes and subsidies

Many of the studies considered in this review also introduce economic instruments to promote a shift away from the use of natural resources, raw materials, or goods produced in materially intensive sectors. Material taxes are the most frequently used instrument, but subsidies are also used in several studies to stimulate production of secondary materials. Taxes are implemented in various ways. Some studies assume that they could feasibly be introduced in all regions of the model, whereas others assume that sufficient political capital will only exist in resource importing countries and regions. The treatment of the revenues raised by these taxes also differs, but what almost all studies have in common is that they implement taxes and subsidies under the assumption of fixed total government expenditures. Some studies model an environmental tax reform whereby labour tax rates are lowered such that overall revenue neutrality is achieved (e.g., Cambridge Econometrics, 2014). Others recycle revenues directly back to households in the form of lump sum transfers (e.g,. UNEP, 2017), or use them to fund investments in public R&D (e.g., Bosello et al., 2016).

Material taxes are also implemented at different points in the value chain, but not on the volume of extraction itself. The resource royalties and mineral taxes utilised in many extractive economies are not therefore modelled directly. In most cases, taxes are instead levied on the output of specific upstream extractive sectors. For example, Bosello et al. (2016) state that their materials tax is, “implemented as a tax on the sales of timber and of mined materials to all other sectors”. Some studies also implement material taxes further downstream. For example, Bosello et al. (2016), Hu et al. (2016), and Meyer et al. (2016) introduce a tax on the output of the meat processing sector. Hu et al. (2016) attempt to introduce consumption taxes based on the embodied materials (in RMC terms) contained in finished goods and services, however these could not be practically implemented[34].

Increasing prices should trigger substitution away from material use and provide incentives for the development of material saving technologies. However, these mechanisms are not always well represented in the models considered in this review. With respect to the former, and as discussed in Section 2.4.3, the nesting structure of production functions in many models and the absence of specific secondary sectors mean that important substitution possibilities are limited. With respect to the latter, only two of the models considered in this review incorporate a mechanism for endogenous technological change, whereby the rate and direction of technological progress is a function of relative prices. Taken together, this may mean that material taxes have a muted effect relative to more realistic “real-world” scenarios where rising resource prices stimulate substitution of secondary for primary materials and the development of material saving innovations. On the other hand, most models tend to ignore specific barriers to changes in behaviour and transaction costs that would imply an overestimation of the effectiveness of policies. The net effect is therefore unclear.

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34 The authors state that “an RMC based tax requires a lot of computation power, because it requires calculating footprints using an input-output model. Every year the footprints change”. They therefore chose to “implement the tax at the extraction level to achieve the same effect”.

3.2.3 Soft policies and exogenous changes in consumption patterns

Many recent studies assume exogenous changes in the preferences of future consumers (Bosello et al., 2016; Hu et al., 2016; Meyer et al., 2016; UNEP, 2017). In some cases, these appear out of nowhere without any underlying explanation. In others, they are motivated by various so-called “soft” policies; public education campaigns or product labelling schemes. The overall effect is the same, consumers increasingly prefer less material intensive goods and services: vegetable based diets to meat based ones, repaired and remanufactured goods to their new equivalents, and services and experiences to physical goods more generally.

Assumptions about changes in material intensity of consumer preferences can theoretically drive modelling results to a significant extent.[35] By promoting a transition from high to low material intensity sectors, they may have limited first order effects on aggregate economic growth while resulting in potentially large reductions in natural resource extraction. That said, such an outcome depends entirely on the feasibility of the underlying assumptions about changing future preferences and associated consumption patterns. Furthermore, by changing preferences, the scenario analysis assumes that there are no welfare costs associated with these changes; in reality, people change their behaviour not because they’re forced to, but because they prefer it. These caveats should be clearly presented.

3.3 Economic consequences projected by the existing studies

The impact of circular economy and resource efficiency enabling policies are presented across various metrics in existing studies. In terms of macroeconomic indicators, almost all studies considered in this review report changes in GDP. Fewer studies present changes in sectoral value added, domestic trade balances, employment, or household income inequality. Similarly, changes in aggregate resource extraction and use are often reported, but are not necessarily split into various resource categories (metallic minerals, energy carriers etc.). The following section focusses on the results of existing studies in terms of GDP and aggregate resource extraction, the metrics for which data is most readily available. This analysis comes with the caveat that the results of individual studies are not directly comparable, since the modelling assumptions as well as the characteristics of the implemented policies differ.

Additional indicators would be worthwhile, among which environmentally-adjusted or “green” GDP, which none of the studies reported. Adjusting GDP for changes in natural capital stocks and ecosystem services has been advocated, for instance in (Boyd, 2007), or as a part of the debate around green growth (Stiglitz, Sen and Fitoussi, 2008; Reilly, 2012). Although measuring green GDP was not widely attempted in an ex-ante modelling framework, it could be considered in future assessments. Beyond natural capital accounting, assumptions concerning the role that natural capital plays in supporting economic growth can influence model results. Most models do not represent natural resources endowment, or the waste assimilation function or ecosystem services that they provide. Key barriers to representing feedbacks on future economic growth following a change in the availability or quality of these resources[36] include uncertainties about: (i) resource endowments, (ii) the responsiveness of natural systems to perturbations, and (iii) the monetary value of environmental damages. That said, several recent OECD publications have assessed the costs of inaction on urban air pollution and greenhouse gas emissions, and found that they could reach 1% and 2% of GDP by mid-century respectively (OECD, 2016c and OECD, 2017b).

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[35] In addition, all sorts of policies can influence consumer behaviour with unchanged underlying preferences by changing relative prices or regulating specific behaviour.

[36] Such as would be likely to occur if ongoing resource extraction results in the depletion of near-surface low-cost mineral deposits, or if capital flows are diverted away from productive investments in order to finance the provision of the ecosystem services currently available at no private cost.

3.3.1 Macroeconomic impacts

With respect to the baseline scenarios used, all of the studies considered in this review generate lower natural resource extraction through the implementation of circular economy policy instruments. This is generally achieved in a process of relative decoupling; future aggregate economic growth is either unaffected (i.e., continues as in business as usual), or shows, often significant, improvements (Figure 5). Only two studies conclude that a circular economy transition could have a significant depressing effect on economic growth; Schandl et al. (2016) find that economic output would be 1.6% below baseline by 2050 while Hu et al. (2016) find that it would 0.6% below baseline. A number of other studies find reductions in GDP of less than 0.1%.

These results provide policymakers with some cause for optimism. They suggest that a transition to a (broadly defined) circular economy might take place without significant negative impacts on aggregate economic growth and employment. That said, there are three important caveats to this conclusion. First, the results of ex ante modelling assessments are not predictions of the future. Rather, they represent one possible evolution of the modelled (endogenous) variables that is consistent with the assumptions contained in the model, and about the enabling policies themselves (for example, the assumptions regarding the achievable rate and cost of technological change). Results need to be interpreted with this in mind (see 3.3.3 and 3.3.4 for additional discussion). Second, that natural resource extraction can apparently be reduced without adverse effects on economic output suggests that there is significant inefficiency in the current economic system. What these inefficiencies are, and whether they can be practically addressed, is not always discussed, but should be in future work. Third, what is positive for the aggregate economy may not necessarily be so for all of the parts. Any transition to a circular economy will likely lead to particular countries, sectors, and types of skills doing better than others.

Possible distributional effects are important; concerns about the potential "losers" can hold back a transition in the first place. One consistent finding in existing modelling is decreased activity in upstream extractive sectors – mining, oil and gas, agriculture, fishing, and forestry – and material transformation sectors – metal smelting and fuel refining. Countries specialising in these activities, and workers employed in them, are likely to emerge worse off from a circular economy transition.[37] For example, in their Global Cooperation scenario, Meyer et al. (2016) find that Russia (-27.7%), Brazil (-16.5%), and Canada (-7%) would experience significantly lower GDP relative to business as usual to 2050 (global GDP increases by 5.2% in this scenario). Other sectors may expand when circular economy enabling policies are implemented. Modelling shows that manufacturing activity often increases as technological change proceeds, waste management and recycling activities grow as manufacturers substitute secondary for primary materials, and the services sector expands as consumers substitute services for goods.

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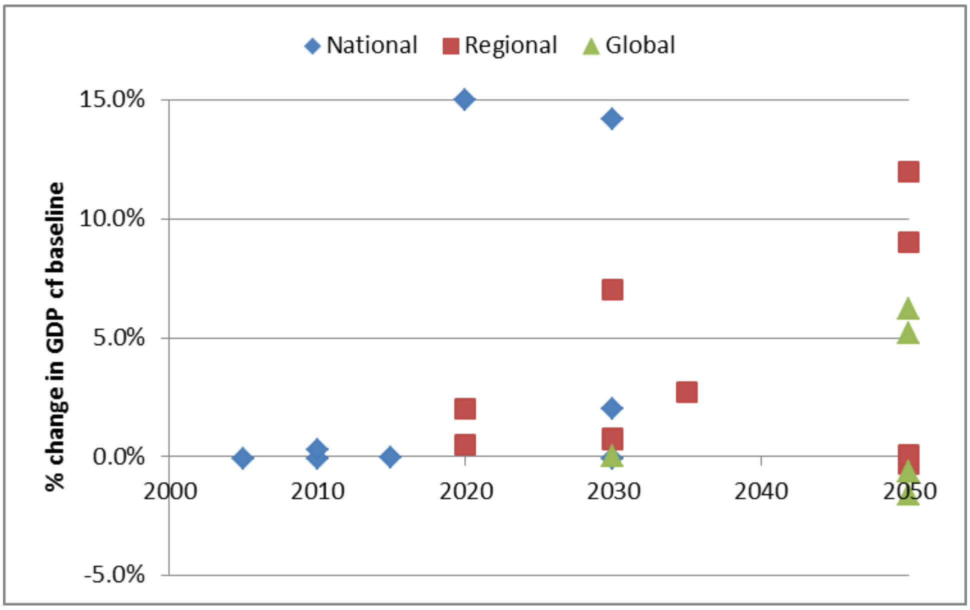
[37] Social and labour market policies can be considered to alleviate the worst impacts on local communities that rely heavily on these shrinking economic activities.

Figure 5. Headline modelling results in the studies considered in this review: GDP with respect to baseline

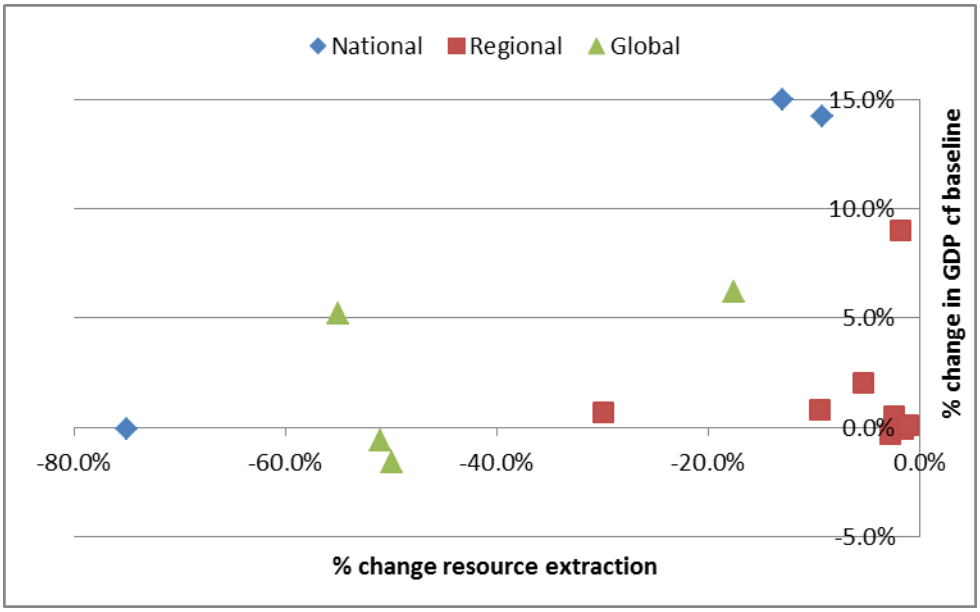


Note: Geographic coverage – national, regional, global – refers to the area that results were reported for. Some models have global coverage but only report results for a particular region.

3.3.2 Impacts on resource extraction

The results of existing studies suggest that the implementation of circular economy policies can reduce resource extraction by up to 80% relative to business as usual (Figure 6). They also highlight the existence of a trade-off, at least in the time horizons considered, between higher rates of economic growth on one hand, and lower resource extraction on the other. As shown in Figure 6, a number of assessments indicate that circular economy policies (almost exclusively those relating to productivity improvements) can boost economic growth, but without any significant reduction in resource extraction. This is probably not surprising; productivity improvements are critical for growth in the long-run, but can also trigger strong rebound effects as household incomes grow. A number of other assessments shown in Figure 6 find that circular economy policies can generate large reductions in resource extraction, but without any significant boost to economic growth. This is probably largely due to additional costs that are imposed on economies due to the material taxes implemented in these studies.

Figure 6. Headline modelling results in the studies considered in this review: GDP and resource extraction with respect to baseline



3.3.3 Assumptions about the implemented policies can determine results

Four of the studies considered in this review find that a circular economy transition could result in GDP gains in excess of 5% by 2050 (Distelkamp et al. 2010; Bohringer and Rutherford, 2015; Bosello et al. 2016; Meyer et al. 2016). With the exception of Bosello et al. (2016), which represents technological change endogenously, each of these studies introduce exogenous changes to either production technologies or consumer preferences. The underlying assumptions about the achievable rates and costs of these changes appear to drive modelling outcomes to a significant extent. For example, Bosello et al. (2016) state that "while the effect of increasing R&D expenditure is notoriously difficult to assess, this instrument was judged as being a necessary precondition for the success of all others". More generally, assumptions concerning the rate and cost of technological and preference changes are not always well presented and sensitivity analysis of changes in key parameters are often not undertaken. These factors, taken together, make it difficult to assess the robustness of the modelled macroeconomic gains.

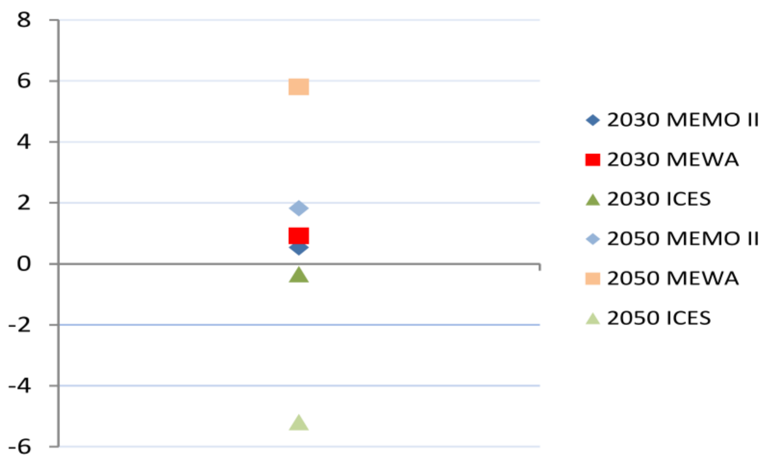
Many studies also introduce material taxes to promote a shift away from the use of natural resources, raw materials, or goods produced in materially intensive sectors. The size of these taxes, and the treatment of the resulting tax revenues, differ considerably across studies and often appear to drive diverging results. In their central scenario, Cambridge Econometrics (2014) introduces raw materials taxation and recycle the revenues back to consumers through lower labour taxes. This results in a small positive GDP impact, but which the authors emphasise is conditional on the revenue recycling assumption. Without this, "the net positive GDP impacts are much smaller and become negative over time". Other studies use revenues originating from material or environmental taxation to finance green R&D programs. One example is provided by Bouzaher et al. (2015), which implements taxes on emissions (PM_{10} and CO_2), solid waste, and waste water, and recycles them in two main ways. In the first, the resulting tax revenues are used to reduce corporate taxation elsewhere in the economy; this results in a large (~14%) reduction of GDP below baseline. In the second approach, these revenues are used to finance green capital investment and R&D; the resulting technological change results in a small increase in GDP (~2%) above baseline.[38]

Whether a particular enabling policy is implemented individually or as one element in a broader policy mix also influences results, as optimal reactions to a policy mix differ from those to the sum of individual policies. In particular, the technological change assumed in many models drives material productivity improvements, but the resulting reduction in material extraction is often, at least partially, offset by rebound effects. Several studies therefore emphasise the importance of coupling R&D policies with those that increase the relative prices of natural resources and primary materials. Bosello et al. (2016) state that "although supporting material efficiency R&D might seem the "optimal" policy to foster absolute decoupling, it should be accompanied by further regulation or incentives limiting material use or promoting dematerialised services".

3.3.4 Assumptions in the models themselves also determine results

Assumptions inherent to the models themselves can also drive modelling results. This is well illustrated in studies that use different models to assess the impact of a particular circular economy policies or policy mixes. For example, Bosello et al. (2016) introduce a material tax on the output of the major extractive sectors, and find quite different results across the models used. Implementation of the tax in the ICES model generated a 5% reduction in GDP by 2050 relative to business as usual whereas implementation in the MEMO II and MEWA models generated increases of 2% and 6% respectively (Figure 7). One key difference between the models is that the latter two include a mechanism for endogenous technical change; the incentives created by increasing material prices can stimulate the development of material saving technologies. The resulting productivity and GDP growth therefore occurs in MEMO II and MEWA, but not in ICES[39].

Figure 7. Effects of a materials tax in the ICES, MEMO II, and MEWA models



38 There are also some other differences between the scenarios that may affect the GDP impacts, but the authors suggest the recycling mechanism is the dominant factor here.

39 Material tax revenues are also treated differently across these models. They are rebated in a lump-sum transfer to households in ICES and recycled through reduced labour taxes in MEWA. MEMO II rebates 50% of tax revenues and recycles the remaining 50%. Some of the variation in modelling results is likely to reflect this.

A second example is provided by the POLFREE project, which utilised two models – EXIOMOD CGE and GINFORS ME – to assess similar circular economy policy mixes. Strongly contrasting results emerged from each model. In the GINFORS simulations, under their Global Cooperation scenario[40], highly ambitious climate and resource extraction targets were achieved with an associated 5.2% increase in world GDP by 2050. When implemented in EXIOMOD, the same set of policies were unable to achieve the desired environmental targets, and resulted in small decline in GDP (-0.6%) relative to baseline. Meyer et al. (2016) highlights underlying differences in the theoretical foundations of the two models as a key reason for this divergence. The Keynesian assumptions embedded in GINFORS – a demand driven economy with underutilised capacity and supply clearing the market – can generate strong multiplier effects. Essentially, new investment, either originating directly from public spending or indirectly from additional private saving associated with efficiency gains, spurs job creation, resulting in higher aggregate income, additional consumption, and ultimately higher aggregate output. This mechanism is a key reason why Walz (2011) concludes that "macro-econometric models tend to assess the effects of environmental protection policy slightly less pessimistically than the equilibrium models. This is particularly distinct in the more Keynesian oriented models…".

One key difference is that some models tend to assume new investments do not crowd out investments (nor employment) in other sectors, while others assume full crowding out. In the latter case, a change in investment from a highly productive but polluting sector to investments in material savings will lead to a negative effect on the macro economy, while in the models without crowd-out the new investment by definition boost income. Whether such assumptions are more valid in the longer run, when there is ultimately a finite supply of productive labour and capital, is questionable. The effects of this assumption are stronger on GDP than on consumption, at least in models than maintain an income constraint (consumption plus savings equal income, and overall savings equal investments), implying that it is more useful to look at consumption impacts than GDP impacts.

40 Which involves a broad set of economic and regulatory instruments implemented across each of the regions in the model.

4. CONSIDERATIONS FOR FUTURE MACROECONOMIC ASSESSMENTS

Ex-ante, economy-wide, quantitative dynamic models appear to be the tool best suited for assessing the likely macroeconomic consequences of a circular economy transition. *Ex-ante* modelling analysis is more appropriate than ex-post empirical analysis because many aspects of a circular economy transition are "out of sample"; the policy mixes that are typically suggested have not been widely implemented historically.[41] *Economy-wide* modelling appears indispensable because a circular economy transition will involve spill-over and interaction effects between sectors, thereby leading to structural shifts across the economy across sectors and regions. The *quantitative* nature of these tools helps paint a comprehensive picture of all the complex systemic interactions brought about by the circular economy transition, and clarifies which mechanisms lead to significant changes in the socioeconomic system. *Dynamic* modelling is preferable as the transition to a circular economy will take place in parallel with other major socioeconomic trends such as digitalisation and automation, and future resource use will significantly differ from current patterns.

Two specific categories pertaining to this class of models – macro-econometric (ME) and computable general equilibrium (CGE) models – have been the main focus of this review. These are only very recently being employed more widely in the context of a circular economy transition; well over half of the known literature has been published since 2015. The main message from the studies reviewed in this paper is that lower rates of resource extraction and use can be achieved with associated increases in aggregate economic output. However, this review identified the issue that the robustness of this key conclusion crucially depends on assumptions about the enabling policies implemented, and about mechanisms in the models themselves. In this respect, there remains considerable room for improvement. The following sections offer four concrete recommendations for future modelling assessments.

Specific recommendations on the choice of the regional aggregation, incl. single-country versus global modelling, cannot be made, as there are merits to having a variety of in-depth national studies in combination with global assessments that provide the international context. Modelling at different regional scales can thus nicely complement and inform each other.

Similarly, it is hard to draw conclusions on which policy instruments need to be modelled. A wide variety of instruments have been included in existing studies (see Table 3), although even these do not include all instruments contemplated by policy makers. It is clear that the 'soft policies', such as extended producer responsibility, green public procurement, eco-design and labelling, are important from a policy perspective, while also being the hardest to adequately represent in modelling exercises due to a lack of data on the costs and effectiveness of these policies and their often local and heterogeneous nature. Nonetheless, future modelling studies would do well to study broad policy packages and not limit themselves to taxes and subsidies, as that would provide a partial and biased view on the potential effectiveness and costs of the transition to a circular economy.

41 This does not imply that empirical analysis on this topic should not be pursued. Empirical studies, that will probably at least initially be of a more local nature, can complement and eventually strengthen modelling exercises.

4.1 Baseline development

There is considerable uncertainty surrounding the evolution of natural resource extraction and use in the coming decades. In a baseline development without new policies, there are still several mechanisms that will influence material use that are fundamentally uncertain. One uncertainty relates to the base year use of resources; although there are different databases, they often contain considerably different numbers. Second, a crucial source of uncertainty concerns the evolution of economic activity over time and the associated changes in economic structures over time. Finally, the uncertainty on the rate of decoupling resource use from economic activity, which relies on the evolution of alternative production technologies, is a critical assumption that affects future resource use.

Given the strong links between economic activity and resource use, the evolution of economic structures and its impact on natural resource use is vital for projecting future resource use. The baselines used in some of the existing models assume decoupling rates that are considerably higher than those observed historically. Historic trends give some indication of what may be possible in the future, but these trends are insufficient by themselves to assess the likelihood and possible impacts of structural changes in production and consumption patterns. The importance of these changes is stressed in many discussions of the circular economy. To some extent, they are playing out already with the emergence of the sharing economy and product as service business models, as well as through major socioeconomic trends such as globalisation. Other factors, such as how consumer preferences are likely to evolve in the absence of new policies, have important implications for resource use but are surrounded by uncertainty. Future assessments would benefit from clearly identifying the driving assumptions behind future resource use to assess the plausibility of these baseline developments.

A possible but more complex route to understand the range of plausible projections of future resource use and the circularity of the economy could be the creation of multiple baseline scenarios, with a range of assumptions about the evolution of key drivers and the impacts of structural change. This would allow the macroeconomic consequences of a circular economy transition to be assessed in different future states of the world; it is clear that projections of future resource use will substantially differ across each of these. Such scenario analysis can take the form of a systematic sensitivity analysis where one major driver at a time is varied, or more complex sets of assumptions that together provide a consistent world view (a storyline). An existing example of the latter methodology is the design of the Shared Socioeconomic Pathways (SSP scenarios) developed in the climate change community, where the deep drivers of climate change mitigation and adaptation serve as basis for creating five contrasting storylines to assess the consequences of policy. However, this route involves an extensive analysis of the produced scenarios and may not improve clarity of the policy insights.

Presenting multiple baselines has at least two major advantages. First, the large underlying uncertainties in projecting future materials use are clearly laid out. Secondly, when analysing the costs and benefits of specific policies across multiple baseline scenarios, no-regret options that are worthwhile regardless of which scenario materialises can be identified. Moreover, robust policy interventions can be identified that work well in all scenarios. More advanced modelling techniques will also allow the identification of hedging strategies, i.e. the specification of policies that maximise the expected net benefits of action, but these are difficult to implement in large-scale models.

To understand the consequences of domestic consumption patterns and resource policies at a global scale, information is needed on how economic activities are internationally linked in global value chains and bilateral trade flows. Building on such information, a footprint type of analysis can be made by looking at the embedded materials use in imported goods and services, i.e. moving from Domestic Materials Consumption to Raw Materials Consumption. This is however very data and computationally intensive, as discussed in Section 2.3. Furthermore, in a global analysis overall materials consumption is identical.

4.2 Modelling technological change

The direction and speed of technological change will be a critical driver of any future resource decoupling. More efficient technologies for upstream processes will mean that a greater proportion of metal can be extracted from ores, and goods could be built with less material (e.g. cars). Innovative new product designs will provide equal or higher levels of functionality without additional material inputs. The emergence of new business models will extend the in-use lifetime of products, others will increase their utilisation rates. Further downstream, the development of improved material sorting technology will allow for more efficient separation of different materials in the waste stream.

In almost all of the studies considered in this review, modelled policy scenarios assume a significantly higher rate of productivity growth than in the respective baselines. Overall technological change is typically implemented exogenously – there are no linkages with the underlying drivers of innovation. Furthermore, in many cases, these productivity gains appear for free; the costs of developing and adopting resource efficient technologies are ignored. Finally, where technological change is costed, it is often done so linearly: there is no decrease in marginal productivity gains with each unit of additional investment. Some studies do, however, explicitly represent competition between existing and future technologies, and substitution towards more efficient technologies. Technology-specific modelling gives a richer description of the technological dynamics, but comes at the price of an increased need in data (and is hindered by the fact that innovations are difficult to predict).

Future macroeconomic assessments of a circular economy transition would benefit from addressing both technology choice and technological change, even if a detailed description of endogenous innovation is currently out of reach for large-scale models. First, assumptions about the potentially available rates[42] of future resource productivity growth need to be considered. For already existing technologies, the development of bottom-up technology models would allow the resource saving potential associated with their widespread adoption to be better constrained. In addition, any assumptions about the emergence of new technologies – those that are currently unknown – should be clearly presented with caveats. Second, the costs associated with the development and adoption of resource efficient technologies should be incorporated into modelling frameworks. These are likely to have a strong influence on technology adoption decisions. They will also have consequences for other parts of the economy; investments in resource efficiency may divert funds that would otherwise be used elsewhere. Only when such costs are considered will the macroeconomic consequences of circular economy enabling policies reflect the net gains from the policies. The main hurdle here is the valuation of those costs, which ultimately require detailed, and often time consuming, bottom up technology modelling to establish in detail.

4.3 Representing substitution

Substitution away from natural resource inputs is a key element in most conceptions of a circular economy transition. Indeed, the main purpose of the resource or material taxes that are often discussed in this context is to stimulate this substitution. Three main supply side substitution possibilities exist: (i) between a particular material and other production inputs such as capital and labour, (ii) between different types of materials, and (iii) between primary materials (derived from natural resources) and secondary materials (derived from waste). Substitution opportunities also exist on the demand side of the economy. Firms and households can substitute away from material intensive goods and services, either by consuming a different bundle of products or by consuming products that fulfil the same use, but in a less material intensive way. Any future substitution will be driven primarily by changes in relative prices and by the

[42] This will likely feature some divergence across different resource types; assigning rates derived from the energy literature to other resources will probably introduce significant biases.

ease with which these inputs can substitute for each other. This suggests that models that capture the sectoral interactions and responses to changes in relative prices, such as CGE or ME models, are particularly well-suited to study the economic effects of circular economy enabling policies.

Many of the models considered in this review do not allow for one or more of the above substitution possibilities. Substitution between natural resources and capital or labour is largely precluded by the nesting structure of most production functions; resource inputs can substitute with other intermediate inputs, but not (directly) with various components of value added. Similarly, substitution between primary and secondary materials is precluded by the absence of secondary sectors in most SAMs.

Future macroeconomic assessments of the circular economy would benefit from addressing both of these issues. The energy modelling literature offers some possible direction in the former case; materials could be allowed to trade off with capital and labour in much the same way that energy does in energy-focussed models. In the latter case, substitution between primary and secondary materials could be achieved in a variety of ways, but ideally requires the introduction of a secondary production sector (for each material of interest) into the SAM. A number of existing single-region models do this. The challenge to do so is the collation of comprehensive data for assessing the potential for substitution. This difficulty is magnified in a multi-region framework given the differences in economic and biophysical circumstances in different countries.

A further complication in adequately representing substitution between virgin and secondary materials is the need to specify supply constraints for secondary materials. Most models do not have any capacity constraint on the secondary sector, which implies an overestimation of the potential substitution effect. In some models, this is overcome by using CES functions with a constant elasticity that inherently assume that substitution becomes more difficult once the share of secondary materials increases. This should ideally be coupled with constraints on the supply of secondary materials. The lack of full stock-flow accounting (as highlighted in Section 2) hampers an endogenous representation of the supply of secondary materials over time, and therefore the most advanced models apply ad-hoc rules on secondary material supply.

Representing these substitution possibilities in a detailed manner in models will thus require a large volume of data for the various, materials, material uses, sectors regions. This data is not yet available[43]. An alternative modelling approach (especially when data is scarce) is the use of CES functions to represent the different inputs (materials, capital, energy, and labour) associated with different technologies. One initial approach may be to use sensitivity analysis to frame the range of likely outcomes.

4.4 Modelling "soft" enabling policies

There is a clear divergence between the circular economy enabling policies emphasised in policy forums and those implemented in modelling assessments. General discussions about how to enable a circular economy transition tend to highlight an extensive list of policy measures, many of which focus on promoting changes in consumer behaviour (so-called soft policies). This is in contrast to the studies considered in this review; most tend to focus on a relatively narrow policy mix consisting mainly of technological change and upstream materials taxes. Many soft policies – those that do not directly affect prices – are significantly under-represented. Important examples include extended producer responsibility (EPR) schemes, public education campaigns, eco-design standards, and green public procurement.

[43] Particularly given that the appropriate elasticity will vary across different resources and materials, and across the different applications they are used in.

Future macroeconomic assessments of a circular economy transition would benefit from considering a broader set of instruments. If nothing else, this would provide policymakers with insights into the cost effectiveness of meeting resource efficiency targets with different policy mixes. Implementing soft policies in a large-scale modelling framework will clearly be challenging but, as highlighted by Dubois (2015), could be done through exogenous changes to production and utility function parameters. For example, the effect of eco-design standards could be modelled by modifying the production function of manufacturing sectors such that raw material inputs are used more efficiently (longer lived products reduce demand for material inputs). Similarly, a future shift in consumer behaviour from ownership to access, perhaps due to some public education campaign, could be represented by modifying the utility function of the representative consumer such that demand for services increases.[44] Doing so however is extremely difficult since the effectiveness of soft policies is not easily measured and thus the translation of such measures in physical and economic terms rests on many assumptions (many of them subjective and dependent on the policy analyst). In all cases, the motivation and assumptions behind these modifications should be clearly stated.

[44] For example, in the case of car sharing, the assumption is that the underlying preferences for mobility do not change because of the policy, but the expressed preference for specific commodities to satisfy this need for mobility do; thus, the modelled preferences for commodities will shift, thereby generating a change in behaviour.

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